Francisco J. Villalobos · Elias Fereres
Editors

Principles of Agronomy for Sustainable Agriculture

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Preface

This textbook is the result of a long experience teaching general agronomy at the University of Cordoba (Spain). After many years of teaching the subject to agronomy engineering students in Spanish, we now offer a separate class, taught in English, and this book reflects the organization and materials used in the class.

The book reflects our vision of agronomy as a complex, integrative subject at the crossroads of many disciplines (crop ecology, agrometeorology, soil science, agricultural engineering) with a strong emphasis on providing quantitative answers to specific problems. Our experience has been primarily with water-limited agriculture; hence, there is an emphasis throughout the book on the role of water in the agronomy of agricultural systems. We also seek to leave behind artificial boundaries that have been created in the past among crop production areas such as horticulture, pomology, and field crops that have led to separate journals and professional careers in the past. In this book, we cover all common aspects of crop management and productivity that should concern anyone dealing with the management of agricultural systems, and we provide relevant examples from different cropping systems, from herbaceous to woody crops.

Our quantitative approach is based on providing the ideas and concepts needed as foundations in all the quantitative assessments required for making informed, technical decisions in farm management. Farmers operate along the philosophy of learning by doing (adaptive management), and agronomists should also follow the same path, but they should have the knowledge and tools that are needed to first correctly interpret the complex responses of the system to change and then provide reasonable options for subsequent actions. This book does not fall in the category of those that focus on providing prescriptive agronomic recommendations or blueprints that cannot be generalized because of their empirical nature. Rather, we have tried to concentrate on the analysis of crop productivity processes which lead to identifying the main factors affecting management decisions and on how to get quantitative answers to agronomic problems in the context of making current agricultural systems more sustainable.

From a teaching perspective, the book includes two short blocks on the environment and crop productivity that could serve as an introduction for students with no background in soil science, crop ecology, or agrometeorology. The third, larger block, is devoted to specific crop production techniques (sowing, soil management, irrigation, fertilizers, etc.). A number of our colleagues have contributed to the writing, all with the aim of providing future agronomists and practitioners with the quantitative tools required to calculate the adequate level of inputs (such as water, nutrients, or energy) for sustainable crop production and to assess the yield responses as a function of climate and soil conditions and of management options.

Cordoba, Spain

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Finally we dedicate this book to our families, whose love and support has been the engine moving us forward.

Contents

Part I The Crop Environment

Part II Crop Productivity

Part III Crop Management

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Chapter 1
Agriculture and Agricultural Systems

Elias Fereres and Francisco J. Villalobos

Abstract Crop Ecology deals with agricultural ecosystems that are manipulated by man to funnel the maximum energy into usable products (food and raw materials). Agricultural ecosystems show normally low biodiversity, low autonomy and a short trophic chain. The main features of farming systems are productivity, stability, resilience, and sustainability, the latter indicating the ability to maintain a certain level of production indefinitely. Production of agricultural systems requires inputs of matter, energy and information. Normally the economic optimum provision of inputs is below that necessary to achieve maximum production. Various parameters have been defined to characterize the productivity of agricultural systems (potential yield, attainable yield, actual yield).

Agricultural activity is characterized by uncertainty due to numerous environmental and economic factors. Faced with uncertainty, farmers' decisions are focused on avoiding risk and that may lead to losing opportunities. To make rational decisions the farmer has access to many sources of information, ranging from their own experience to research/technology transfer. The current trend is to improve the acquisition, sources, and the use of information on the agricultural system for improved decision-making.

1.1 Introduction

According to recent FAO statistics, agriculture occupies 28 % of the land area of the Earth, with 30 % devoted to crops and 70 % to pastures. Broadly, the cultivated area is less than 10 % of the total land area, encompassing around 1500 million ha largely unchanged since 1960, as expansion of new cultivated land has been offset

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by the disappearance of arable land due mostly to urbanization and to irreversible soil degradation. Of this area, 90 % is devoted to annual crops and 10 % to perennial crops. Irrigated lands occupy more than 300 Mha, representing 17 % of the cultivated area. Cereals are the dominant crops representing nearly 60 % of the total cropped area. In fact, although more than 7000 plant species are used in agriculture, only about 120 are considered important, and more than 90 % of the calories consumed by humans today come from less than 30 species. This does not mean that agricultural biodiversity is low, because there are germplasm collections harboring many thousands of different genotypes for all the main crop species.

Farming allows man to produce food and other products by managing and manipulating the trophic webs of ecosystems (Box 1.1). Agriculture is a set of human interventions that alter ecosystems to maximize the yield of the desired product and minimize energy losses along trophic chains. The science and technology of producing and using plants for human use is Agronomy. It deals with the exploitation by man of terrestrial ecosystems and has, therefore, its roots in ecology. The ecosystems modified by agriculture are called agroecosystems and the science that deals with their study is Crop Ecology. An agroecosystem is an ecosystem managed by man with the ultimate goal of producing food and other goods and services derived from agriculture. Population pressure has reduced the area of ecosystems free of human intervention. However, there are reserves, forests and other areas that may be called natural ecosystems, which are generally characterized by higher biodiversity, longer trophic chains and higher autonomy than agroecosystems.

The agroecosystem is characterized by the presence of a lower number of species than the natural ecosystem. This lower diversity is a result of the need to reduce energy losses along trophic chains in agricultural ecosystems, which aim to remove all unwanted energy transfers (to parasites, pathogens or plants which compete with the crop) and is usually associated with a shortening of the trophic chain. The energy autonomy of agroecosystems is relatively low because they depend on inputs of materials, energy and information provided by humans.

The unit of study in Crop Ecology is the field or plot. A community of plants, along with management practices (e.g. tillage method, rotation, etc.) located on a field is called cropping system. At this level one can analyze the production processes of plants, their relationships with the soil and their dependence on the aerial environment. By observing the same plot for several years we can analyze the effects of rotation, tillage practices or crop residue management on soil properties and resulting yields, as they are affected by the use of resources such as water and nutrients. Economic analyses or determining manpower needs are often made at the plot scale. A farm represents a single management unit constituted by a number of fields or plots.

At a higher level of organization, the cropping system is part of a farming system where other elements (e.g. livestock) are also managed by the farmer providing inputs to the crops or using crop products. The different crops and management practices prevalent in a given area, are called agricultural systems at a regional scale.

Agriculture, like all human activities, has known successes and failures throughout its history. Today agriculture produces enough food for the vast majority of the world population, despite the unprecedented population growth experienced over the last 50 years. However, it has also negative environmental impacts such as soil degradation and water pollution from the use of fertilizers and pesticides, excessive use of water resources, and the reduction of biodiversity. Furthermore, other sectors of society are very sensitive to a diverse set of problems created by agriculture, notably those related to food safety and to the threats to natural ecosystems.

Box 1.1 Ecology and Ecosystems

Ecology is the science that studies the relationships between organisms and their environment. The environment is the set of biotic and abiotic factors affecting growth, reproduction or mortality of organisms. Environmental factors may also be divided into resources when the factor is directly consumed by the organism (e.g. a nutrient) or regulators, when they affect the rate of use of resources (e.g. temperature).

An ecosystem is a group of organisms and the environment that coincide in time and space. The ecosystem is the fundamental unit of study of ecology. The organisms in an ecosystem are interrelated by flows of energy and materials. The dimensional characterization of the energy flows in the ecosystem is called the trophic chain. The primary source of energy is solar radiation, the driving force of life on Earth. Primary producers fix solar energy through photosynthesis, transforming it into usable energy that will move along the trophic chains. Over millions of years, the man has obtained the energy required for living from different trophic chains, by hunting and by gathering edible plants until 10,000 years ago, when agriculture was invented.

1.2 Characteristics of Agricultural Systems

The primary objective of farming is the production of sufficient food and other goods and services so that the farm stays viable. Therefore, a key feature of farming systems is their productivity, defined as output per unit of resource used, commonly referred to the cultivated area, which is the primary limiting factor of agriculture. Thus, productivity is defined as the yield of usable product per unit area but can be applied to other natural or artificial inputs as radiation, water, nutrients or labor, which are also typically measured per unit of area. The productivity level further serves as an indirect measure of the efficiency with which these inputs are used.

When characterizing agricultural systems, the term efficiency is often used to define the ratios of crop productivity and certain inputs. For example, efficiency of water use is defined as the ratio of yield to the volume of water used, but it would be more correct to speak of the productivity of water or nutrients, expressed as kg/m^3 water or kg/kg nutrient. In engineering, efficiency is the ratio between the output and the input of any entity in a system, for example, the energy supplied to an engine.

Besides productivity and efficiency there are other important properties of agricultural systems. Yields may vary from year to year by weather and other causes. The term stability refers to the magnitude of these oscillations. The lack of stability causes fluctuations in production that threaten the persistence of agricultural systems. This is particularly true when there are sequences of successive years of low yields that may have a catastrophic effect on their economic viability. Related to the fluctuations in productivity, there is another feature termed resilience which is defined as the capacity of the system to recover from a catastrophic event, for example a drought. High resilience is a desirable property of agroecosystems.

Another feature of farming systems is their sustainability which indicates the ability to maintain a certain level of production indefinitely. This feature stems from the concept of sustainable development, a development model that proposes economic growth without adversely affecting the opportunities of future generations. A farming system is considered sustainable when it is economically viable and socially acceptable, however, one must define the time frame, because what is feasible and acceptable today may not be so in the future. Thus in agricultural systems it would be more correct to speak of the degree of sustainability: a system will be more sustainable when its exploitation does not degrade the quality of water and soil resources, and when current management practices do not affect the productivity and viability of the system in the future. The improvement the sustainability should be based on two objectives: reducing or eliminating, if possible, the negative environmental effects of agriculture while maintaining high productivity. Decades of intensive production in many agricultural systems have caused negative environmental effects and have created awareness of the need to focus on the sustainability of the agricultural systems, leading to a debate about developing new forms of agriculture that ensure economic and ecological sustainability.

1.3 Management of Agricultural Systems

The strategy of agriculture is to manipulate the environment and the plant community to optimize the yield of goods useful to mankind. This involves establishing communities (crops or pastures) dominated by species that distribute a large proportion of the primary production to usable organs or materials. In addition, the farmer tries to minimize system losses due to insects, diseases and weeds.

Farmers have numerous management tools to control their crops, such as tillage for weed removal and seedbed preparation, choice of species and cultivars, sowing date and sowing density, application of fertilizers and pesticides, etc. External factors such as climate and markets are difficult to predict so the flexibility in managing the crop is very important to minimize the risk of crop failure or of economic losses in the farm. For example, an application of fertilizer may be reduced or waived if the rainfall is very low or if the expected price of the product is very low.

In general, for many resources the response curve of yield versus input level is curvilinear and the maximum profit is obtained at a level of resources below (but not far from) that required for maximum yield. This is because of the synergies that occur among inputs and of the addition of fixed costs, which make low input strategies generally inefficient. The more productive and more profitable farms are those that use resource levels which are commensurate with the production target, without any input clearly limiting yield. For example, there is little point to provide additional water as irrigation if the additional quantities of fertilizer required to realize the targeted yield are not provided.

Example 1.1 The response of a wheat crop to N fertilizer in a rainfed Mediterranean area is shown in Table 1.1. In this case the highest yield is achieved using 250 kg of fertilizer N per hectare. However, the economic optimum is achieved with an application of 200 kg N/ha. We can also see that a very limited use of resources leads to worse economic performance than overuse.

Table 1.1 Analysis of the response of a cereal crop to N fertilizer applied. The selling price is 0.25 €/kg, the fertilizer cost is 0.80 €/kg and the fixed cost is 200 €/ha

N applied	Yield	Income	N cost	Income – N cost	Net profit
kg N/ha	kg/ha	€/ha			
0	1200	300	0	300	100
50	1929	482	40	442	242
100	2329	582	80	502	302
150	2558	640	120	520	320
200	2883	721	160	561	361
250	3020	755	200	555	355

The criteria for managing agricultural systems must take into account many factors that are affected by farmer decisions. Not only plant and animal production processes are important, as are economic objectives, but also the effects on soils, water, animal welfare and human health, landscape and biodiversity, among others, have to be considered. All these items have a different weight depending on the farming system under consideration, although, as in any other business, when the farm is not dedicated to the subsistence of the owner, it is handled essentially based on economic criteria. Nevertheless, there are many facets to the management of farming systems. In areas where the ratio population/arable land and input prices are low (e.g. USA and Australia), the emphasis is on maximizing profit per unit of labor. In Northern and Central Europe and in Japan, where arable land is the limiting factor and input prices and wages are high, farmers tend to maximize productivity per unit area. Similar goals are pursued in the agriculture of China and India due to the limited availability of land per farm. These situations contrast with those of many poor countries where labor is abundant and access to inputs and capital is scarce.

Crop yields are close to their maximum potential only in a few areas (as in farms of Japan and Northern Europe), so that the average yields of agricultural systems are generally poor indicators of potential productivity. Actual yields lie in a broad interval from zero (crop failure) to a maximum attainable level which is only limited by the aerial environment (solar radiation and temperature regime), this yield level is called potential yield. Actual yield is defined as the average yield of a cultivar in all the fields of a farm or of a specific region, and represents the state of the climate and soil and the ability of farmers to apply successfully the technology available to them.

The potential yield of a species in an area is achieved when the technology is not limiting, that is, when all inputs are used optimally. Strictly, this concept applies to the yield of a well fit cultivar with no limitations due to water or nutrients and full control of weeds, pests and diseases. In general, the potential yield is calculated using theoretical models based on climate and other environmental factors and on the morphological and physiological characteristics of the crop in question. In practice, these estimates of potential yield should be contrasted against record yields obtained by the best farmers in the same geographical area.

There is a considerable gap between actual and potential yield in most agricultural systems, so sometimes other indices are defined for diagnostic purposes For example, attainable yield is defined as the yield achieved within environmental constraints of climate and soil of the area, using the best technology available today. The yields obtained by the best farmers and research stations in the area are an indicator of attainable yield. The attainable yield in particularly favorable years, result in record yields.

The concepts of potential and actual yield (and to some extent attainable and record yields) are very useful for the evaluation of farming systems and the identification of possible improvements that will help in closing the gap between them. These concepts are also used to define cultivation intensity. In the intensive agriculture of Japan and Northern Europe, actual yields are close to potential yields and the yield gap is small. As yields approach potential levels, there is little incentive for farmers to further intensify production and there is always some gap between actual and potential production in all systems. As the difference between actual and potential yield increases, so do the opportunities to increase productivity.

1.4 Types of Agricultural Systems

Agricultural systems can be classified according to various criteria. An ecologically based approach is based on the type of trophic chain. The shorter chain is one in which crops are directly consumed by humans. In other chains, crops or pastures are eaten by livestock, which in turn is consumed by humans. The energy efficiency of a system is lower the greater the number of levels of the trophic chain. On average each transfer in a food chain has a net efficiency of about 10 %. Thus, for a net primary productivity of 100 units, if it is consumed directly (vegetarian diet), the transfer of energy is close to 100. If cattle are employed to transfer the energy to humans only 10 would be recovered. This does not imply that animal husbandry should be abandoned. On the one hand, animals are the only choice for exploiting marginal areas where crop production is not possible (see below). On the other, some animals can use materials not digestible by humans (e.g. cellulose in crop residues) or not suitable for food (e.g. food leftovers, residues from industrial processing).

Farming aims at minimizing energy flows through undesired routes (weeds, insects, etc.) that end up in the level of decomposers. As we have seen, a short food chain (crop → humans) is the most efficient from an energy transfer standpoint. However in many agricultural systems environmental conditions (for instance, very shallow/poor soils) prevent obtaining products for direct use by humans (e.g. grain production) and only pastures may be grown. There is also the case of areas with semi-permanent flooding or the very arid areas. In all of these situations, cattle allow the conversion of primary production to other usable forms by man, even at the cost of lower efficiency.

Agricultural systems may be characterized also according to their position within an interval that goes from subsistence agriculture to intensive agriculture. In subsistence farming, many species are used, cultivars are adapted to the specific environments, yield potential is low and actual yields are low but stable. They are also very labor-intensive and livestock is a main component in nutrient management. This leads to high energy efficiency. At the opposite extreme, intensive agriculture is characterized by lower genetic diversity (both in terms of species and cultivars) in search for high yields, greater use of machinery replacing labor, as well as high use of fertilizers and pesticides, resulting in high productivity but often with low efficiency.

Historically agriculture in developed countries has undergone a transition from subsistence farming to intensive agriculture with a continuous increase in productivity and a gradual decline in energy efficiency. The routes differ depending on how land use has evolved in the different countries: For instance, Canada, Australia and large parts of the USA and Argentina, have not intensified their agriculture as much as it has occurred in Northern and Central Europe and in Japan. In many Asian countries, a very intensive agriculture is practiced with high use of certain inputs and low yield gaps. Therefore in some developed countries we may find extensive systems with low inputs, but high level of mechanization, that require large areas for the farm to be economically viable, while in other countries (mostly developing) highly productive systems with high use of labor may coexist with subsistence agricultural systems.

The intensification of agriculture in many countries has led to major pollution episodes due to excesses in the use of inputs such as fertilizers and pesticides and, in some cases, to the production of agricultural surpluses due to ill-conceived subsidies. In some cases, food safety incidents have been related by the public opinion of these countries to agricultural intensification. This has led to proposals to develop alternative agricultural systems, some based on avoiding the use of mineral fertilizers and synthetic pesticides, such as in the different forms of biological or ecological agriculture, called organic farming. Other alternatives have proposed to adopt agricultural practices that are environmentally friendly and that ensure the quality and safety of food. The term “sustainable agriculture” refers to farming practices that allow the indefinite maintenance (sustainability) of agricultural systems, which requires the conservation of resources and the maintenance of economically viable farms. Some experts speak of a transition from traditional agriculture (low input, low control) to intensive agriculture (high input, low control), from which we must move to an agriculture which is more sustainable (inputs optimized, high control), where resources are used only in the appropriate amounts for each system and where there is a better control of the environment and the crop.

1.5 Decision Making in Agriculture

Farmers must combine a number of biological, physical and economic factors when making their decisions. The success of a farmer’s activity can be measured by several variables (e.g. net income, yield, minimum risk, etc.), But not only is the average value of the variable important, also are its statistical distribution and extreme values. Agricultural activity is characterized by the uncertainty of a system that depends on the weather, which is highly variable and on relatively unpredictable biotic factors (pests and diseases). Therefore, the same agricultural practices can lead to different yields in different years. One can therefore assume that a set of agricultural practices will result in a frequency distribution of the variable considered (e.g. yield). Knowledge of this distribution would be necessary for the farmer to make decisions rationally. For example, a set of agricultural practices can result in a high average yield, but very low yields in certain years, which would have catastrophic effects on the economic viability of the farm. A farmer may choose to get a lower average yield in exchange for avoiding those years of very low yield.

Example 1.2 The result of two different nitrogen fertilization strategies (A = no fertilizer, B = 50 kg N/ha) over 30 years in a cereal crop is shown in Fig. 1.1. The average yield is higher for strategy B, but strategy A has a lower standard deviation (217 vs 583 kg ha^{-1}). Strategy B (apply fertilizer) implies a higher risk (lower yields in the worst years). If the farmer cannot stand a single year of low yield, strategy A will be preferred, although it involves lower average yield.

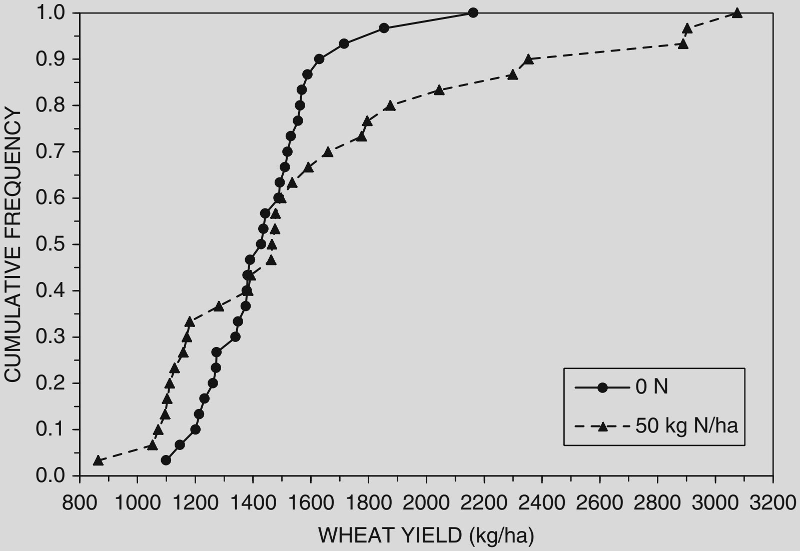

Fig. 1.1 Cumulative frequency of wheat yield with zero N fertilizer or 50 kg N/ha in a very dry area. The mean and standard deviations are 1447 and 217 kg/ha for zero N and 1606 and 583 for 50 kg N/ha, respectively

The uncertainty of farming is not just the result of climate variability and the possible occurrence of pests or diseases. Prices of agricultural products and inputs can deviate substantially from the expected prices for the farmer, which further hinders the process of decision making. The uncertainty of markets is proverbial, and more recently, the volatility of grain prices has caused food crises in several countries. The large price fluctuations have a very negative influence in the sustainability of farming, particularly in the case of fruits and vegetables, where there are many intermediaries between the producer and the consumer.

The general historical trend in agricultural systems around the world has been to develop management practices that reduce the risk, that is, to ensure sufficient yields in adverse years, but that do not fully exploit the potential in the most favorable years, even by sacrificing some yield in average years, thus not achieving the maximum average yield. In the past, when farmers did not have access to insurance or subsidies, a sequence of several years of bad harvests put in serious jeopardy the very existence of farming and the farmer. This has meant that avoiding risk is a priority in the strategic decisions of agriculture in many areas, particularly in rainfed systems. Examples would be the adoption of low tree density in rainfed olive orchards so that the tree always has enough water available, even in the worst droughty years, or the use of fallow in cereal rotations to store rainwater in the soil during the fallow year for the next crop. This tendency to avoid risk partly explains the slow adoption of new technologies in many agricultural systems, as compared to other productive sectors.

Decisions on a farm can be classified into four types (operational, tactical, strategic and structural) that correspond to different temporal scales. Operational decisions are made during the growing season (e.g. irrigation dates, amounts of fertilizer, date of application of an insecticide). Tactical decisions are made only once for each crop (crop choice and sowing date, target yield, etc.). Strategic and structural decisions have an impact on a number of crops (e.g. farm production orientation, investment in machinery, infrastructure improvements). Obviously, if we deal with multiannual crops (e.g. orchards), the temporary classification is changed, as in this case, the tactical decision affects a number of crop seasons.

1.6 Sources of Information for Decision Making in Agriculture

The farmer needs to know how the crop responds to different agricultural practices in a particular environment (soil and climate). Also, in order to make operational decisions, information is needed on the status of the crop and of the soil throughout the season. The sources of information available to the farmer to make decisions are quite diverse in terms of quality of information and of the cost associated with its acquisition. Today we tend to consider information as a production factor, absolutely necessary for efficient agriculture. The different sources of information available on how crops respond to different management practices are discussed below, with the exception of new technologies and the concept of Site Specific or Precision Agriculture which are presented in Chap. 33.

1.6.1 Farmer's Experience

The experience of the farmer is the traditional way on which all agricultural activity is based, and it may be the best source of information on agricultural systems that vary little over time. Local knowledge has developed over many generations and it integrates the multiple features of the environment and the society as they affect agriculture. It represents the human capital of a rural area which needs to be protected and preserved. While traditional knowledge is always useful, sometimes it presents difficulties for adopting innovations or to adapt to new situations (crop or variety changes, new technologies, appearance of new pests and diseases, etc.).

The complexity of the agricultural system in which many biotic and abiotic factors interact, makes it difficult to correctly interpret the observed responses and to achieve a good understanding of system performance based solely on experience. Often, a particular phenomenon may be due to causes that have nothing to do with the apparent causes.

An additional problem is the adoption of farming practices, based on the "collective experience", which may be detrimental in the long term, even if they do not cause any apparent injury, thus remaining unchanged over time. As an example, we can cite the excessive tillage used for decades in many agricultural systems. Finally, another drawback of using only experience as the basis for decision making is the difficulty to detect processes that damage natural resources over the long term. A classic example is the loss of soil by water erosion, difficult to detect except when torrential rains create gullies that are obvious. However, corrective measures, once gullies occur, are no longer effective. Other problems such as salinization or acidification are very difficult to detect just by experience until the problem is severe and difficult to overcome.

1.6.2 Research, Experimentation and Technology Transfer

Research leads to new knowledge, new processes or new products. Research and experimentation are the only ways to produce new knowledge about the management of agricultural systems. There has been great emphasis in many developed countries for significant investment in agricultural research since the mid-nineteenth century. It can be said that these investments were the engine of economic development in these countries until the early decades of the twentieth century. Subsequently, investments in agricultural research have been the basis on which they have founded the notable increases in agricultural productivity since 1950, to the point that all the impact studies show that these investments stand as one of the best business of the public sector of all times. The success of agricultural research in the developed countries led to the creation around 1960 of a network of international agricultural research centers located in developing countries such as Mexico, the Philippines, India, Nigeria, etc. These centers are managed and coordinated through the Consultative Group on International Agricultural Research, which brings together more than 50 countries and international organizations and have been responsible for the worldwide development and dissemination of new varieties for the major crops, and for the introduction of management techniques to intensify production in a more sustainable fashion.

For scientific knowledge to reach the farmer and to adapt it to its needs, institutions were needed to transfer the new knowledge in parallel to those dedicated to research. These institutions are called agricultural extension services. The prestige and usefulness of extension services have been highly variable in the different countries, according to the investment, its tradition and the various forms of organization adopted. The growing use of the Internet as a source of information and of technology transfer has also taken place in agricultural extension. Extension services of U.S. universities often maintain pages with plenty of information for farmers in different states. An example is the page about horticulture at the University of California at Davis (http://virc.ucdavis.edu).

Agricultural research is often based on field experiments, usually performed in experiment stations, which are farms devoted to research and technology transfer. Results of experimentation have a limited validity in agriculture. As said before, a set of agricultural practices could have different results in different years. The same applies to the results of one experiment. Thus agricultural experimentation is slow and expensive (needs to be replicated for a number of years). Adopting the experimental results of a single year can lead to significant errors. It is necessary, therefore, to consider the results of several years and yet, there is uncertainty in extrapolating the results to other environments. This limitation highlights the need to use other tools to complement experimentation in decision-making.

1.6.3 Commercial Information

Many of the inputs needed in farming are commercialized and the private sector has made significant investments in research, particularly in recent years, and is very active in technology transfer in the agricultural sector. For products and services offered by the private sector, technology transfer is very effective. However, there are issues of agricultural production systems, for example in the area of natural resources management, where there are many stakeholders and where societal interests may not always compatible with the interests of the private sector. Furthermore, there are no economic incentives for the private sector to generate all the information that is required for the sustainable management of natural resources. While commercial information can be very useful for the farmer, often it is promoted in such a way that tends to overestimate the benefits of the products. Examples include the indiscriminate use of foliar fertilization and of some soil amendments.

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Part I
The Crop Environment

Chapter 2
The Soil. Physical, Chemical and Biological Properties

Antonio Delgado and José A. Gómez

Abstract This chapter provides a basic description of soil properties and processes, stressing the concept that the soil is a dynamic entity where complex interactions among its biological, chemical and physical components take place. All these components and properties determine the functioning of the soil for different purposes; this functioning is included in the concept of "soil quality". One of the most used definitions of soil quality is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (https://www.soils.org/publications/soils-glossary). Land use and management can have a profound impact on many soil properties, thus indirectly affecting soil quality which can result in improvements or constraints for productivity of agricultural lands and for agricultural sustainability in the long term.

2.1 Introduction

From the point of view of agriculture, the soil offers support to plants and acts as a reservoir of water and nutrients. However, in addition to being a physical medium, the soil may be considered a living system, vital for producing the food and fiber that humans need and for maintaining the ecosystems on which all life ultimately depends. Soils directly and indirectly affect agricultural productivity, water quality, and the global climate through its function as a medium for plant growth, and as regulator of water flow and nutrient cycling. The soil structure should be suitable for the germination of the seeds and the growth of the roots, and must have

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characteristics that enhance the storage and supply of water, nutrients, gases and heat to the crop. Soil chemistry is dominated by the interaction between its solid components (primarily the insoluble compounds of silica, calcium and aluminum) and its water phase. Understanding soil chemistry is of paramount importance, since it is the basis of soil fertility and provides the needed knowledge to understand the differences in fertility among different soils and their response to fertilization. Sometimes soil chemistry can have a direct impact on soil physical conditions as in the case of sodic soils with high exchangeable sodium content. The soil also hosts a complex fauna and microbial web involved in many different biological processes, which also affects its physical and chemical properties, and ultimately the productivity of agricultural ecosystems.

For a given soil, its properties depend on the history of the soil formation (Fig. 2.1) and can be substantially modified by human intervention (e.g. through agricultural practices). A proper understanding of soil characteristics and adequate interpretation of the magnitudes of its properties, both combined under the broader term of soil quality (Table 2.1), is required for proper management of agricultural soils.

Fig. 2.1 Soil profiles showing two different degrees of development. Shallow Calcaric Cambisol (*left*) and deeper Vertic soil (*right*)

Table 2.1 Some soil properties normally used in evaluating soil quality

Soil property			
Physical	Soil texture	Bulk density	Infiltration rate
Chemical	Cation exchange capacity	Organic carbon concentration	Soil pH
Biological	Soil respiration	Earthworms presence	Microbial biodiversity

2.2 Dynamics of Soil Formation and Soil Loss

Soil genesis refers to the developmental processes that the soil, as a natural entity, has undertaken over long time periods as the result of the complex interactions of physical, chemical and biological processes, as described in Fig. 2.2. Soil forming processes usually refer to the results of the interaction of these processes of different nature, such as the accumulation of soil components (e.g. organic matter), formation on site of new ones (e.g. clay minerals or oxides), transport within the soil profile (e.g. clay, carbonate or soluble salts), or changes in the aggregation state of soil particles (e.g. formation of a structure). As mentioned in Sect. 2.1., these processes will define the soil type and can strongly affect soil quality.

Available soil depth for plant growth (the depth of the soil profile that can be explored by plant roots also termed rootable soil depth), a determining factor in agronomy since it strongly affects overall crop development and soil productivity, is the result of the balance between soil formation and erosion rates. Soil formation rates are extremely low and mostly related to geology (bedrock properties) and climate conditions. It is usually less than 5 mm per century (although rates range from 0.01 to 40 mm per century). In landscapes that are not under quick geological transformations, eg. alpine uplifting, these soil formation rates tend to be in equilibrium with the erosion rates under natural vegetation. Natural erosion rates range between 0.005 and 60 mm per century, and are mostly the result of water and wind erosion and mass movement by gravitational forces.

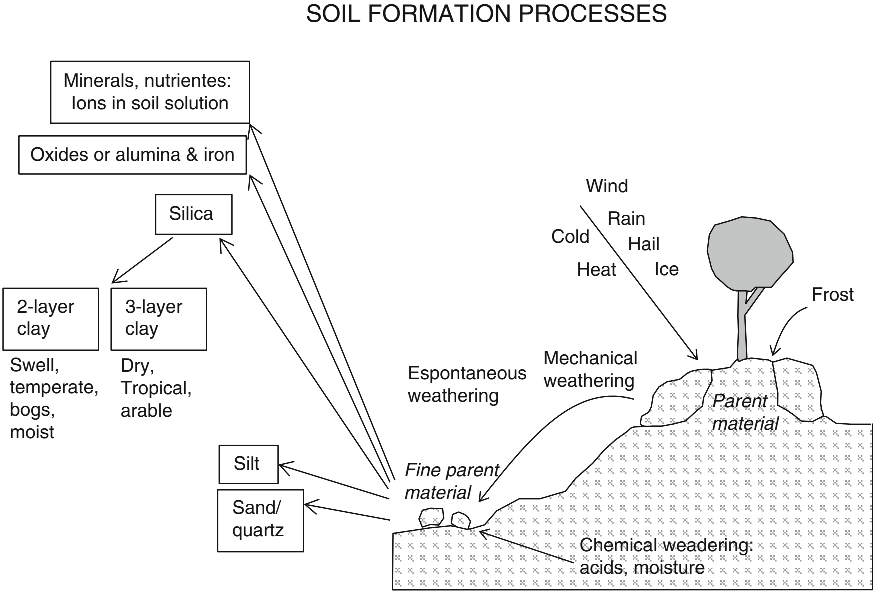

Fig. 2.2 Description of key processes in soil formation

Human interventions mainly by removing the protective plant cover can result in accelerated erosion rates under inappropriate land use or soil management practices. These accelerated erosion rates can reach up to 50 mm per year, resulting in a reduction of the soil profile depth and its degradation. Achieving sustainable erosion rates is a major goal of soil conservation practices. Such rates are defined as those which are either close to the soil formation rates or, at least below a given safe rate (customarily below 10–100 mm per century) that extends far into the future the impact of the imbalance between soil formation and soil erosion rates. The use of soil conservation techniques aim at reducing erosion rates within the range of 0.003–60 mm per century for achieving a more sustainable agriculture.

2.3 Soil Physical Properties: Texture and Structure

Soil physical properties determine many key soil processes (Fig. 2.3), and thus the agronomical potential of a soil. Soil texture, which is a description of the size distribution of the mineral soil particles composing the solid fraction of the soil (from clay <2 μm to coarse particles >2000 μm) is perhaps the most important, since it determines many other physical properties (such as infiltration rate) and some chemical properties (such as cation exchange capacity). Clay mineralogy influences the physical and chemical properties of soils, one of them the swelling-shrinking behavior of the soil, e.g. vertisols, if the clay is an expansive type. Soil structure describes the arrangement of mineral particles and organic matter in the soil, and particularly the arrangement of pores among these particles, and also the stability of this arrangement under external forces such as traffic or rainfall drops. In contrast to texture, soil structure can be substantially modified by soil management. Distribution of pore space and texture determines soil water retention properties (see Chap. 8) which are characterized by the relationship between soil water content

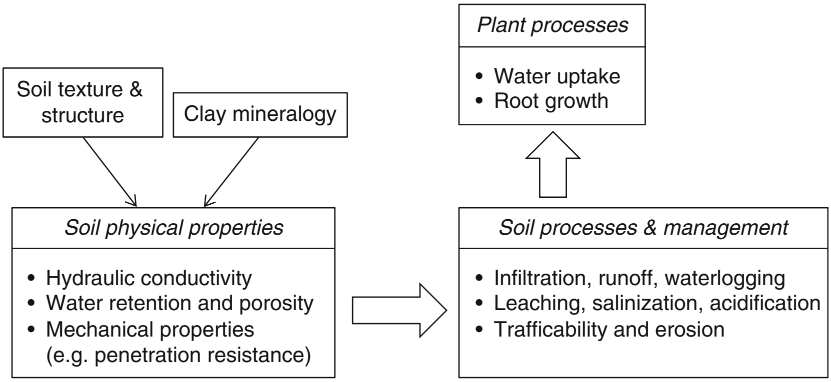

Fig. 2.3 Description of key soil physical properties and related soil processes and management issues (Adapted from Geeves et al. (2000))

and soil water potential (tension). This relation is determined by soil structure and pore size distribution when the soil is at low water tension (wet) and mostly by soil texture at high water tension (dry soil). Bulk density, the ratio between soil dry mass and volume, is a very important soil property influencing soil water retention, aeration, trafficability, and infiltration rate, and is extremely sensible to soil management. Average soil porosity (calculated as $P = 1 - \text{bulk density}/\text{particle density}$ [taken usually as 2.65 t/m^3]) is a useful parameter. Soil mechanical resistance reflects the resistance encountered in the soil to penetration and is directly related to soil compaction. Mechanical resistance of the soil increases sharply as the soil dries and is used to complement the information provided by bulk density.

Soil permeability is a broad term used to define the ability of the soil for transmitting water. It is important to understand the water dynamics and the water balance of the soil (Chap. 8) and it must be known for accurate management of irrigation (Chaps. 19 and 20). It is determined partly by texture, with sandy soils having high permeability as compared to clay soils and it can be altered by soil management (e.g. tillage, Chap. 17). Other parameters that reflect the water transmission properties of the soil are the infiltration rate, i.e. the rate of water flow through the soil surface, and the hydraulic conductivity, i.e. the ability of a soil to conduct water, a parameter extremely sensitive to soil water content.

Soil particles and the void spaces with their continuity and sizes are all arranged in clusters giving way to a certain structure. Soil physical, chemical and biological properties all influence soil structure by providing means that help held together soil aggregates. Structure affects many soil properties that are relevant in agronomy. The penetration of plant roots, the movement and storage of soil water, the aeration and the mechanical resistance of a soil are some of the more relevant properties influenced by the way soil aggregates are clustered together in a structure. Common management practices such as tillage can change soil structure very rapidly. Such short-term changes are reversible but the long-term degradation of soil structure is a serious problem as it is associated with decreased water infiltration and increased erosion risks. Organic matter plays an important role in facilitating aggregate formation and its long-term decline contributes to the loss of soil structural stability.

2.4 Soil Chemical Properties

2.4.1 pH

Soil pH is that of the soil solution that is in equilibrium with protons (H^+) retained by soil colloids (clays, organic matter, oxides). The soil pH is determined in the laboratory as the pH of soil suspensions in water or salt solutions (usually 0.1 M $CaCl_2$ or 1 MKCl). The degree of acidity or alkalinity of a soil is a very relevant property affecting many other physicochemical and biological properties. Problems derived from *acidic soils* or acidification of agricultural soils can be overcome by increasing base saturation and pH with soil amendments (liming). Basic or alkaline soils are the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. *Calcareous soils* are those with an appreciable concentration of $CaCO_3$ which buffers soil pH near 8.5; the presence of other carbonates (Mg or Na in sodic soils) can buffer soil pH well above 8.5. The pH of a calcareous soil cannot be changed due to its high buffering capacity and its limitations for agricultural use, mainly related to restrictions in nutrient uptake and in plant nutrition, may be overcome with special fertilizer products and fertilization strategies.

Some of the soil fertility features affected by soil pH include:

(a) Availability of mineral elements to plants in the soil. At low pH, the risks of deficiency of base nutrients (Ca, Mg, and K) increases due to their low content; also the solubility of Mo and P compounds is decreased, thus decreasing its availability. On the contrary, Al concentration is increased (usually at pH <5.5) and thus its toxicity effects; the concentration of Fe and Mn, essential nutrients for plants, can be high enough at low pH as to cause toxicity. At high pH, the solubility of many metals and trace elements is decreased, including essential nutrients for plants such as Fe, Mn, Cu or Zn. Deficiency of Fe, known as *iron chlorosis*, is frequent in basic soils (typically in calcareous ones).

(b) Biological properties: extreme pH values decrease microbial activity in soils, which affects many soil processes (for instance, soil organic matter decomposition, nitrification, and biological N_2 fixation under acidic conditions, see Chap. 24).

(c) Physical properties: low Ca concentration in acidic soils is usually related to an increased dispersion of colloids if Al is not present at high concentration. Thus, acidic soils can have poor soil physical properties, including poor structural stability or low permeability.

2.4.2 Redox Status

The redox status of a soil is determined by the availability of electrons which can participate in redox reactions (pE, – logarithm of the activity of electrons) and it is controlled by physical conditions (water content and porosity) and biological activity. It affects the solubility and speciation of elements with different redox states, such as N, S, Fe, Mn, some toxic trace elements (e.g. As, Se), and even C. Reducing conditions in agricultural soils usually occur at very high water contents (saturation) since, under these conditions, oxygen is quickly consumed by biological activity. Reducing conditions increase the solubility of Fe and Mn compounds, enhancing the uptake of these nutrients by plants (which can become toxic) and of elements adsorbed on Fe and Mn oxides (e.g. P and heavy metals).

2.4.3 Ion Retention in Soils

Ions can be retained in soils by precipitation and adsorption processes. *Precipitation* means the formation of a new solid phase, e.g. when P fertilizer is applied to a soil with a high Ca concentration, new crystals of Ca phosphates can be formed. *Adsorption* is the accumulation of chemical species (sorbate) on the surfaces of an existing solid in the soil (sorbent). Precipitated and adsorbed species are in equilibrium with the soil solution (precipitation/dissolution and adsorption/desorption equilibria).

Adsorption can be the consequence of chemical reactions with functional groups of sorbent surface which is sorbate specific (e.g. P on hydroxilated surfaces), or electrostatic attraction by sorbent surface which is not sorbate specific. Charge associated with mineral and organic surfaces can be permanent and variable. Permanent charge arises from isomorphic substitution within clay minerals. Variable charge is the result of unsatisfied bonds at the edge of minerals and organic matter and is pH dependent.

2.4.3.1 Exchange Capacity

Exchangeable ions are those weakly adsorbed by soil particles that can be displaced from sorption sites by other ions in the solution. Exchangeable ions are essential for maintaining plant nutrient reserves in the soil.

Cation exchange capacity (CEC) is measured as the amount of cations (equivalents or moles of charge) which can be extracted by a high concentrated cation solution (usually, 1 M K^+ or NH_4^+). The CEC is usually dominated by Ca, Mg, Na, K, Al, and protons. The selectivity or relative affinity of cation by sorbent surfaces is based on the ion's charge and size: the smaller the hydrated radius (cation + water molecules strongly interacting by ion-dipole interaction) the greater the affinity (ions with small dehydrated radius have large hydrated radius), and the higher the valence the greater the exchanger preference for the cation; the affinity scale for dominant cations in soils can be summarized:

$$Al^{3+} > Ca^{2+} > Mg^{2+} > NH_4{}^+ > K^+ > Na^+$$

Base saturation is defined as ratio of base exchangeable cations (Ca, Mg, K, and Na) to total CEC, which decreases at decreased pH in the soil. Ca, Mg, and K are nutrients for plants; thus a high base saturation means a greater nutrient reserve than a low base saturation for the same CEC. Low base saturation related to soil acidity can determine Ca deficiency for crops. In order to guarantee good physical soil properties (soil aggregation, structure stability, good aeration, and drainage) and nutrition for crops, Ca must be the dominant cation in the exchange complex (ideally $>50\,\%$ of CEC); also it is desirable that the Ca/Mg ratio would be 5–10 and the K/Mg ratio 0.2–0.3 in order to avoid nutritional disorders (antagonisms) for plants which can lead to a deficiency of a nutrient promoted by a high level of the antagonistic nutrient.

2.4.4 Salinity and Sodicity

Salinity is defined as a high concentration of soluble salts (more soluble than gypsum) in soils. A saline soil has a soluble salt concentration high enough to negatively affect the growth and development of most cultivated plants. Classification of saline soils and the assessment of the negative effects of salinity on crops are based on the electrical conductivity (EC) of the saturation extract of the soil. If the EC of the soil is higher than 4 dS/m it is defined as saline. There is ample variation in the responses to salinity among different crops (Chap. 22). Crops highly sensitive to salinity (e.g. carrot, bean, strawberry) are affected by EC values slightly above 1 dS/m. On the opposite side tolerant crops such as barley and sugar beet among others, can tolerate EC levels above 4 dS/m. Impact of salinity on plant growth is caused by osmotic effects (decreased water potential in soil), and from specific toxicity, typically due to high Cl or Na concentrations.

Sodicity is referred to a high exchangeable Na concentration in soils. Since Na salts are common in saline soils, both problems are usually related. Na is a monovalent cation with a big hydrated radius. Hence, high contents of Na adsorbed on soil colloids promote their dispersion, thus negatively affecting soil physical properties. A soil is classified as sodic if exchangeable Na accounts for more of 15 % of the CEC (Exchange Na percentage –ESP– >15). However, crops sensitive to Na toxicity are affected at ESP >7 (e.g. peach, citrus, strawberry). Problems in crops tolerant to Na toxicity (e.g. cotton or rye) usually are derived from physical degradation of soil. Soils with EC $>$ 4 dS/m and ESP >15 are classified as saline-sodic. Problems derived from sodic soils can also be related to their very high pH values (usually >8.5 if the soil is not saline).

Chapter 22 expands on the salinity problem in agriculture and describes the approaches for its management and control.

2.5 Soil Biological Properties

Soils host a complex **web of organisms** (Fig. 2.4) which can influence soil evolution and specific soil physical and chemical properties. For instance earthworms activity increases infiltration rate, or microbial activity decreases soil organic matter due to mineralization.

Soil biological properties are also interconnected with other soil physical and chemical properties; e.g. aeration, soil organic matter or pH affect the activity of many microorganisms in soils which in turn perform relevant activities in carbon and nutrients cycling. Examples of this interconnection were given in Sect. 2.4.

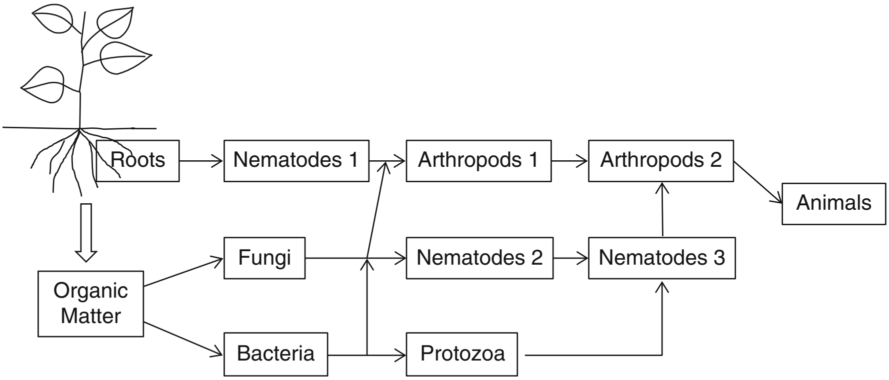

Fig. 2.4 Soil food web

Thus, changes in soil properties due to management can significantly affect biological properties in soils, some of them being extremely sensitive to soil management; e.g. soil microbial activity can be greatly increased by improved drainage, liming or organic amendments. That is why some soil biological properties can be used as indirect indicators of appropriate soil management and good soil quality, like soil respiration rate or some enzymatic activities that can be derived from living organisms in soil.

Soil organic matter is a key factor affecting biological activity in soils. It is the carbon source for many organisms, including soil microbiota. Not only the amount, but also the type of organic compounds in the soil determines its biological activity; e.g., microbial activity is greatly increased by incorporating fresh organic residues (such as green manure or crop residues), which can be readily mineralized by microbes. On the other hand, stable forms of organic matter (humic and fulvic compounds), which constitutes most of the organic matter of soils in temperate regions, is not a very suitable carbon source for soil microbiota, which explains the long half-life of these compounds in soils (usually >1000 years); thus, stable organic compounds do not contribute significantly to soil microbial activity but constitutes an stabilized stored soil C pool which is very relevant to the C global cycle, partially buffering the consequences of increasing C emissions to the atmosphere.

The **rhizosphere** is the volume of soil altered by the root system and is the part of the soil profile where the concentration of suitable C sources for many microorganisms is greatest. Organic compounds exuded by plant roots (including organic anions of low molecular weight) alter soil chemical properties and greatly increase the biological activity in comparison to the bulk soil. The rhizosphere is a space of intense interaction of plant roots with soil microorganisms. Rhizospheric microorganisms can significantly affect plant development through the production of growth regulators, by decreasing the incidence of plant diseases, and by increasing nutrient availability to plants.

Table 2.2 Some soil biological properties

Property	Comments
Respiration rate	CO_2 evolution under standard laboratory conditions or at the field
Potential N or C mineralization	Increase in mineral N or C content under standard laboratory conditions
Earthworms	Density of earthworms
Bacterial biomass	Total bacterial biomass for a given soil mass
Bacterial diversity	It can be determined by functional groups, or describing genetic diversity
Presence of pathogens	By different pathology techniques, from cultures to DNA profiling

Understanding soil biological properties is important for soil management but also for prevention and control of crop pests and diseases. Many of the properties indicated in Table 2.2 are a description of the diversity and activity of parts of the soil food web, or of related properties such as soil respiration rate or organic matter content.

2.6 Nutrient Cycles and Balances in the Soil

Nutrient in soils are present in different chemical forms, which can remain in solution or bound to soil particles. Exchange of nutrients between different forms or “soil pools” is governed by physical, chemical, or biological processes. All these processes are included in the concept of “nutrient cycle” in soils. Since the soil is not a “closed system”, gains or losses of nutrients from the soils occur to/from the atmosphere or water courses (leaching or erosion), which links the “soil nutrient cycle” with the “global nutrient cycle” in the Earth crust. The soil and global nutrient cycles are affected by human activities. In agricultural soils, fertilization clearly alters the cycle, introducing nutrients in the system. Without this supply, the natural input of nutrients in soils would be much lower than typical crop extractions, thus inducing a “negative balance” which would cause a progressive depletion of nutrients and thus a progressive loss of soil fertility.

A general nutrient cycle is represented in Fig. 2.5. The flux of nutrients to plant roots comes from the soil solution, mainly as dissolved ions. The “labile nutrient pool” is that readily equilibrated with the solution, as adsorbed ions described in Sect. 2.4.3.1, those precipitated as soluble salts, or those present in organic compounds which are readily mineralized. The “available pool” of nutrients is the amount in solution plus that readily equilibrated with the solution (“labile forms”); for a given nutrient it can be considered the amount that can be extracted by successive crops until severe deficiency of this nutrient appears in crop.

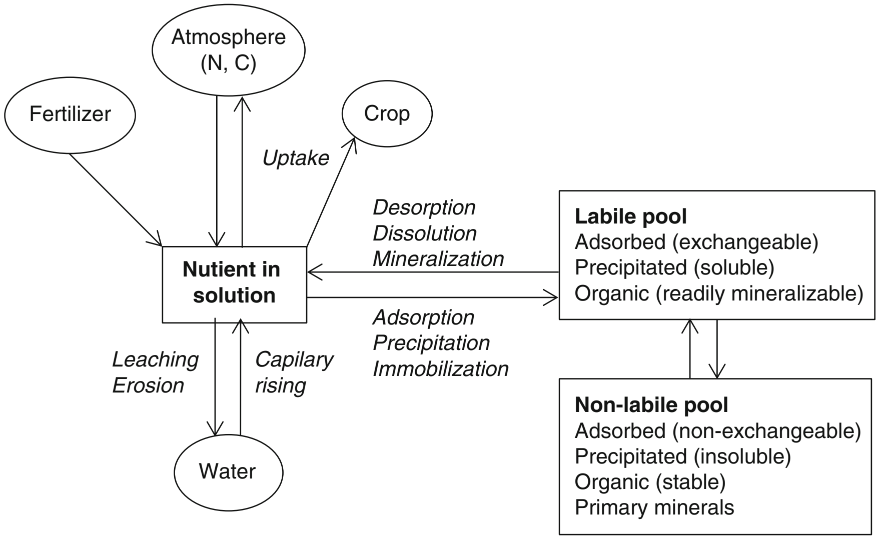

Fig. 2.5 General cycle of nutrients in soil. In italics physical, chemical or biological processes involved in nutrient cycle. Residue incorporation to soil involves nutrient recycling: not only in soluble forms (e.g. K); most in organic forms or organic bound forms that can become part of the labile or non-labile pool. Exchange between labile and non-labile forms implies the same processes that those involved in the equilibria between labile forms and solution

Chemical (e.g. adsorption/desorption or precipitation/solubilization) and biological (immobilization/mineralization) interactions affecting nutrient equilibria and exchange rates between the labile fraction of the soil solid and solution phases, ultimately determine the solution ionic activities and the transport of nutrients to plant roots.

Accurate estimation of fertilizer requirements in modern agriculture is based on the knowledge of nutrient cycles and the precise estimation of available nutrients pools in soils through chemical methods. *Mobile nutrients* are considered those which are not bound to soil particles. Nitrogen, in spite of ammonium being adsorbed, it is readily transformed to nitrate, which is not adsorbed to soil particles. In agricultural systems, where the contribution to available nutrient pool by organic matter mineralization can be low, the major contributors to the available pool of mobile nutrients are usually inorganic ions in the soil solution. *Immobile nutrients* are those which are bound to soil particles through adsorption or precipitation processes, being in this case the labile pool the major contributor to the available pool. Immobile nutrients, such as P, K, Ca, or Mg, are less susceptible of loss through leaching; on the other hand, the nature of chemical reactions involved in their retention cause that only part of the nutrients supplied as fertilizer are available to plants.

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Chapter 3
The Radiation Balance

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Abstract Solar radiation (short wave) is the energy source for photosynthesis, warming and evaporation in agricultural systems. Its value can be calculated as a function of latitude, time of year and cloud cover. Fifty percent of solar radiation is available to photosynthesis and is called photosynthetically active radiation (PAR), although only a very small fraction is actually used in this process. Net radiation is obtained by discounting the reflected solar radiation (which depends on the albedo) and longwave losses that depend on air temperature, humidity and cloud cover. Plants intercept all the radiation fluxes. Shortwave radiation interception is modulated by leaf angle distribution that varies with LAI and plant type. The fraction of radiation intercepted by trees can be calculated assuming simple geometrical forms (spheroids).

3.1 Introduction

Electromagnetic radiation is the basic physical phenomenon determining the environment of crops. Solar radiation, which is shortwave radiation, constitutes the primary energy source for crop production. In addition we have to consider the long wave thermal radiation emitted by any object on the planet, including soil, crops, water and the atmosphere. Moreover, light quality, i.e. its composition in different

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wavelengths, plays a key role in many developmental processes of plants, as discussed in Chap. 11.

The total energy emitted for the whole electromagnetic spectrum is calculated by the Stefan-Boltzmann Law:

$$E = \varepsilon\, \sigma\, T^4 \tag{3.1}$$

where ε is emissivity (or effectiveness of the body in the emission of radiation), σ is the Stefan-Boltzmann constant (5.67 10^{-8} $W/m^2/K^4$) and T is the absolute temperature of the surface of the emitting body. This Law applies to any object, either the sun or the earth's surface. In the wavelength interval between 8 and 14 μm, the emissivity of plant surfaces is between 0.97 and 0.99 which is fairly close to that of the "black body", which by definition has unit emissivity.

3.2 Solar Radiation

The flux density of solar radiation in the limit of the atmosphere (extraterrestrial radiation), on a surface perpendicular to the beam, when the sun and the earth are at average distance apart, is called the "solar constant" and its value varies between 1350 and 1400 W/m^2, with an average value of 1370 W/m^2.

Considering a horizontal surface, if the ray and the normal to the surface are not parallel, flux density can be calculated by the Lambert's cosine law:

$$I = I_p \cos \theta \tag{3.2}$$

where θ is the zenith angle (angle between the radiant beam and the vertical) and I_p is the flux density in the direction of the beam.

The zenith angle for a horizontal surface on the planet depends on the latitude (λ_s), the solar declination (δ_s) and the time of day (expressed as hour angle, h_a, that varies from 0 to 360°, taking the value of 0° at solar noon):

$$\cos\theta = \sin \lambda_s \sin \delta_s + \cos \lambda_s \cos \delta_s \cos h_a \tag{3.3}$$

The solar declination ranges from +23.45 at summer solstice (Northern hemisphere) to −23.45 at winter solstice and may be calculated (in degrees) as:

$$\delta_s = 23.45 \cos \left[\frac{360\,(DOY - 172)}{365}\right] \tag{3.4}$$

where DOY is day of the year (DOY = 1 for January 1 and DOY = 365 for December 31).

Example 3.1 On February 1 (DOY 32) in Cordoba, Spain ($\lambda_s = 37.85°$), the solar declination is

$$\delta_s = 23.45 \cos\left[\frac{360\ (32 - 172)}{365}\right] = 23.45 \cos\ (-138°) = \quad -17.4°$$

At 3 h after solar noon: $h_a = (15–12)\ 15 = 45°$, thus:

$$\begin{aligned}\cos\theta = &\ \sin\ (37.85)\ \sin\ (-17.4) + \cos\ (37.85)\ \cos\ (-17.4)\ \cos\ (45)\\ &= 0.35\ \text{ and then } \theta = \text{arc}\ \cos(0.35) = 69.5°.\end{aligned}$$

Legal time is obtained by adding or subtracting a certain number of hours to standard time, plus a daylight savings time (usually 1 h) in summer. For instance in Spain there is 1 h difference in the fall-winter period and 2 h in spring and summer (daylight savings). To calculate actual solar time we must take into account the longitude of the place as the path of the sun to the west has an apparent speed of 15 per hour. However we will ignore other phenomena related to the rotation of the Earth that can change up to 16 min our predictions of solar time.

Example 3.2 Santiago de Compostela (Spain) is located at 42.9°N and 8.43°W. We will calculate solar time at 1500 h (legal time) on May 1.

As the date corresponds to spring-summer, solar time at the standard meridian (in this case the Greenwich meridian) will be:

$$15–2 = 13\ \text{h}$$

Then we subtract 1 h per 15° longitude to the West:

13–8.43·1/15 = 12.44 h, which means that actual solar time is 12:26.

In crop ecology and agronomy, we are especially interested in three major bands in the spectrum of solar radiation reaching the upper atmosphere. The infrared and visible wavebands represent approximately 51 % and 40 % of the solar constant, respectively, while the ultraviolet waveband is approximately 9 %. The visible waveband, which ranges from 400 to 700 nm, is also the Photosynthetically Active Radiation (PAR), although a very small fraction of this radiation is actually used in this process. PAR may be expressed as radiation flux density (W m^{-2}) or as photon flux density (mol m^{-2} s^{-1}).

As the sun rays pass through the atmosphere, the radiation is altered in quantity, quality and direction by the processes of absorption and scattering. The absorption, which is a change from radiant energy to heat, results into heating of the atmosphere and a reduction of the amount of radiant energy that reaches the ground. Absorption is mainly due to ozone and oxygen, especially in the ultraviolet waveband, and water vapor and carbon dioxide, in the infrared waveband. Some aerosols are also important absorbers of shortwave radiation. The scattering occurs when photons hit against the molecules composing the air and airborne particles and aerosols, causing changes in the direction of radiation, but without removing energy from the radiation. In the visible region of the spectrum, absorption by molecules of the atmosphere is less important than scattering while in the infrared waveband the opposite occurs. Solar radiation on the surface of the earth, measured perpendicularly to the sun's rays, rarely exceeds 75 % of the solar constant, due to absorption and scattering.

3.3 Solar Radiation at Ground Level

As a result of atmospheric attenuation, solar radiation reaching the earth's surface is no longer only beam radiation as part of the radiation comes from all directions. Beam radiation coming directly from the sun is called *direct solar radiation* and the remaining part is called *diffuse solar radiation*, thus being the radiation scattered in the atmosphere that reaches the surface coming from the entire sky hemisphere. The sum of direct and diffuse solar radiation, measured on a horizontal flat surface, is called *global radiation*, *total* radiation or simply *solar radiation*. On average, PAR represents 50 % of the global radiation flux, while in the extraterrestrial radiation it represents only about 40 %.

In general, the ratio of diffuse and direct radiation increases with latitude and with the zenith angle as the path of the rays through the atmosphere gets longer. This implies that both at sunrise and at sunset, the diffuse/direct ratio is higher than at noon. Cloudiness also increases the ratio of diffuse to direct radiation, and when the sky is completely overcast all solar radiation is diffuse. However, the absolute maximum of diffuse radiation is reached when cloud cover is around 50 %.

Global radiation (R_s) during clear days follows a sinusoidal curve during the daytime (Fig. 3.1) which can be measured by pyranometers or, on a daily time step, estimated from extraterrestrial radiation (R_A) and the ratio of the actual number (n_s) and the maximum possible number (N_s) of sunshine hours:

$$R_s = \left(0.25 + 0.50\,\frac{n_s}{N_s}\right)R_A \tag{3.5}$$

Alternatively, when no data on sunshine duration is available we may use the Hargreaves-Samani equation to calculate solar radiation as a function of air temperature and extraterrestrial radiation as follows:

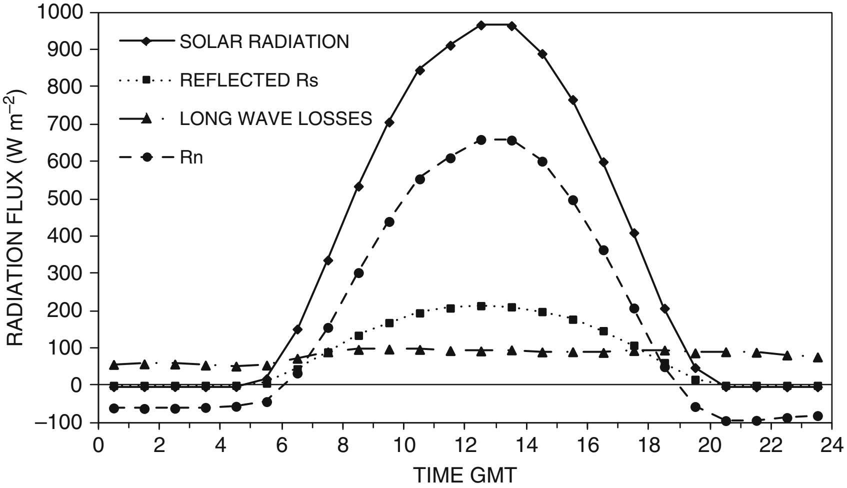

Fig. 3.1 Daily time course of solar radiation, reflected shortwave radiation, long wave losses and net radiation over a cotton crop in Cordoba (Spain) on June 27, 2003

$$R_s = K_{RS}\, R_A \sqrt{T_{max} - T_{min}} \tag{3.6}$$

where T_{max} and T_{min} are the daily maximum and minimum air temperature, respectively.

Usually, the values of K_{Rs} vary between 0.16 and 0.19 $K^{-0.5}$ for interior and coastal locations, respectively.

Daily extraterrestrial radiation (MJ/m^2/day) may be calculated by integrating the cosine law throughout the day:

$$R_A \quad = 37.4\, d_r \;\left[\sin\lambda_s \sin\delta_s h_s \frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s\right] \tag{3.7}$$

where h_s is half the daylength (degrees):

$$h_s = arc\cos\left[-\text{tg}\lambda_s\ \text{tg}\delta_s\right] \tag{3.8}$$

And d_r is the correction for changes in the distance between the earth and the sun, which depends on the day of the year:

$$d_r = 1 + 0.033\cos\left[\frac{360\, DOY}{365}\right] \tag{3.9}$$

From Eq. 3.7 we may deduce day length, i.e. the maximum duration of sunshine, as:

$$N_s = \frac{2h_s}{15} = \frac{1}{7.5}\ arc\ \cos\left[-\text{tg}\lambda_s \cdot \text{tg}\delta_s\right] \tag{3.10}$$

On the other hand, Eq. 3.5 indicates that on clear days solar radiation is around 75 % of extraterrestrial radiation. On the average, solar radiation on overcast days is only 25 % of extraterrestrial radiation.

Example 3.3 We will calculate daylength and solar radiation for clear days on December 21 at Grand Rapids, Michigan (42.9°N) and South Hobart, Australia (42.9°S).

Solar declination and the correction d_r depend on the day of the year only:

December 21: DOY = 355

$$\delta_s = 23.45 \cos\left[\frac{360\,(355 - 172)}{365}\right] = 23.45 \cos(180) = \; -23.45°$$
$$d_r = 1 + 0.033 \cos\left[\frac{360\;355}{365}\right] = 1.033$$

Grand Rapids:

$$h_s = arc\cos\left[-\mathrm{tg}42.9\ \cdot \mathrm{tg}(-23.45)\right] = 66.23°$$

Daylength: $N_s = 2\ h_s/15 = 8.82$ h

$$R_A = 37.4\, d_r \left[\sin\lambda_s \sin\delta_s\ \ h_s\frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s\right]$$
$$= 11.66\,\mathrm{MJ\ \ m^{-2} day^{-1}}$$

Clear day: $R_s = 0.75\ R_A = 8.74\ \mathrm{MJ\ m^{-2}\ day^{-1}}$

South Hobart:

$$h_s = arc\cos\left[-\mathrm{tg}(-42.9)\,\mathrm{tg}(-23.45)\right] = 113.8°$$

Daylength: $N_s = 2\ h_s/15 = 15.17$ h

$$R_A = 37.4\, d_r \left[\sin\lambda_s \sin\delta_s\ h_s\frac{\pi}{180} + \cos\lambda_s \cos\delta_s \sin h_s\right]$$
$$= 44.5\,\mathrm{MJ\ m^{-2}\,day^{-1}}$$

Clear day: $R_s = 0.75\ R_A = 33.4\ \mathrm{MJ\ m^{-2}\ day^{-1}}$

The annual time course of global radiation follows also sinusoidal patterns, with amplitude that depends on the latitude of the site and its cloudiness. For example Fig. 3.2 shows the annual curve of the average values of solar radiation at two sites with very high and very low rainfall along with maximum solar radiation, calculated as 75 % of the extraterrestrial radiation. On the other hand, Fig. 3.3 shows the

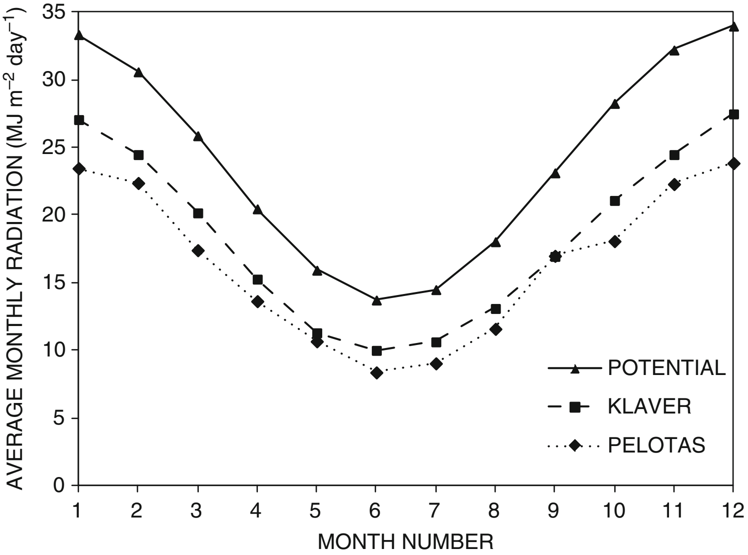

Fig. 3.2 Annual time course of the mean monthly solar radiation for two locations, Pelotas (Brazil) with mean annual rainfall of 1395 mm and Klawer (South Africa) with mean annual rainfall 174 mm

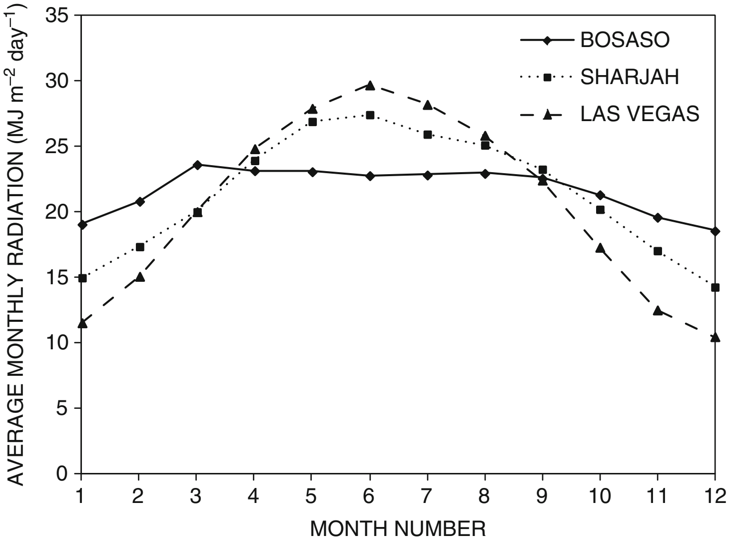

Fig. 3.3 Annual time course of the mean monthly solar radiation for three dry locations: Bosaso (Somalia) (11.28°N), Sharjah (United Arab Emirates) (25.33°N) and Las Vegas (NV, USA) (36.08°N)

annual curves of solar radiation for three dry locations differing in latitude. As we move away from the Equator the amplitude of the annual radiation curve increases.

Mean annual solar radiation is usually between 15 and 22 MJ m^{-2} day^{-1} for latitudes from 30°S to 30°N and decreases for higher latitudes (Fig. 3.4).

Once the solar radiation reaches the earth's surface, part of the radiation is reflected. We use the term albedo (α) to express the ratio of reflected to incident radiation in the range of 0.3–3 μm. Some values of albedo of natural surfaces are shown in Table 3.1.

Therefore, the short-wave radiation remaining on the surface of the earth can be calculated as (1-α) R_s. The vegetation albedo values are usually between 0.15 and

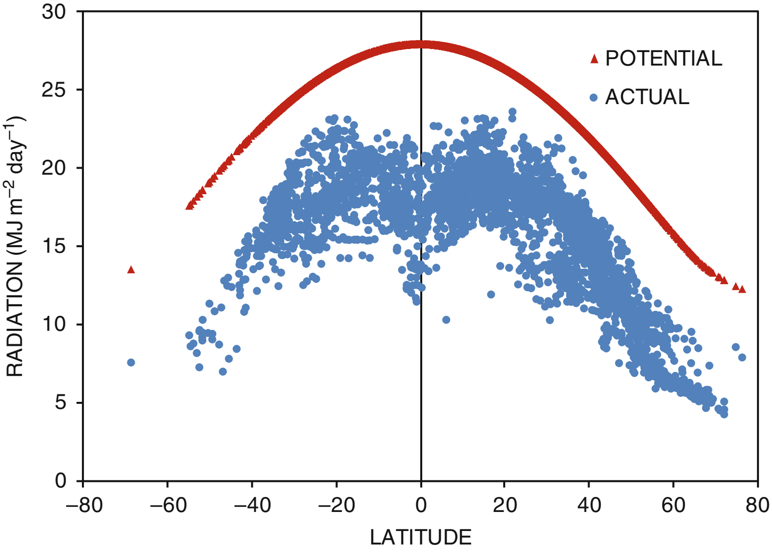

Fig. 3.4 Mean annual solar radiation for different locations as a function of latitude

Table 3.1 Albedo for daily solar radiation of different surfaces

Surface	Albedo
Fresh snow	0.80–0.95
Dry sand	0.35
Soil, wet, dark when dry	0.08
Soil, dry, dark when dry	0.13
Soil, wet, light when dry	0.1
Soil, dry, light when dry	0.35
Water bodies	0.05–0.14
Annual crops	0.16–0.26
Orchards, deciduous forests	0.10–0.20
Coniferous forests	0.05–0.15

0.20 for forests and between 0.20 and 0.25 for field crops. The main factor that determines the albedo of a soil is its color and surface water content. It is easy to see that a dry soil gets darker after wetting. For example the soil of the Agricultural Research Center of Cordoba (Spain) (medium texture, low in organic matter) has an albedo of 0.16 when wet and 0.23 when dry.

3.4 Long Wave Radiation

All surfaces are emitters of long wave radiation following the law of Stefan-Boltzmann (Eq. 3.1). Under clear skies, most of the radiation emitted by the earth's surface (i.e., *terrestrial radiation*) is absorbed by the molecules composing the atmosphere, mainly water vapor and carbon dioxide, although nitrous oxide (N_2O) and methane (CH_4) are also important absorbers. Radiation in the waveband 8–12 μm (i.e., the *atmospheric window*) is almost not absorbed by these gases due to the small size of its molecules. Under cloudy skies, cloud droplets, however, when present, contribute extensively to the absorption of the longwave radiation, thus "closing" this atmospheric window. The remainder that is not absorbed is lost into the extraterrestrial space. The radiation absorbed can be re-emitted to the earth surface, thus constituting *atmospheric radiation*. This downward flux originates mainly from the first kilometer of the atmosphere, from the emissions of those constituents mentioned above, that are highly selective absorbers (thus highly selective emitters) of long-wave radiation. For practical proposes only, since the average temperature of the layer of air in the lower atmosphere is related to the air temperature near the ground, although a lot colder than this air, it is possible to apply the Stefan-Boltzmann law with a fitted apparent emissivity that take into account the differences between the average temperature of this lower layer of the atmosphere and air temperature near the ground, the amount of cloud cover and the fact that the lower atmosphere is far from being a black body. Terrestrial radiation is almost always higher that atmospheric radiation, and that results in net losses of long-wave radiation.

Daily losses of long-wave radiation (R_b, MJ m^{-2} day^{-1}) can be calculated as:

$$R_b = \left(0.9\frac{n_s}{N_s} + 0.1\right)(0.34 - 0.14\sqrt{e_a}\,)4.9\ 10^{-9}T^4 \tag{3.11}$$

where 4.9 10^{-9} is the Stefan-Boltzmann constant expressed in MJ m^{-2} K^{-4}, e_a is the air vapor pressure (kPa), T is air temperature (K) and n_s/N_s is the ratio of actual sunshine duration (n_s) and daylength (N_s).

Equation 3.11 indicates that long wave losses will be greater under clear skies (high n/N), with lower humidity and with higher air temperature. Cloud cover has a dramatic impact on losses of long wave radiation, as for given air temperature and humidity, long-wave losses under an overcast sky are only 10 % of those when the sky is clear.

3.5 Net Radiation

The net balance of radiation that remains on a surface of albedo α is expressed by the equation:

$$\mathrm{R_n} = (1 - \alpha)\mathrm{R_s} - \mathrm{R_b} \tag{3.12}$$

Net radiation is thus the difference between the flux of radiation towards the surface and from the surface of the Earth. It is therefore the energy available on the surface for evaporation, heating of the air, the soil and the crop and to a lesser extent, for photosynthesis.

Example 3.4 Let us calculate the net radiation over short grass ($\alpha = 0.23$) in South Hobart (42.9°S) for a clear day on December 21 if the average air temperature is 25 °C and the air vapor pressure is 1.8 kPa. Solar radiation was already calculated in Example 3.3.

Long wave loss:

$$R_b = \left(0.9\frac{15.17}{15.17} + 0.1\right)\left(0.34 - 0.14\sqrt{1.8}\right)4.9\ 10^{-9}(273 + 25)^4$$
$$= 5.88\ \mathrm{MJ\ m^{-2}day^{-1}}$$

Net radiation:

$$\mathrm{R_n} = (1 - 0.23)33.4 - 5.88 = 19.8\ \mathrm{MJ\ m^{-2}day^{-1}}$$

Figure 3.1 represents the daily time course of solar radiation, net radiation and reflected solar radiation on a summer day on a cotton field in Cordoba, Spain. Curves of $\mathrm{R_s}$ and $\mathrm{R_n}$ have similar shape but while the solar radiation flux is always positive during the day and nil during the night, the net radiation is negative at night.

The daily values of net radiation in summer are usually positive and become very small as the nights get longer in the fall. At higher latitudes daily net radiation reaches negative values during winter. In Cordoba, for example, solar and net radiation values are highest in July although extraterrestrial radiation peaks in June. This is explained by the higher average cloudiness of June as compared to July.

3.6 Intercepted Radiation

Leaf area is a good indicator of the ability of the crop to intercept radiation. To characterize the leaf area of a crop canopy we use the leaf area index (LAI), defined as the ratio of total green leaf surface area (one side) and the ground surface.

According to Monsi and Saeki radiation transmitted through the canopy is an exponential function of LAI:

$$I = I_0 \, e^{-k \; LAI} \tag{3.13}$$

where I_0 and I are the flux densities above and below the canopy, respectively, and k is the extinction coefficient.

Intercepted radiation will be the difference between incoming radiation and that reaching the soil surface. Therefore:

$$I_0 - I = I_0 \left(1 - e^{-k \, LAI}\right) \tag{3.14}$$

The above equations may be applied to any type of radiation in terms of wavelength (e.g. PAR or Near Infrared, NIR), directional properties (direct or diffuse) or time scale (instantaneous or daily) by taking the appropriate extinction coefficient.

The extinction coefficient depends on the angle of elevation of the sun and the leaf angle distribution. The most useful approach is given by the ellipsoidal leaf angle distribution of Campbell. For daily time step computations, extinction coefficient is a parameter that may be fixed for the whole growing season or for specific phenological phases. Example values of these parameters are given in Table 3.2.

The extinction coefficient may be related to the inclination angle of the leaves as shown in Fig. 3.5. Vertical leaves (parameter of leaf inclination = 0) have extinction coefficients around 0.4 while horizontal leaves approach 1.

The leaf angle distribution has agronomic and ecological implications. Small plants with horizontal leaf distribution (i.e., higher k values) result in higher radiation interception than those with more erect leaves. The drawback is that when LAI is high the light distribution is very unequal, the lower leaves receive too little light, which usually accelerates their senescence. On the contrary, more vertical leaf angle distributions (i.e., lower k values) may be advantageous to intercept radiation when the zenith angle is large (winter or high latitudes) and leads to a more homogeneous distribution of radiation within the canopy when LAI is high. Therefore the maximum LAI that may be sustained will be higher for low extinction coefficient values. Ideally, for optimal radiation interception, the upper leaves should be more erect and the lower ones more horizontal. In fact, modern maize canopies have such leaf angle distribution.

Leaf level photosynthesis saturates with high irradiance (Chap. 13), but irradiance decreases as we move down into the canopy, so that a large fraction of the leaves will be below the irradiance saturation level. This results in crop carbon

Table 3.2 Daily extinctions coefficients (k) of PAR and X parameter of the ellipsoidal inclination angle distribution for some crop canopies

Crop	k (PAR)	X parameter	Source
Beans, pea	0.4–0.5		2, 3
Bell pepper	0.72	2.5–2.9	7
Cassava, peanut, cotton	0.80–0.87		5, 6
Forage and pasture (legumes)	0.8–0.9	1.5–3.3	3
Maize, sorghum, millet	0.57–0.70	1.40	1, 4, 5, 6
Oil palm	0.48		5
Oilseed rape	0.84	1.9–2.1	1, 2, 6
Potato	0.64	1.7–2.5	1, 6
Soybean, cowpea, pigeon pea	0.7–0.8		3, 5, 6
Sugar beet	0.68	1.5–1.9	1, 2, 6
Sugar cane	0.46		6
Sunflower	0.90	1.8–4.1	1, 6
Sweet potato	0.60		6
Wheat, barley, rice	0.44–0.52	1–1.2	1, 2, 6

Notes: (1) Campbell and Norman, 1998. (2) Hough, 1990. Eur. Commission Report EUR 13039 EN. (3) Jeuffroy and Ney, 1997. Field Crop Res. 53:3–16. (4) Kanton and Dennett, 2008. West Afric. J. Appl. Ecol. 13:55–66. (5) Squire 1990. The Physiology of Tropical Crop Production. CAB Int. (6) van Heemst, 1988. Simulation Report CABO-TT 17, Wageningen. (7) Vieira et al. 2009. Sci. Horticul. 121:404–409

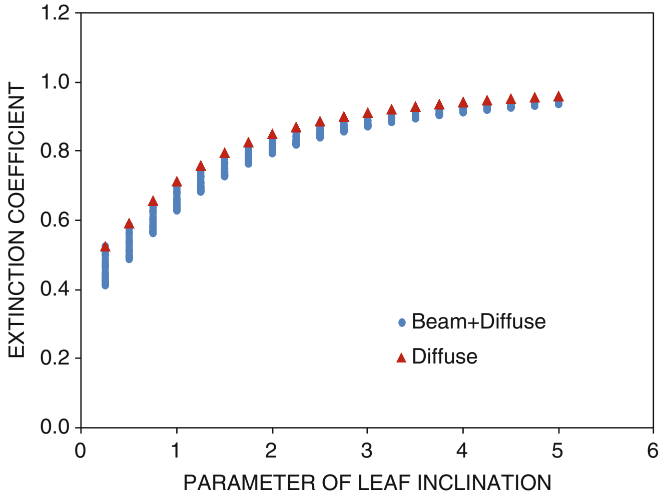

Fig. 3.5 Extinction coefficients for daily solar radiation using the ellipsoidal model of Campbell

assimilation increasing linearly with irradiance at the canopy level, as will be shown in Chap. 13.

When leaf area cannot be determined, the degree of intercepted radiation may be estimated by calculating the fraction of the ground area covered by the crop canopy (horizontal projection). This can be easily assessed in the field using photography and the appropriate software and is expressed as a percentage of full cover (100 %). The ground cover is a useful parameter for characterizing canopy size from remote sensing.

3.7 Radiation Interception of Trees

We consider the tree crown as a spheroid with constant Leaf Area Density (μ_l, $m^2\ m^{-3}$), horizontal radius r and height h_t.

For any isolated tree radiation interception for rays with zenith angle θ is the product of incoming radiation flux in the direction of the beam (I_p), Projected Envelope Area in the θ direction ($PEA(\theta)$) and the mean interception over PEA:

$$I_i = \ I_p PEA(\theta)[1 - t_c(\theta)] \tag{3.15}$$

where $t_c(\theta)$ is the mean transmissivity of the crown in the direction of the sun rays.

For a spheroid we have:

$$PEA(\theta) = \pi r^2 \sqrt{cos^2(\theta) + \left(\frac{h_t}{2r}\right)^2 sin^2(\theta)} \tag{3.16}$$

Note that PEA is related to the area of the shadow envelope (S_s) projected by the tree on the horizontal plane ($PEA = S_s \cos(\theta)$). The average transmissivity of the spheroid may be calculated as:

$$t_c(\theta) = 2\frac{1 - (1 + A)e^{-A}}{A^2} \tag{3.17}$$

where

$$A = G(\theta)\frac{3}{2}\ \frac{\mu_l\, V}{PEA(\theta)} \tag{3.18}$$

where $G(\theta)$ is the projection function in the θ direction and V is the tree volume (m^3). Similar equations may be written for other solids of revolution like semi-spheroids.

Daily radiation interception of isolated trees may be calculated using interception for zenith angle 1 rad. For spheroids and semi-spheroids, of height h and horizontal radius r, the relative intercepted radiation, i.e. the ratio of radiation intercepted by the tree and incoming radiation on a horizontal surface may be calculated as:

$$RR_i = 0.95\ (1 - t_{c1})\ PEA_1 \left[1 - \ \alpha' + \ \alpha'\ \frac{0.0036\, R_{sn}\, N_s}{0.75\, R_A}\right] \tag{3.19}$$

where R_{sn} (W m^{-2}) is average solar radiation normal to the sun beams for clear sky conditions, which can be calculated as:

$$R_{sn} = \ -0013\, x^2 + 2.19\, x - 79.7 \tag{3.20}$$

where x = 0.75 $10^6 R_A/(3600\, N_s)$. The previous equations can be simplified to:

$$RR_i = c_1\ \ PEA_1 \left[1 - \ \alpha' + \ \alpha' \left(1.84 - \frac{0.75 R_A}{3.6 N_s}\right)\right] \tag{3.21}$$

N_s is daylength (hour) while R_A is daily extraterrestrial radiation (MJ m^{-2} day^{-1}). The factor α′ reflects sky conditions, being 0 for completely overcast skies and 1 for clear sky, and may be calculated using measured radiation:

$$\alpha' = 2\frac{R_s}{R_A} - 0.5 \tag{3.22}$$

The factors related to the trees are, in the first place, the projected envelope area for 1 rad:

$$PEA_1 = \pi\, r^2 \left(a_p + {b_p}^{h/r}\right) \tag{3.23}$$

The mean interception of the tree envelope for 1 rad is:

$$1 - t_{c1} = 1 - exp\left[-c_p A + d_p A^2\right] \tag{3.24}$$

where

$$A = \frac{\mu\, \pi\, r^3 h}{2\, PEA_1} \tag{3.25}$$

The coefficients depend on tree shape:

For spheroids: $a_p = 0.3$, $b_p = 0.35$, $c_p = 0.64$, $d_p = 0.026$
For semi-spheroids: $a_p = 0.36$, $b_p = 0.4$, $c_p = 0.646$, $d_p = 0.047$

The equations presented here require knowing the value of leaf area density, the ratio of leaf area and crown volume. We may take values as low as 0.5 m^2m^{-3} for very sparse crowns up to 2–3 m^2m^{-3} for dense crowns.

Example 3.5 We have an olive orchard in Cordoba, Spain. Plant spacing is 7 × 3.5 m. The trees have horizontal radius 0.5 m, height 1.5 m and Leaf Area Density 2 $m^2\ m^{-3}$. Let's calculate radiation interception on 21 March, under clear sky conditions. For that day and location: $R_A = 29.8$ MJ $m^{-2}\ day^{-1}$ and N = 12 h.

Using Eqs. 3.23, 3.24, and 3.21:

Assuming a spheroid:

$PEA_1 = 1.06\ m^2$ and $c_1 = 0.49$, so $RR_i = 0.69\ m^2$ and intercepted PAR is 7 MJ day^{-1}.

Assuming a semi-spheroid:

$PEA_1 = 1.23\ m^2$ and $c_1 = 0.44$, so $RR_i = 0.71\ m^2$ and intercepted PAR is 7.2 MJ day^{-1}.

If we want to express radiation interception at the orchard level to get the fraction of intercepted radiation we simply divide the value of RR_i by the area per tree ($7 \times 3.5 = 24.5\ m^2$):

$$f_{PI} = 0.69/24.5 = 0.03$$

The same orchard would have $RR_i = 0.79\ m^2$ on January 1 and $0.65\ m^2$ on June 21. This illustrates the fact that isolated trees will intercept a higher fraction of radiation in winter than in summer.

As in herbaceous crops, the degree of radiation interception by a tree may be estimated by determining the ground cover as the horizontal projection on the ground of the tree shade at solar noon divided by the tree spacing. Given the wide diversity of tree architecture, this is only a first approximation of the intercepted radiation as calculated above.

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Chapter 4
Wind and Turbulent Transport

Francisco J. Villalobos, Elias Fereres, and Luca Testi

Abstract The flow of wind over crop canopies causes a transfer of momentum from the air to the canopy that generates turbulence which enhances the exchange of matter and energy between the atmosphere and crops. Turbulence increases with wind velocity and aerodynamic roughness which is proportional to crop height. Wind speed varies logarithmically with height. This profile can be described mathematically by two parameters that are related to crop height. Turbulence can also be expressed as an inverse function of aerodynamic resistance, which is indicative of the difficulty for turbulent transport and is therefore very high when U is low and for smooth (short) crops. Inside the canopy layer the wind speed acquires profiles more dependent on the architecture of the canopy than to the wind vector over it. Wind speed changes considerably over space and time, being generally low at night and maximum after noon; over the long term, higher average wind speeds are often registered at high latitudes.

4.1 Transport of Mass and Energy from Crops

The disposition of net radiation over a crop surface takes place in several forms; part is spent in convection, thereby increasing the temperature of the air within the crop and the atmosphere above (sensible heat). The rest is spent in conduction leading to an increase in the soil (and the crop) temperature, or as latent heat as a result of evaporation. A small fraction of the energy is also spent on reduction of CO_2 (photosynthesis).

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The transfer of mass (e.g. water vapor) or energy (e.g. sensible heat) is usually expressed by the analogy of Ohm's Law:

$$Flow = \frac{Cs - Ca}{r}$$

where *Cs* and *Ca* are the concentrations of material or energy levels at the canopy top and in the atmosphere, respectively, and r is the resistance to the exchange. This resistance may refer to different processes (e.g. conduction, convection, etc.). In the case of heat transport by convection which is very similar to the transfer of chemicals between the crop and the atmosphere, fluxes are enhanced by turbulence, which in turn depends on wind speed.

4.2 Wind and Exchange of Matter, Energy and Momentum

Crops are subject to the mechanical action of wind, which moves and bends their leaves, stems and branches. But wind has another essential effect on crops, as it enhances the turbulent transport of water vapor, CO_2 and heat. This flow is characterized by turbulent air currents or eddies of many different sizes and variable direction and is very effective as a transport mechanism. If the heat and the gases were transported by a pure diffusion mechanism, the surface conditions on earth would not be suitable for plant life due to the high temperatures which would be reached and the limitation on the rate of downward flow of CO_2 required for photosynthesis.

Wind speed is determined by the transport of turbulence in the surface boundary layer, i.e. the layer of atmosphere closer to the crops and the soil. If air flows parallel to a flat surface, the profile of wind speed would be logarithmic (exponential increase with height) and velocity would tend to zero as we approach the surface. This tendency is due to a frictional force between the surface and the air, which is transmitted to upper air layers through the intermediate layers. The friction force per unit area is called the shear stress (τ_s) and is proportional to the gradient of wind speed:

$$\tau_s = \mu_a \frac{dU}{dz} \tag{4.1}$$

where μ_a is the dynamic viscosity of air, U is wind speed and *z* is the height. The dimensions of τ_s are the same as those of momentum per unit area and unit time (momentum flux). This variable allows an analogy between heat (or mass) transport and vertical transfer of momentum. The magnitude of the momentum flux is indicative of the amount of eddies that are formed and, therefore, of the effectiveness of the turbulent exchange of water vapor, heat, CO_2 and other particles, between the crop and the atmosphere.

4.3 Profiles of Wind Speed Above Crop Canopies

Perfectly flat surfaces are very rare in nature, especially on land. When obstacles are present (for example stones, soil aggregates, crop canopies) the wind profile is affected. The obstacles hinder the movement of the air in comparison to an ideal flat surface. First, the wind velocity is not zero at the surface as shown in Fig. 4.1, but at an intermediate level between the surface and the obstacles' height. This height is called the *zero plane displacement* (d) and indicates the level above which momentum is absorbed, namely the virtual level where friction forces are exerted by the crop.

Another feature that influences the aerodynamics of a surface is the *roughness length* (z_0). This is a parameter used to quantify the distortion of the real wind profile over a rough surface from the ideal logarithmic profile if the surface were smooth; it is thus a measure of the aerodynamic surface roughness. Like the zero plane displacement, it has also the dimensions of a length and its value ranges from 10^{-6} m for smooth ice to 0.3 m for orchards to 1 m for forests. Both d and z_o are related to the form of the crop canopy. Obviously, z_o depends on the roughness of the crop (uniformity of height among plants, distance between plants or between rows, amount of ground cover, etc.). The parameter d also depends on the height and flexibility of the plants, on foliage density, etc. A simple approximation for the values of the two parameters for different crops is to calculate d as 0.65 h and z_o as 0.13 h, where h is the crop height.

Typical profiles of mean horizontal wind speed above crops are shown in Fig. 4.1. These profiles may be calculated for neutral conditions (see Chap. 5) as:

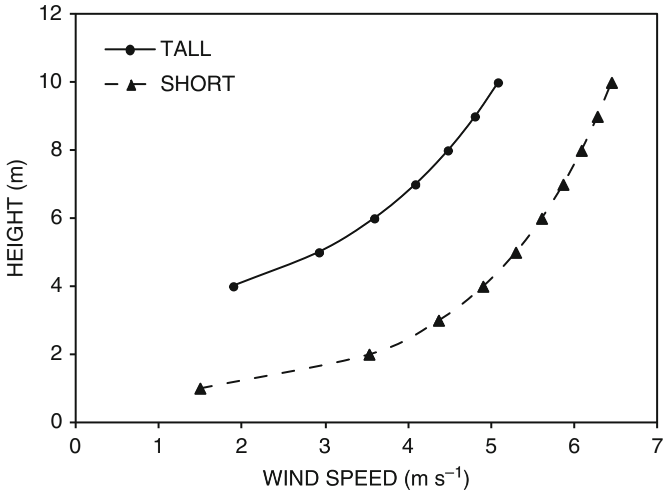

Fig. 4.1 Wind profiles over a short (height 0.1 m) and a very tall (height 4.0 m) canopy

$$U(z) = \frac{u*}{k_k} \ln\left(\frac{z - d_z}{z_0}\right) \tag{4.2}$$

where U(z) is mean wind speed at height z, k_k is the von Kármán's constant (about 0.4), u_* is friction velocity, z_o is roughness length and d_z is the zero plane displacement.

The friction velocity (so named for having the dimension of m s^{-1}), is related to momentum flux by:

$$\tau_s = \rho_a\, u_*^2 \tag{4.3}$$

where ρ_a is air density (kg m^{-3}), that depends on air temperature (T in K) and atmospheric pressure (P_{at} in kPa) (the effect of air humidity is neglected):

$$\rho_a = 3.484\, \frac{P_{at}}{T} \tag{4.4}$$

Applying the above equations, once z_o and d are known, we may generate the whole profile of wind speed as a function of wind speed measured at a reference height (z_m):

$$U(z) = U(z_m)\,\frac{[\ln(z_m - d) - \ln z_0]}{[\ln(z - d) - \ln z_0]} \tag{4.5}$$

Example 4.1
Figure 4.1 shows the wind profiles of two crops with height 0.10 m (e.g. prairie) and 4.0 m (e.g. grain maize), respectively. To construct this curve we assumed that the wind speed at 100 m height is 10 m/s in both cases. The wind speed above maize is significantly lower than above grass, namely maize slows down the wind more, or, in other words, it takes a greater amount of momentum away from the wind. Friction velocities are 0.45 m/s and 0.67 m/s, for grass and corn, respectively, which correspond to values of momentum transfer of 0.26 and 0.59 N/m^2.

Often the only available information on wind speed comes from a nearby weather station where the wind is measured at a standard height (z = 2 m in agrometeorological stations). However we often need to know U at a height z over a canopy of height h. We can use Eq. 4.5 to calculate first U_{100}, the speed at a height of 100 m, which we may assume that does not vary spatially, i.e. it is the same above the weather station and above the crop. If the station is located over grass (h = 0.12 m) then:

$$U_{100} = U_{2g}\,\frac{[\ln(100 - 0.078) - \ln(0.0156)]}{[\ln(2 - 0.078) - \ln(0.0156)]} = 1.82\,U_{2g} \tag{4.6}$$

where U_{2g} is wind speed measured at 2 m over grass.

And then we can calculate U(z) above our crop of height h:

$$U(z) = \ 1.82\,U_{2g}\,\frac{[\ln(z - 0.65\,h) - \ln(0.13\,h)]}{[\ln(100 - 0.65\,h) - \ln(0.13\,h)]} \tag{4.7}$$

Example 4.2

Wind speed at $z = 2$ m above grass (U_{2g}) is 2.5 m/s. We will calculate U at $z = 5$ m over a 4-m maize crop.

$$U(z) = 1.82 \cdot 2.5\,\frac{[\ln(5 - 0.65 \cdot 4) - \ln(0.13 \cdot 4)]}{[\ln(100 - 0.65 \cdot 4) - \ln(0.13 \cdot 4)]} = 1.33\ m/s$$

4.4 Aerodynamic Resistance

The equation describing the flow of momentum in terms of the gradient of horizontal wind speed (Eq. 4.1), can be written using the Ohm's Law analogy, by introducing an aerodynamic resistance to the transfer of momentum between heights z_1 and z_2. Therefore, if

$$\tau_s \ = \rho_a\,\frac{U_2 - U_1}{r_{aM}} \tag{4.8}$$

and using Eqs. 4.2 and 4.3, then the aerodynamic resistance between a height z where wind speed is U(z) and height d + z_o (where the extrapolated wind speed is zero), will be:

$$r_{aM} = \frac{\left[\ln\left(\frac{z-d_z}{z_0}\right)\right]^2}{{k_k}^2\,U(z)} = \frac{U(z)}{{u_*}^2} \tag{4.9}$$

This equation indicates that the aerodynamic resistance to the flux of momentum will be greater for short than for tall crops. In fact short and smooth surfaces are less effective in slowing the wind that flows above them, thus less energy is transferred from the wind to the surface for a given wind flow. The resistance decreases as wind speed increases. In theory the resistance tends to infinity as U tends to 0. However in the atmosphere that does not occur during the daylight hours because of buoyancy, which will be treated later in Chap. 5. Suffice it to note here that as U decreases, the lack of turbulence reduces the exchange of heat between the crop and the atmosphere thereby increasing the temperature of the canopy and of the air in contact therewith. This heated air tends to rise because of its lower density which causes turbulence. This type of turbulence is called “thermal” as opposed to “mechanical” turbulence which is due to friction of the wind on the crop. Both types of turbulence coexist although mechanical turbulence prevails when U is high and thermal turbulence is enhanced during the daytime when U is low.

Example 4.3
Let us calculate the aerodynamic resistance for z = 5 m in the two cases mentioned in Example 4.1 (maize with h = 4 m and grass with h = 0.12 m) if the wind speed at 2 m height over grass (U_{2g}) is 2.5 m/s.

We need to know first U(z) for z = 5 m in both cases. We saw in Example 4.2 that U(z = 5) = 1.33 m/s for maize.

For grass, using Eq. 4.5:

$$U(z=5) = U_{2g}\,\frac{[\ln(5-0.078)-\ln(0.0156)]}{[\ln(2-0.078)-\ln(0.0156)]} = 1.195\,U_{2g} = 2.99\,m/s$$

then applying Eq. 4.9 for the two surfaces:

Maize:

$$r_{aM} = \frac{[\ln(\frac{5-0.65\cdot 4}{0.13\cdot 4})]^2}{0.4^2\cdot 1.33} = 11\,s/m$$

Grass:

$$r_{aM} = \frac{\left[\ln\left(\frac{5-0.65\cdot 0.12}{0.13\cdot 0.12}\right)\right]^2}{0.4^2\cdot 2.99} = 69.2\,s/m$$

4.5 Wind Speed and Turbulence at Canopy Height

The mathematical analysis of wind profiles above crops presented above should allow the calculation of wind speed at canopy height as a function of crop height. However, the existence of the so called Roughness Sub-layer which extends up to 2–2.5 times canopy height has not been taken into account. In that layer the profiles of temperature and wind are distorted due to the proximity of vegetation. Including this effect, the following equation allows calculating wind speed at canopy height as a function of wind speed measured at 2 m height over grass:

$$U_h = \frac{2.6\,U_{2g}}{6.6 - \ln(h)} \tag{4.10}$$

This equation indicates that for most agricultural crops, with heights between 0.2 and to 3 m, wind speed at canopy height ranges between 0.32 and 0.46 times the wind speed at 2 m over grass.

In the previous sections we have defined turbulence as an ensemble of eddies of different size and properties (temperature, humidity, CO_2 concentration) moving up or down and following, on the average, the direction of wind speed. This vertical exchange of eddies is responsible for the fluxes between the crop and the atmosphere. For instance the convective transport of heat is due to warm eddies moving up and cooler eddies moving down. We can characterize this turbulent exchange using the average velocity of eddies going up which is equal to the average velocity of those going down (as the mean vertical velocity is always close to zero). This upward velocity, accompanied by a downward velocity of the same magnitude may be seen as a mean renovation rate for the air located below, and we name it w_r. The renovation rate is proportional to horizontal wind speed (U) at canopy height. For neutral conditions we can write:

$$w_r = 0.14\,U \tag{4.11}$$

Note that w_r has dimensions of velocity. By combining Eqs. 4.10 and 4.11 we can calculate the renovation rate of air in contact with a canopy of height h:

$$w_r = 0.14\,\frac{2.6\,U_{2g}}{6.6 - \ln(h)} \tag{4.12}$$

And the relative renovation rate with dimensions T^{-1} would be obtained by dividing w_r by h.

Example 4.4

When wind speed over grass is 2 m/s the renovation rate of a maize crop with height 2 m is:

$$w_r = 0.14\,\frac{2.6 \times 2}{6.6 - \ln(2)} = 0.123\ m/s$$

And the relative renovation rate is $0.123/2 = 0.0615\ s^{-1}$

This means that the air in contact with the canopy would be completely renovated in 16.3 s (inverse of the relative renovation rate). A similar concept of renovation rate is applied to greenhouses as a measure of ventilation, and usually expressed in number of renovations per hour. In the example above the relative renovation rate is equivalent to $0.0615\ s^{-1} \times 3600\ s/h = 221.4\ h^{-1}$.

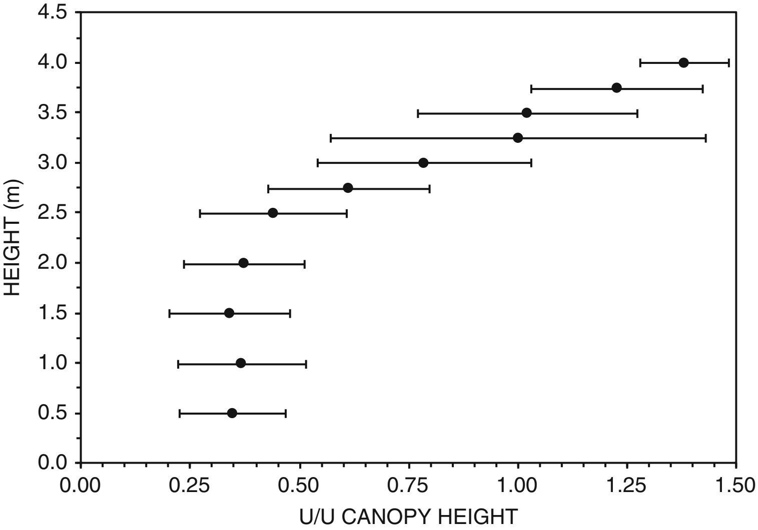

Fig. 4.2 Profile of wind speed (relative to that at canopy height 3.25 m) measured in an olive orchard close to Cordoba (Spain) in summer 2012. *Horizontal* segments represent twice the standard deviation

4.6 Wind Speed Inside Canopies

If the wind profiles are complicated above the canopy, they are even more complicated inside it. In simple terms, the canopy height is divided into two or three zones. The top layer (above d_Z), absorbs most of the momentum. In this layer the wind speed decreases logarithmically as we enter the canopy and has the same direction as the average wind over the canopy. This is clearly seen in Fig. 4.2 for a hedgerow olive orchard down to 2.5 m height. Below that height, wind speed is almost constant and rather small (35–40 % of that at the top of the canopy in the example of Fig. 4.2).

4.7 Daily and Seasonal Variation of Wind Speed and Direction

Both the daily and the seasonal time courses of wind speed are highly variable. The predominant winds have traditionally been characterized by the wind rose, which is a representation of the frequencies of occurrence of each wind direction. The seasonal time course, besides being highly variable from year to year, is often site-specific. As an example, Fig. 4.3 shows the wind speed in Fuente Palmera (Spain) during the year. In this case the highest values of U occur in spring and summer and lower values occur in autumn and winter. The large differences

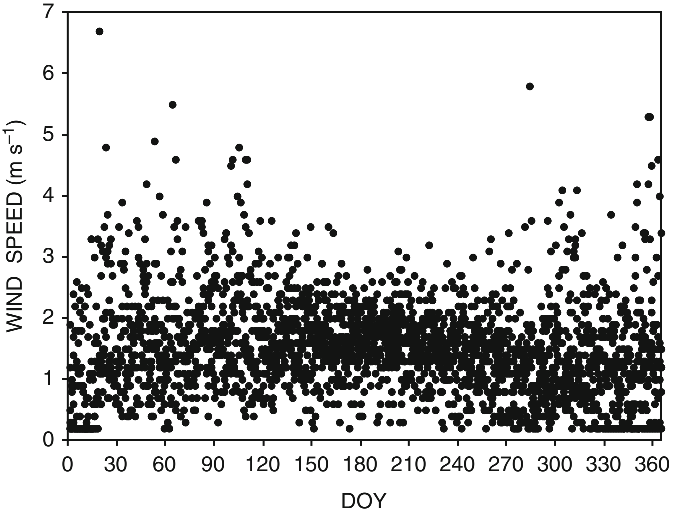

Fig. 4.3 Mean daily wind speed at 2 m height at Fuente Palmera (Spain) 2007–2013

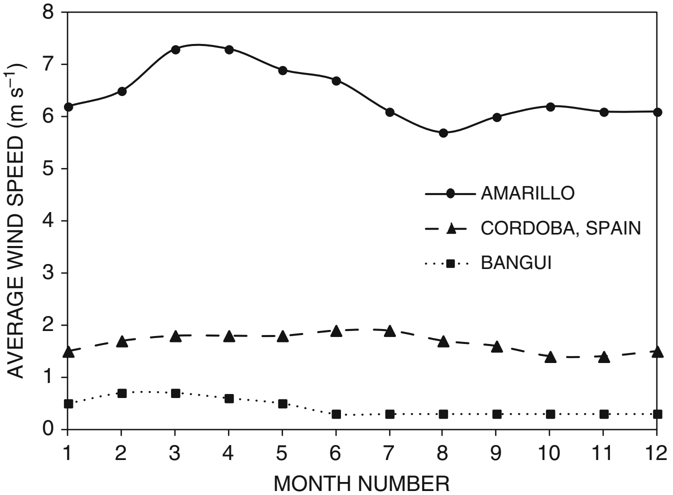

Fig. 4.4 Time course of monthly mean wind speed in Bangui (Central African Republic), Amarillo (Texas, USA) and Cordoba (Spain)

between locations in wind patterns are evident in Fig. 4.4 which shows the monthly average values of U in Bangui (Central African Republic), Cordoba (Spain) and Amarillo (Texas). The large variation among locations in wind speed is illustrated in Fig. 4.5 that shows mean annual wind speed for many locations as a function of latitude. Both mean wind speed and its variability increase as we move away from the Equator.

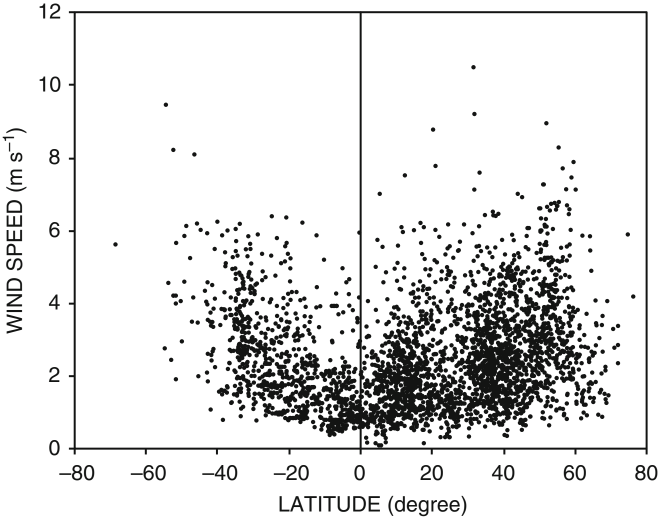

Fig. 4.5 Mean annual wind speed for different locations as a function of latitude (Source: Climwat-FAO)

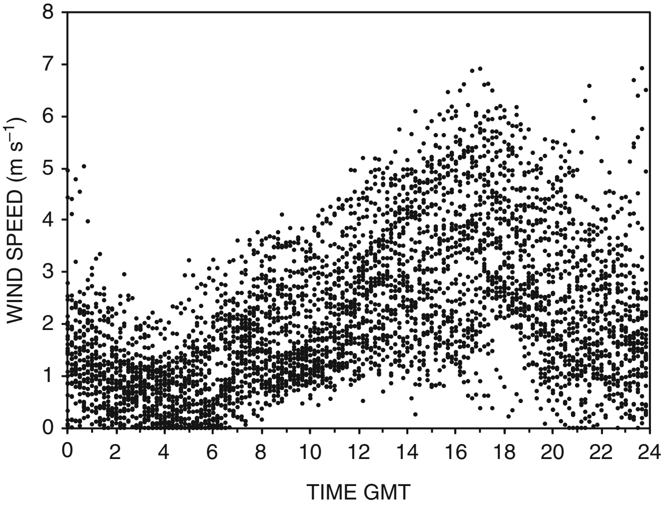

Fig. 4.6 Wind speed at Cordoba (Spain) in June 2003 plotted as a function of time. Each point is the 10-min average wind speed

In the diurnal time course we usually observe that calm winds predominate during the night while the maximum wind speed occurs during the day. Figure 4.6 shows the diurnal time course of wind over grass at Cordoba during June: we observe that U is low at night, especially at dawn, and that U increases during the day.

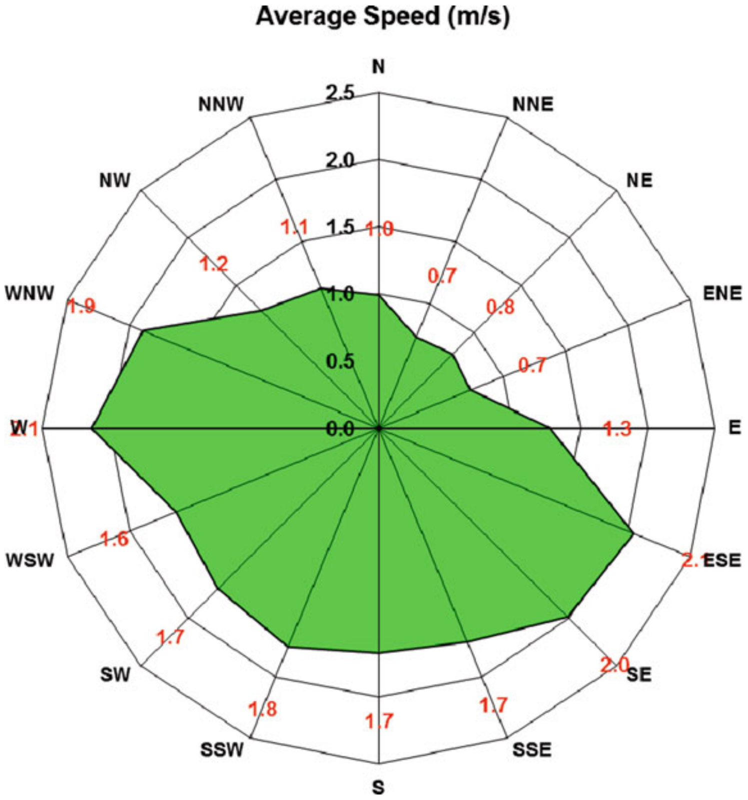

Fig. 4.7 Wind rose for wind speed at Espiel (Spain) 2003–2012

A wind rose is a graphical representation of the distribution of wind speed and wind direction at a given site over a specific period of time. Presented in a circular format, the wind rose shows the frequency of winds blowing from each direction, typically classified in 16 cardinal directions, such as north (N), NNE, NE, etc., where North corresponds to 0°, East to 90°, South to 180° and West to 270°. The distance from the center represents the frequency of that particular direction, which may also be given for different wind speed classes (see example in Fig. 4.7).

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Chapter 5
Air Temperature and Humidity

Francisco J. Villalobos, Luciano Mateos, Luca Testi, and Elias Fereres

Abstract Air temperature shows unstable profiles during the day and stable profiles during the night. Therefore, canopy temperature is generally higher than that of the air during the day and lower during the night. Heat transfer between the crop and the atmosphere is sustained by turbulence and will be more effective the higher the wind speed, i.e. when aerodynamic resistance is low. In situations of unstable atmosphere, turbulence is enhanced (by added thermal turbulence) while in a stable condition turbulence is reduced. The water vapor content of the atmosphere can be expressed by different variables (vapor pressure, relative humidity, vapor pressure deficit, mixing ratio, vapor density). The flow of water vapor (equivalent to energy spent as latent heat) between the crop and the atmosphere is directly proportional to the vapor pressure difference and inversely proportional to the sum of the canopy and aerodynamic resistances.

5.1 Introduction

Air temperature controls the functioning of terrestrial ecosystems. Crop temperature affects photosynthesis, growth and development rates, transpiration, etc. Crops are heated by radiation absorption. Part of the absorbed energy is used to heat the air (sensible heat) which, in turn, determines the air temperature above the crop.

Air humidity is important in crop production for several reasons. First, water and/or humidity are essential for living organisms in the agricultural ecosystem to grow and complete their life cycles. Secondly, moisture plays an important role in energy exchange. Changing water from liquid to vapor state, which occurs in the

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process of evaporation, requires 2.45 MJ/kg. When 1 kg of water vapor condenses and then freezes, 2.8 MJ are released. The first process relates radiation absorption to water use by crops and the second process is the basis of some methods used for frost protection in horticulture.

5.2 Thermal Stability

An air parcel that rises adiabatically (see Box 5.1) from one level to a higher one is always at the same temperature (and thus, the same density) as the surrounding air. The corresponding adiabatic temperature profile is drawn as the dashed line in Fig. 5.1. Consider now an actual temperature profile such as that shown in Fig. 5.1 (right). In this case, by raising a parcel of air adiabatically from point C to D, that parcel of air will have a higher temperature than the surrounding air (D′), will be less dense and therefore will tend to continue rising. This atmospheric condition is called unstable. This adiabatic rise happens when a hot eddy jumps suddenly from the crop by a wind gust. If the movement is fast enough, the heat exchange between the eddy and the air it finds will be very small allowing the assumption of adiabatic conditions.

Suppose now that the actual temperature profile is of the type shown in Fig. 5.1 (left). In this case, by raising an air parcel adiabatically, its temperature will be lower than the surrounding air and its density will be higher, so it will tend to return to its original height. This condition of the atmosphere is termed stable and the temperature profile is called inverted profile.

If the actual temperature profile follows the adiabatic profile, the corresponding atmospheric condition is called neutral (dashed line in Fig. 5.1).

Box 5.1 Adiabatic Processes

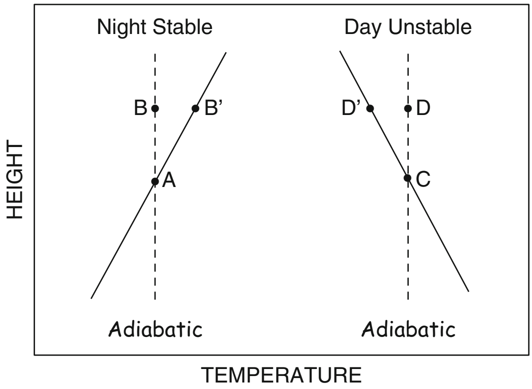
A process (change of state) that occurs without gain or loss of heat is called adiabatic process. If the pressure of an air volume changed adiabatically from P_1 to P_2, the change of temperature (from T_1 to T_2) is given by:

$$(T_2/T_1) = (P_2/P_1)^{1-Cv/Cp} \tag{5.1}$$

where C_p and C_v are the specific heats of air at constant pressure and constant volume, respectively.

The above equation means that a mass of air at pressure 100 kPa and temperature 30 °C will cool down to 20.8 °C if it is risen adiabatically to a height where the pressure is 90 kPa. This temperature drop as height increases is called adiabatic lapse rate. Its value for dry air is about 0.01 K/m while for moist air it shows lower values (approx. 0.008 K/m).

Fig. 5.1 Typical temperature profiles during the day and during the night



5.3 Basic Principles on Air Humidity

According to Dalton's Law, the pressure of air in the atmosphere is the sum of the partial pressure of water vapor (e_a) and the partial pressure of dry air (P_d). Both partial pressures may be expressed as the product of their respective molar fractions by the total pressure (P).

From a water surface some molecules are escaping in the evaporation process while some others return to the liquid state. When the number of molecules escaping equals that of those returning, the system has reached a steady state and the atmosphere is said to be saturated. In this state, the vapor pressure has reached its saturation value (e_s). For a given temperature there is a single value of e_s, and the relation between the two variables is an exponential function:

$$e_s = 0.61078\exp\left(\frac{17.27T}{237.3+T}\right) \tag{5.2}$$

where e_s is expressed in kPa and T is temperature (°C). The atmosphere is usually not saturated, thus, e_a is lower than e_s for that temperature.

Relative humidity (%) indicates the degree of saturation as:

$$RH = 100\frac{e_a}{e_s} \tag{5.3}$$

However, as it depends on the temperature, it is not a good indicator of the amount of water vapor in the air.

Another interesting feature of air humidity, widely used in crop ecology, is the vapor pressure deficit (VPD) which is the difference e_s-e_a. Its value gives an idea of the drying power of the atmosphere and is therefore a key factor determining the rate of evaporation and transpiration.

Air humidity may also be quantified by the dew point temperature (T_d) which is the temperature required for a portion of air at constant pressure and constant water vapor content, to reach saturation. If air temperature falls below T_d, condensation will start. This is the phenomenon that can be seen on cold mornings when a film of water covers the soil or plants.

The mixing ratio is the ratio of mass of water vapor per unit mass of dry air and can be calculated (in g/kg) as:

$$X_v = 622\frac{e_a}{P_{at} - e_a} \tag{5.4}$$

where P_{at} is atmospheric pressure (kPa) and e_a is vapor pressure (kPa). Finally, air humidity may be expressed as vapor density (ρ_v), also known as absolute humidity, which is the mass of water vapor per unit volume of air, and can be calculated (g water vapor m^{-3}) as:

$$\rho_v = \frac{1000\, e_a}{0.4615\, T} \tag{5.5}$$

where T is air temperature (K).

Example 5.1 Air temperature is 20 °C and relative humidity is 80 %. We will calculate vapor pressure, VPD, mixing ratio, vapor density and dew point temperature. We will assume standard atmospheric pressure (101.3 kPa).

First we calculate saturation vapor pressure :

$$\mathrm{e_s} = 0.61078 \exp[17.27 \cdot 20/(20 + 237.3)] = 2.338\ \text{ kPa}$$

Therefore: $\mathrm{e_a} = (\mathrm{HR}/100)\mathrm{e_s} = 80/100 \times 2.338 = 1.87\,\text{kPa}$

$$\mathrm{VPD} = \mathrm{e_s} - \mathrm{e_a} = 2.338 - 1.87 = 0.467\ \text{ kPa}$$
$$\text{Mixing ratio: } \mathrm{X_v} = 622 \times 1.87/(101.3 - 1.87) = 11.7\ \text{ g/kg}$$
$$\text{Vapor density: } \rho_\mathrm{v} = 1000 \times 1.87/(0.4615 \times 293) = 13.83\ \text{ g m}^{-3}$$

Dew point temperature may be deduced by equating Eq. 5.2 to 1.87 kPa, which is the actual vapor pressure, and then solving for temperature as:

$$T_d = \frac{237.3 ln\left(\frac{e_a}{0.6108}\right)}{17.27 - ln\left(\frac{e_a}{0.6108}\right)} = 16.44^\circ\mathrm{C}$$

If this air is cooled down to 16.4 °C we would reach saturation. This may be checked by putting T = 16.44 °C into Eq. 5.2, yielding 1.87 kPa.

5.4 Temperature Profiles Within and Above Crop Canopies

The soil or crop surface undergoes cooling during the night as solar radiation is zero, while maintaining its emission of long-wave radiation (R_n negative). The air in contact with the surface transfers heat to the surface, and thus also cools and its

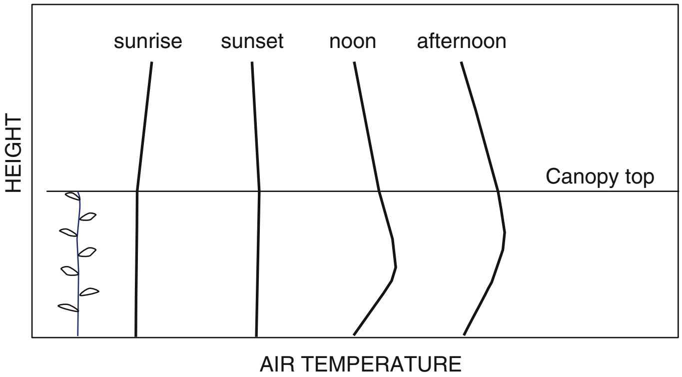


Fig. 5.2 Typical temperature profiles above and within a crop canopy

density increases. The consequence is that a temperature inversion develops and the atmospheric condition is stable (Fig. 5.2).

During the day the opposite occurs. The surface absorbs radiation that, in part, serves to heat the lower layers of the atmosphere. The temperature now decreases with height and the atmospheric condition is unstable (this can be clearly seen in the afternoon in Fig. 5.2).

The shape of the temperature profiles has important implications for the temporal and spatial distribution of temperature on crops. As we approach the crop surface, thermal oscillation (the difference between maximum and minimum temperature) increases as higher maximum and lower minimum temperatures will be observed.

Also during the day, inverted profiles can be observed by cooling as a result of crop evapotranspiration. This situation is typical of summer when hot dry air blows over irrigated crops. The phenomenon is called sensible heat advection and is explored in more detail in Chap. 7.

Both the day and night profiles, are often highly variable and are affected by other factors, particularly wind speed. When wind speed is very high, the temperature profile above the crop is very uniform with height, so that the air and the crop temperature are similar. In contrast, during low wind the temperature profile is very sharp and the crop is much hotter than the air (during the day) or much colder (overnight). The temperature profiles (stable or unstable) have an important effect on turbulence (Box 5.2).

The temperature profiles within the crop canopy are quite different from those observed above the canopy. During the day, in general, temperature reaches a maximum at the level where leaf density is highest. A high leaf area density allows greater radiation absorption and therefore higher temperature. Above this level the daytime temperature profile is generally unstable and below that height it is usually slightly inverted. During the night, the profile within the canopy is usually isothermal as the crop traps and re-emits radiation emitted from the soil (Fig. 5.3).

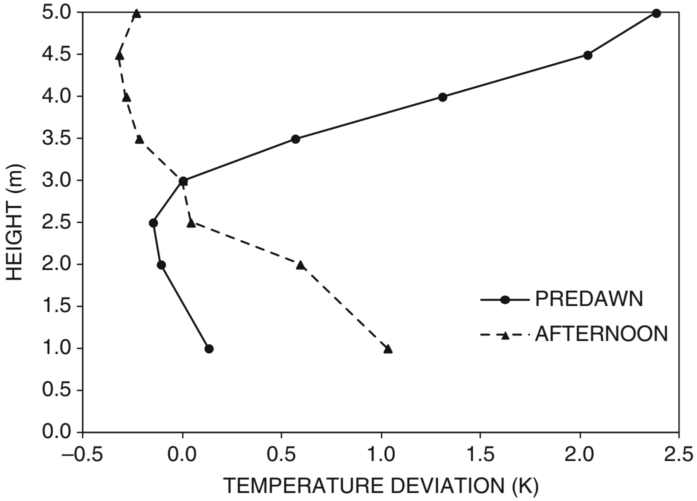


Fig. 5.3 Air temperature profiles above and within an olive canopy of 3.25 m height on a summer day (July 30, 2011) near Cordoba (Spain). The values are shown as departures from the temperature measured at 3.0 m height

Box 5.2. Effects of Atmospheric Stability on Turbulence

The mathematical treatment of stability effects lies outside the scope of this book. However, some remarks should be made on the importance of stability. During the daytime, turbulent transport is insured as wind speed is higher. If wind speed is low, buoyancy increases and turbulence will be sustained. Therefore only in rare cases the lack of turbulence in the daytime may restrict the vertical transport of energy or matter. The opposite will occur at night as wind speed is usually lower and the temperature profile is inverted. That creates a layer above the crop where turbulence is almost absent so H and LE are small and canopy cooling follows the loss of long wave radiation.

5.5 Air Humidity Profiles Above Crop Canopies

During the day, because of transpiration, the vapor pressure is high near the crop surface and decreases with height. Water vapor is removed more effectively with increasing wind and turbulent transport. Therefore, the more pronounced profiles occur at noon when evapotranspiration is high and the water vapor is easily removed. The vapor pressure profile at night is much more uniform, and may even increase with height in nights when dew deposition occurs

5.6 Time Course of Air Temperature and Humidity

The time course of air temperature along a clear day follows a sine function with the minimum around sunrise and a maximum that occurs 2–3 h after the peak of radiation (Fig. 5.4). The delay of air temperature relative to radiation is due to the balance between the energy reaching the surface and the energy being used. Part of the radiation in the morning is spent in heating the soil and the crop. Once these surfaces have been heated, there will be sensible heat transfer to the air that will then be heated. Furthermore, other factors (such as advection) can contribute to raising air temperature in the afternoon.

Vapor pressure varies relatively little in comparison with other variables related to humidity. Therefore variations in VPD along the day are mainly due to variations in air temperature. In any case, vapor pressure close to the canopy is proportional to evaporation rate, so it will be higher during midday (Fig. 5.5).

In contrast with the vapor pressure, the maximum relative humidity occurs during the night because, although the water vapor content of the atmosphere is somewhat lower, the temperature is much lower. The minimum relative humidity occurs sometime after noon because although the vapor pressure can be high then, the temperature will also be high.

To calculate the average daily vapor pressure as a function of maximum and minimum RH we can use the following equation:

$$e_{avg} = 0.5\left(e_{sx}\frac{RH_n}{100} + e_{sn}\frac{RH_x}{100}\right) \tag{5.6}$$

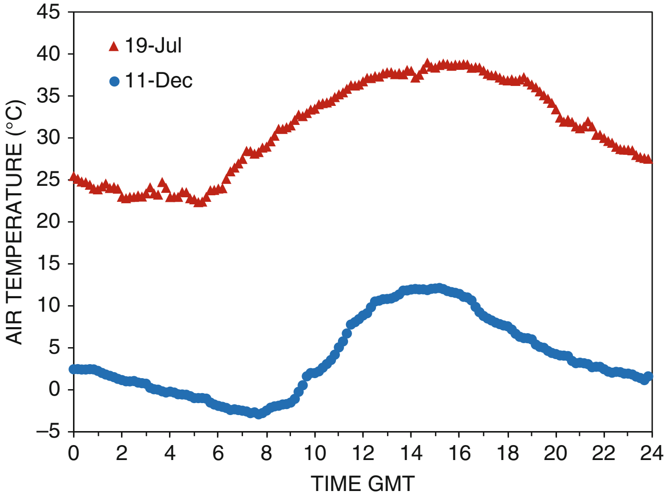


Fig. 5.4 Time course of air temperature throughout the day on a summer (19 July 2012) and a late fall day (11 December 2012) in Espiel (Spain)

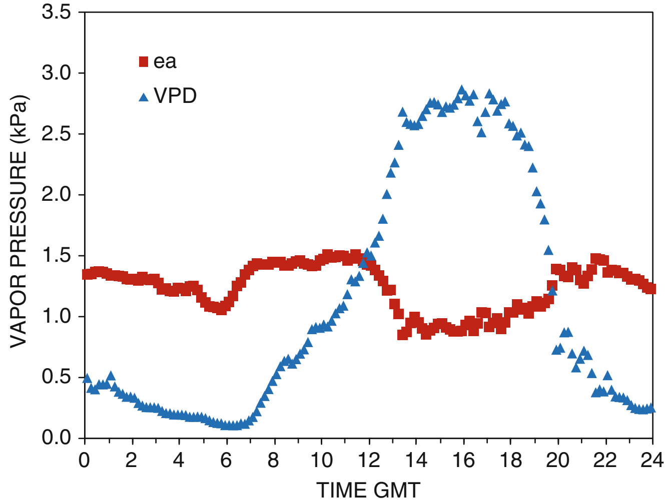


Fig. 5.5 Time course of vapor pressure and vapor pressure deficit throughout the day on a spring day (5 May 2013) in Cordoba (Spain)

where RH_n and RH_x are minimum and maximum RH, respectively and e_{sx} and e_{sn} are saturated vapor pressure for the maximum and minimum temperature, respectively. Therefore the average VPD will be:

$$VPD_{avg} = 0.5 \left[e_{sx} \left(1 - \frac{RH_n}{100} \right) + e_{sn} \left(1 - \frac{RH_x}{100} \right) \right] \tag{5.7}$$

The annual time courses of the maximum and minimum temperatures of the air follow a pattern very similar to the daily curve (Fig. 5.6). Something similar occurs for vapor pressure.

Figure 5.7 shows the mean monthly vapor pressure in two locations with the same latitude (31.8°S) but with low (Klawer, South Africa) and high rainfall (Pelotas, Brazil). In both locations vapor pressure is maximum in summer and minimum in winter, but the two curves reflect clearly the difference in rainfall.

On average, the minimum and the maximum temperature occur with a certain delay with respect to the minimum and maximum radiation, respectively. This is seen, for example, in Fig. 5.8, that shows the annual curves of average radiation and temperature in Cordoba, normalized with respect to their extreme values. The reasons for the delay between the temperature and radiation waves are similar to those described for the daily curve. During the spring part of the radiation is used to heat the soil. As the soil temperature rises above the air temperature, more energy will be available to be converted into sensible heat. A similar reasoning can be applied to explain when the minimum winter temperature occurs.

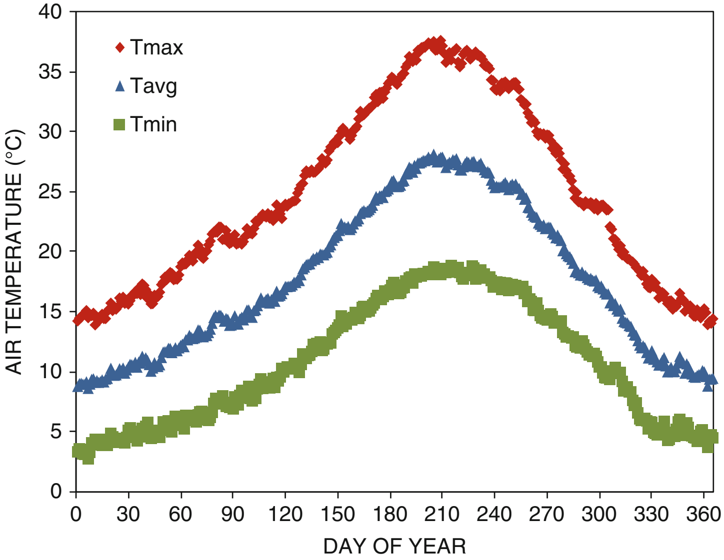


Fig. 5.6 Time course of average maximum, minimum and mean air temperature. Cordoba (Spain). 1964–2002

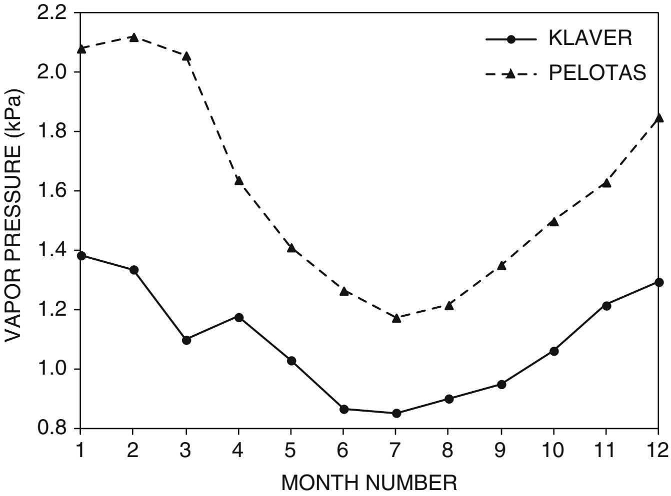


Fig. 5.7 Time course of mean monthly vapor pressure for two locations, Pelotas (Brazil) with mean annual rainfall of 1395 mm and Klawer (South Africa) with mean annual rainfall 174 mm

The amplitudes of the waves of air temperature, both for daily and annual cycles, depend largely on the partitioning of energy between evaporation and heating of the soil and air above as we will see in following sections. So in arid areas the amplitude will be higher than in wet areas (or near the sea).

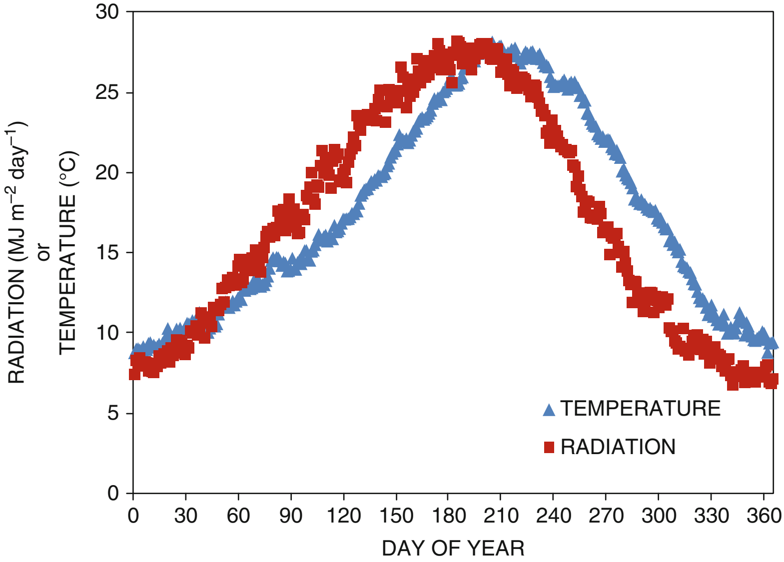


Fig. 5.8 Time course of mean air temperature and solar radiation. Cordoba (Spain). 1964–2002

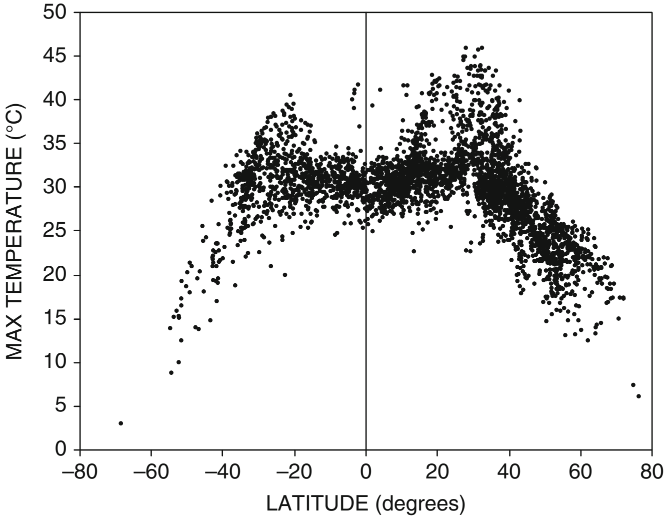


Fig. 5.9 Mean maximum temperature in July (Northern locations) or January (Southern locations) as a function of latitude. Only locations with altitude lower than 1000 m have been included

The maximum temperatures expected in summer are typically between 30 and 45 °C with larger values occurring at mid latitudes (Fig. 5.9). Minimum winter values are around 20 °C for zero latitude and decrease as we move North or South (Fig. 5.10). The variation of mean annual vapor pressure parallels that of minimum temperature in winter (Fig. 5.11).

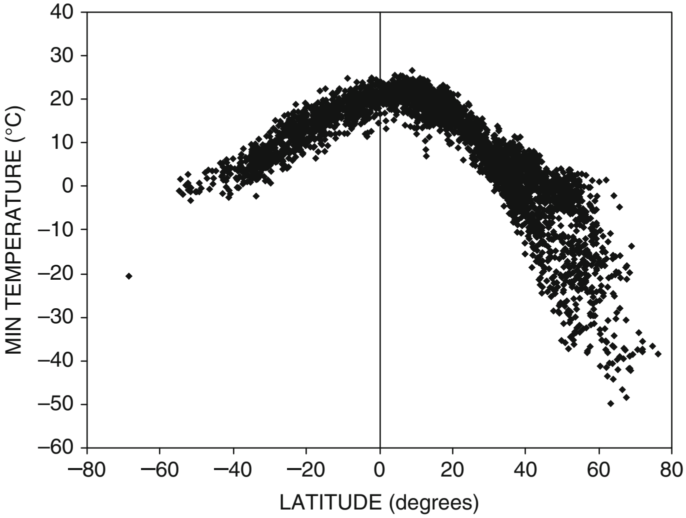


Fig. 5.10 Mean minimum temperature in February (Northern locations) or August (Southern locations) as a function of latitude. Only locations with altitude lower than 1000 m have been included

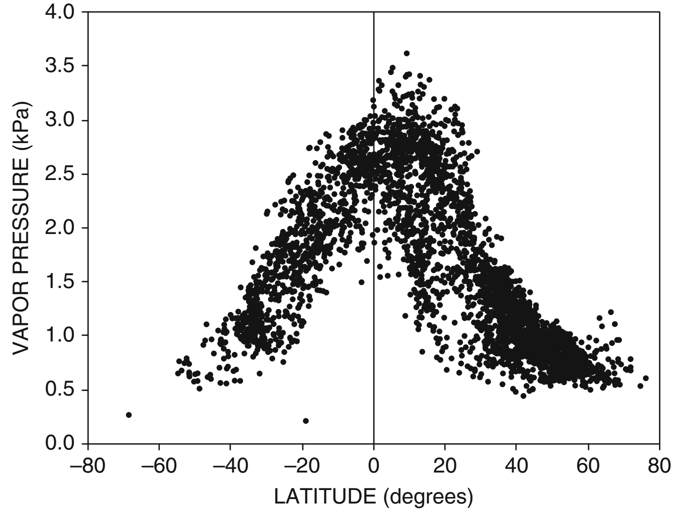


Fig. 5.11 Mean annual vapor pressure for different locations as a function of latitude

5.7 Sensible Heat Flux

One consequence of the temperature gradients that occur over canopies will be a sensible heat flux (convective heat transfer) from the layers of higher temperature to those of lower temperature. Normally, the flux is directed towards the crop at night and from the crop to the atmosphere during the day. The term "sensible" means that this flux has an effect that can be detected as it involves changes in air temperature.

The sensible heat transfer is mainly controlled by turbulence. The sensible heat flux (H) between the canopy and the atmosphere at height z where temperature is T_a, may be calculated as:

$$H = \rho\, C_p\, \frac{T_c - T_a}{r_{aH}} \tag{5.8}$$

where ρ is air density, C_p is specific heat of air at constant pressure, T_c is canopy temperature and r_{aH} is aerodynamic resistance for heat transport (s m^{-1}).

The product ρ C_p (units J K^{-1} m^{-3}) can be calculated as:

$$\rho C_p = \rho_a \left(1.01 + 1.88 \frac{X_v}{1000} \right) = \frac{29 \cdot 10^3 P_{at}}{8.31 T} \left(1.01 + 1.88 \frac{0.622\, e_a}{P_{at} - e_a} \right) \tag{5.9}$$

where ρ_a is the density of dry air (g m^{-3}), X_v is the mixing ratio (g kg^{-1}), e_a is vapor pressure (kPa) and P_{at} (in kPa) is atmospheric pressure which can be calculated as a function of altitude (AL, m) as:

$$P_{at} = 101.3 \left(1 - \frac{AL}{44308} \right)^{5.2568} \tag{5.10}$$

Calculation of r_{aH} is not straightforward as it depends on atmospheric stability. For neutral conditions, the following equation may be applied:

$$r_{aH} = \frac{\ln\left(\frac{z - d_z}{z_0}\right) \ln\left(\frac{z - d_z}{z_{0H}}\right)}{k_k^2\, U(z)} \tag{5.11}$$

where z_{oH} is roughness length for heat exchange which may be estimated as 0.2 z_o.

5.8 Latent Heat Flux

Water vapor flows normally from the surface of the soil or the crop to the air above the crop. This involves a latent heat flux required for the evaporation of water. A downward water vapor flow and therefore a negative latent heat flux can be observed in cases of deposition of dew. Similar to the fluxes of momentum or sensible heat, the latent heat flux (LE) is expressed as:

$$LE = \frac{\rho\, C_p}{\gamma} \frac{e_{sc} - e_a}{r_{aW} + r_c} \tag{5.12}$$

where γ is the psychrometric constant (around 0.067 kPa/K), e_{sc} is saturation vapor pressure at canopy temperature, r_c is canopy resistance and r_{aW} is aerodynamic resistance to water vapor flow, which should be equal to aerodynamic resistance for heat transport (Eq. 5.7). Note than in writing this equation we are considering the gradient of vapor pressure between the inside of the leaves, namely in the substomatal cavities (where air is saturated and at the same temperature as the crop) and the air above. Therefore water vapor transfer will be subjected to two resistances in series, one due to the stomata and the second due to aerodynamic conditions. The canopy resistance is then a parameter reflecting the degree of stomatal closure and is discussed in more detail in Chap. 9. Typical values of r_c are 40–80 s/m for well watered annual crops and 100–200 s/m for forests and some fruit crops (e.g. olives) with good water supply. In water deficit situations, r_c can reach much higher values than those indicated above.

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Chapter 6
Soil Temperature and Soil Heat Flux

Francisco J. Villalobos, Luca Testi, Luciano Mateos, and Elias Fereres

Abstract The soil temperature regime depends on its thermal properties (specific heat, thermal conductivity, thermal diffusivity and thermal admittance). The main factors affecting the thermal regime are water content, soil texture and compaction. The rate of heating (or cooling) of the soil is proportional to its diffusivity which is higher in sandy soils. The amount of energy stored in the soil is proportional to its thermal admittance. Soil heating occurs as a wave train with the amplitude decreasing with depth and a phase shift that also increases with depth.

6.1 Introduction

The heat flux in the soil is an important component of the energy balance of the crop. The soil acts as a large energy accumulator that stores heat during the day and releases it at night. Something similar happens in annual terms. The balance of these exchanges determines the time course of soil temperature. Soil temperature is important in many crop growth and development processes such as seed germination, root growth and distribution in the soil, nutrient uptake, root respiration, microbial activity, etc.

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6.2 Soil Thermal Properties

The specific heat of the soil is the heat required to raise 1 K the temperature of the unit mass (specific heat per unit mass, C_M) or unit volume (specific heat per unit volume, C_V) of soil. C_M and C_V are related through the actual soil density ($C_V = \rho\ C_M$). Using the definitions of bulk density (ρ_b = mass of solids/volume) and gravimetric moisture content (θ_g = mass of water/mass of solids), the relationship between C_V and C_M can also be expressed as:

$$C_V = \rho_b\ \left(1 + \theta_g\right) C_M \tag{6.1}$$

C_V can be computed as the sum of specific heats of the soil components (air, water, solid fraction), weighted by the volumetric mass densities of each of these components:

$$C_V = \frac{M_{solid}}{V} C_{M\ solid} + \frac{M_{water}}{V} C_{M\ water} + \frac{M_{air}}{V} C_{M\ air} \tag{6.2}$$

where M and C_M refer to mass and specific heat per unit mass, respectively, for each component. Neglecting the third term due to the small specific heat of air, assuming that $C_{M\ solid} = 0.85$ J/g/K and reorganizing:

$$\begin{aligned} C_V &= \rho_b \left(C_{M\ solid} + \theta_g\ C_{M\ water}\right) = \rho_b \left(0.85 + 4.18\ \theta_g\right) \\ &= 0.85\ \rho_b + 4.18\ \theta_v \end{aligned} \tag{6.3}$$

This equation shows that soil specific heat per unit volume increases linearly with volumetric water content (θ_v) and with soil bulk density.

6.3 Soil Heat Flux

Applying Fourier's law of heat conduction, the flux of heat in the soil (J) can be expressed as:

$$J = -k \frac{dT}{dz} \tag{6.4}$$

where dT/dz is the gradient of temperature and k the thermal conductivity of the soil. When referring to J at the soil surface ($z = 0$), it is denoted G.

The thermal conductivity has units of W/m/K and depends on the porosity of the soil, on water content and organic matter content. The dependence of k on soil water content is complex. The thermal conductivity of a very dry soil increases twofold when a rather small amount of water is added. This is because relatively large amounts of energy can be transferred by evaporation and condensation of water in the pores of the soil. For example, for a sandy soil, k can increase from 0.53 to 1.1 W/m/K when its water content increases from the permanent wilting point (PWP) to the field capacity. A further increase of the soil water content to saturation implies a smaller gain in k, since the water vapor diffusion is restricted as pores are filled with water (Table 6.1). Therefore, the thermal conductivity of wet soils is affected very little by water content variations in that range.

The change with time of the stored heat in a soil layer of thickness Δz has to be equal to the difference between the heat flow going in, J(z), and the heat flow going out, J(z+Δz) so, using Eq. 6.4 we may write:

$$\rho C_M \, \Delta z \frac{\partial T}{\partial t} = \Delta z \frac{\partial J}{\partial z} = \Delta z \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \tag{6.5}$$

and assuming that *k* does not vary with depth, we obtain:

$$\frac{\partial T}{\partial t} = D \, \frac{\partial^2 T}{\partial z^2} \tag{6.6}$$

where D is thermal diffusivity (m^2/s), defined as k/C_v. According to Eq. 6.6 thermal diffusivity characterizes how fast a soil warms or cools.

By adding water to a very dry soil, *k* initially increases faster than C_V so that *D* also increases with the water content. However, in a wet soil, k increases more slowly than C_V, so that D becomes constant or even may decrease. As shown in Table 6.1 the diffusivity of a sandy soil is higher than that of a clay soil especially when wet. In addition it should be noted that the diffusivity varies little with changes in water content in the clay soil and more in the sandy soil.

6.4 Spatial and Temporal Variations of Soil Temperature

When a soil is exposed to solar radiation, part of it is reflected and the rest absorbed, increasing its temperature during part of the daytime. The temperature will then decrease during the night, when no energy input is present and the heat is transferred to the rest of the soil and/or is irradiated into the atmosphere. Soils are subjected to cycling intensity of input energy at daily or annual frequency.

To analyze the cyclic behavior of soil temperature we will use *T(z,t)* to denote temperature at depth z and time t. Then we will assume that the temperature of the soil surface follows a sine function:

$$T(0,t) = T_m + A(0) \sin(\omega \, t) \tag{6.7}$$

where T_m is the time-averaged temperature of the surface, A(0) is the amplitude of the temperature wave at the surface, $\omega = 2\pi/P_o$ and P_o is the period of the

Table 6.1 Thermal properties of soils and soil components (based on Monteith, 1973). We have assumed bulk densities of 1.5, 1.4 and 1.3 t/m^3 for sandy, loam and clay soil, respectively. For each soil type the table shows the thermal properties at soil water content of wilting point, field capacity and saturation

Component	Density	Specific heat		Thermal	Thermal	Thermal
		Unit mass	Unit volume	Conductivity	Difussivity	Admittance
Components	t/m^3	MJ/t/K	MJ/m^3/K	W/m/K	10^{-6}m^2/s	J/K/m^2/s$^{0.5}$
Air at 20 °C	0.0012	1.01	0.001212	0.025	20.63	5.5
Water	1	4.18	4.18	0.57	0.14	1544
Soil minerals	2.65	0.87	2.31	2.5	1.08	2403
Quartz	2.66	0.8	2.13	8.8	4.14	4327
Clay	2.65	0.9	2.39	2.92	1.22	2639
Granite	2.64	0.82	2.16	3	1.39	2545
Organic matter	1.3	1.92	2.5	0.25	0.1	790
Soils						
Sandy PWP	1.53	0.93	1.43	0.53	0.37	871
Sandy FC	1.59	1.06	1.68	1.1	0.65	1359
Sandy SAT	1.87	1.52	2.85	1.8	0.63	2265
Loam PWP	1.52	1.13	1.72	0.65	0.38	1057
Loam FC	1.67	1.41	2.35	0.8	0.34	1371
Loam SAT	1.84	1.66	3.06	1.1	0.36	1835
Clay PWP	1.57	1.44	2.26	0.7	0.31	1258
Clay FC	1.7	1.65	2.8	0.8	0.29	1497
Clay SAT	1.77	1.8	3.18	0.9	0.28	1692

temperature oscillations (86,400 s for daily cycles and 31,536,000 for annual cycles). With this boundary condition, we can integrate the differential Eq. 6.6 for T:

$$T(z,t) = T_m + A(0)\ e^{-z/M} \sin(\omega t - z/M) \tag{6.8}$$

where $M = (2D/\omega)^{0.5}$ (m) is called the damping depth which determines how much the amplitude of the wave is attenuated with depth and how much the phase is shifted in time.

The above equation indicates that the amplitude of the temperature wave decays exponentially with depth in the soil. Furthermore, the wave is shifted in proportion to depth, i.e. the maximum temperature occurs later as the depth increases. Both deductions are reflected in Fig. 6.1 that represents the daily time course of the measured soil temperature at various depths. The annual trend shows a similar pattern (Fig. 6.2).

The depth at which most of the heat exchange occurs in the soil is called effective depth and is equal to √2 M. The heat flux density at the soil surface may be deduced by differentiating Eq. 6.8, applying Eq. 6.4 and setting z = 0, which leads to:

$$G = \sqrt{2}\, A(0) \frac{k}{M}\ \sin(\omega t + \pi/4) \tag{6.9}$$

This equation indicates that the temperature wave on the surface (Eq. 6.7) and the heat flow are offset by π/4, i.e. the maximum temperature occurs 3 h after the

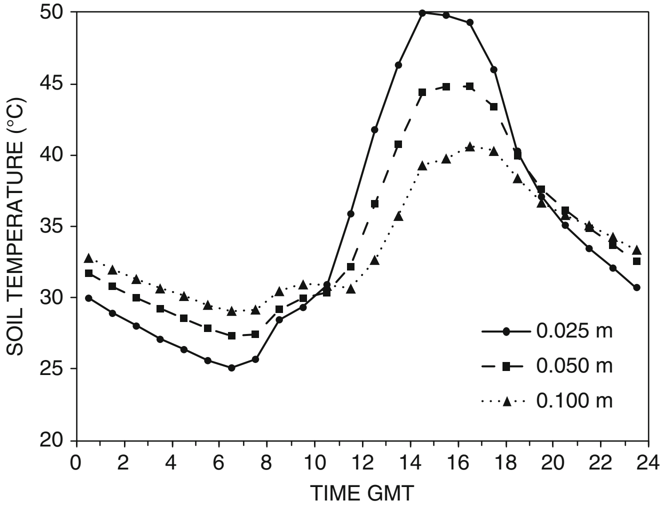

Fig. 6.1 Daily time course of soil temperature at various depths (0.025, 0.050 and 0.10 m) in an olive orchard. Cordoba (Spain). July 19, 2004

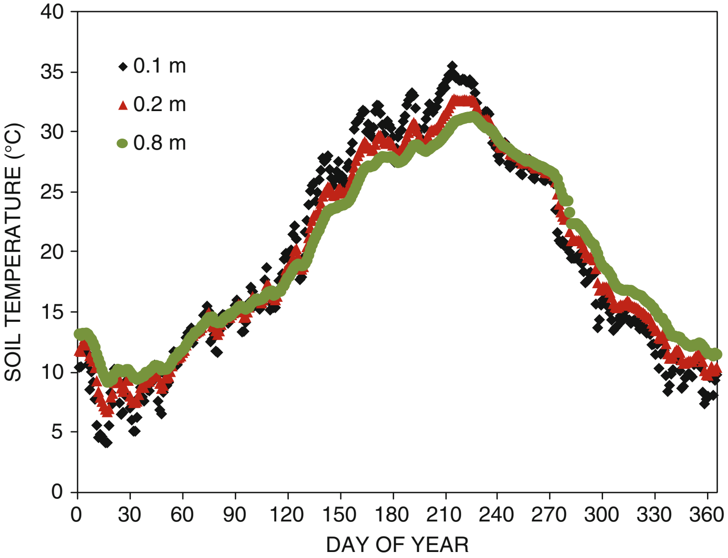

Fig. 6.2 Annual time course of soil temperature at various depths (0.10, 0.20 and 0.80 m) in an olive orchard. Cordoba (Spain). 2003

maximum G (daily cycle) or 46 days (annual cycle). If the maximum of G occurs at the time of maximum radiation, (1200 h, solar time) then the surface temperature should reach its maximum at 1500 h (solar time) for daily cycles. For annual cycles the maximum temperature should occur on day 216 (August 5) in the Northern Hemisphere and on day 36 (February 5) in the Southern Hemisphere.

Soil heat flux at the surface may be integrated over a half-cycle to determine the total heat input into the soil:

$$\int G = \sqrt{2}\, M\, A(0)\, C_v = \sqrt{\frac{2P_0}{\pi}}\sqrt{k\, C_v}\, A(0) \tag{6.10}$$

This total flux that enters the soil in one half-cycle will be equal to that going out in the other half-cycle since we start from a sinusoidal model of temperature, i.e. the temperature at the end of the period is equal to the initial temperature. According to Eq. 6.10 the amount of heat stored in the soil (and released by the soil) will be proportional to $(k\, C_V)^{0.5}$, which is called the thermal admittance and has the units of J K^{-1} m^{-2} $s^{-0.5}$. For sandy soils thermal admittance increases dramatically with water content from values of less than 1000 at PWP to more than 2000 J K^{-1} m^{-2} $s^{-0.5}$ at saturation (Table 6.1). In clay soils admittance changes little with water content.

The amplitude of the temperature wave decreases with soil texture in the order sandy-loam-clay. This order is due to differences in thermal admittance. In Mediterranean climate conditions, in late winter, soils are often wet. The sandy soils have a higher diffusivity than the clay soils, so they will warm up more rapidly in

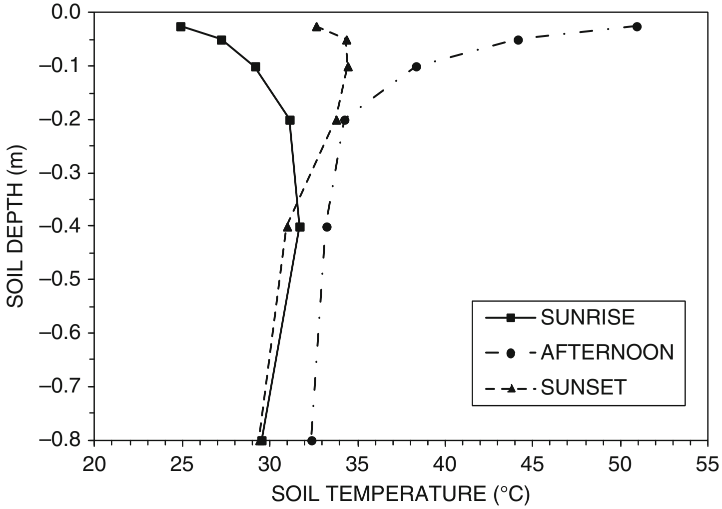

Fig. 6.3 Profiles of soil temperature in an exposed area of an olive orchard. Cordoba (Spain) 3 August 2002

spring. If the water content is high in autumn, sandy soils will also cool faster, which has agronomic implications in the decision about planting date. Conversely if the soil is very dry the diffusivity of sandy and clay soils is similar, so we should not expect significant differences in their thermal regime.

The temperature profile in the soil changes significantly over the day (Fig. 6.3). In the early morning, the soil surface is the coldest zone and in the afternoon it becomes the hottest. The profile along most of the day indicates downward heat flux while at night the flow is towards the surface.

6.5 Effects of Evaporation and Wind on Soil Temperature

The prediction of soil temperature at a given time and depth is important at the time of making some agronomic decisions. The practical importance of understanding the soil heat flux will become more evident when we address the energy balance at the earth surface in Chap. 7.

For a dry soil surface with no evaporation the ratio of soil heating and atmospheric heating may be written as:

$$\frac{G}{H} = \frac{\sqrt{k\,C_v}}{\mu_{atm}} \tag{6.11}$$

where μ_{atm} is the atmospheric admittance which increases with wind speed and may go from 2000 for a calm atmosphere to 10,000 J K^{-1} m^{-2} $s^{-0.5}$ for windy conditions. This implies that a very dry soil will show ratios of G/H between 0.5 and 0.1 as wind speed increases.

The thermal regime in a soil may be evaluated using Eq. 6.8 which requires knowledge of the amplitude at the soil surface. Using Eq. 6.10 we may write:

$$A(0) = \sqrt{\frac{\pi}{2\,P_0}\frac{\int G\,dt}{\sqrt{k\,C_v}}} \tag{6.12}$$

The integral of G during the daytime depends on wind speed (Eq. 6.11) and on the amount of energy spent in soil evaporation. For a wet soil, evaporation may take a large fraction of net radiation (say 70–80 %) while for a very dry soil evaporation may be negligible. Table 6.2 shows an example of calculated values of surface temperature amplitude for wet or dry clay and sandy soils in clear winter and summer days in Cordoba (Spain). The amplitude is large when the soil is dry and for calm conditions. The sandy soil presents always a larger oscillation than the clay soil due to the smaller admittance. Equation 6.12 may be used to calculate the expected minimum and maximum soil temperatures.

Table 6.2 Calculated temperature amplitude at the soil surface for winter and summer days in sandy and clay soils

Conditions		Soil surface	Soil type	G integral	Admittance	T amplitude
				MJ/m^2	J/K/m^2/s$^{0.5}$	K
Winter	Calm	Dry	Sandy	2	870	9.8
	Windy	Dry	Sandy	0.55	870	2.7
	Calm	Wet	Sandy	0.4	1300	1.3
	Windy	Wet	Sandy	0.1	1300	0.3
Winter	Calm	Dry	Clay	2	1200	7.1
	Windy	Dry	Clay	0.55	1200	2.0
	Calm	Wet	Clay	0.4	1500	1.1
	Windy	Wet	Clay	0.1	1500	0.3
Summer	Calm	Dry	Sandy	4.7	870	23.0
	Windy	Dry	Sandy	1.3	870	6.4
	Calm	Wet	Sandy	0.9	1300	3.0
	Windy	Wet	Sandy	0.3	1300	1.0
Summer	Calm	Dry	Clay	4.7	1200	16.7
	Windy	Dry	Clay	1.3	1200	4.6
	Calm	Wet	Clay	0.9	1500	2.6
	Windy	Wet	Clay	0.3	1500	0.9

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Chapter 7
The Energy Balance

Francisco J. Villalobos, Luca Testi, Luciano Mateos, and Elias Fereres

Abstract The main components of the energy balance are net radiation, latent heat flux (LE), sensible heat flux (H) and soil heat flux (G). These can be manipulated through changes in net radiation, LE, H or G. The relative importance of the components depends mainly on the availability of water for evaporation. The extreme cases will be the humid environment (LE approaches R_n) and the desert environment (R_n is partitioned between H and G). The energy balance of farming (energy produced per unit energy consumed in all farming operations) may be also analyzed in terms of inputs and outputs which can be estimated by assessing the energy embodied in the amount of materials employed (fertilizers, water, seeds) and in the operations performed.

7.1 Introduction

The exchange of matter and energy between the crop and the atmosphere determines the variations of air temperature and humidity and the soil temperature as seen in the previous chapters. Turbulence facilitates the flux of heat, water vapor and carbon dioxide which are all key factors in crop production. It also affects the transport of contaminants, pesticides, spores or pollen. Understanding the partitioning of available energy among the different processes is required for manipulating the aerial or the soil environment of the crop, which not only affect the plant community but the whole ecosystem (weeds, insects, pathogens, and other soil microorganisms).

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7.2 The Energy Balance Equation

According to the principle of conservation of energy, the equation of the energy balance of a crop may be written as:

$$R_n = H + LE + G + P + S \tag{7.1}$$

where all terms have been defined in previous chapters expect for P, that represents the flux of energy consumed in photosynthesis, and S, which is the flux of heat stored in the crop biomass and the surrounding air. As will be seen later, P is negligible compared to the others. S may be significant only in very tall plant communities (e.g. forests) but can be neglected in the case of crops (Box 7.1). Note that in Eq. 7.1 fluxes are considered positive when they involve a loss of energy from the crop, i.e. when moving away from the canopy.

Changes in net radiation may be accomplished by variations in the short wave or long wave radiation balances. The former may be due to changing the incoming flux using shades or due to changes in the soil slope and aspect and also by manipulating the albedo of the soil (mulches) or the plants (e.g. whitewash or kaolinite). The long wave radiation balance is usually manipulated by blocking losses with glass or plastic covers or non solid barriers (e.g. smoke).

Soil heat flux may be changed by artificial soil heating or altering the thermal admittance by applying irrigation or compacting the soil.

LE is mainly determined by water availability, so rainfall or irrigation management will affect greatly LE fluxes. If the soil is wet, important reductions in LE may be achieved using plastic impermeable mulches (Box 7.2).

The only alternative for manipulating sensible heat flux in the field is using barriers (windbreaks) to reduce wind speed. In controlled environments (greenhouses) we may add or remove heat or increase turbulence with fans.

Box 7.1 Calculation of Energy Spent in Heating the Canopy

The maximum standing biomass of annual crops usually does not exceed 20 t/ha (dry matter).

Assuming water content of 70 g water/100 g fresh mass (e.g. maize for silage) we may calculate the energy term S for an increase in canopy temperature of 20 K in 9 h. This would be indicative of typical conditions of summer in mid latitudes.

The water mass can be calculated based on dry biomass (B) as:

$$\text{mass water} = 20\ \frac{\text{t dm}}{\text{ha}} \times \frac{0.7\ \frac{\text{t water}}{\text{t fresh}}}{(1-0.7)\frac{\text{t dm}}{\text{t fresh}}} = 46.67\ \frac{\text{t water}}{\text{ha}} = 4667\ \frac{\text{g water}}{\text{m}^2}$$

The specific heat of water (C_{Mw}) and organic matter (C_{Mo}) are 4.18 and 1.92 J/g/K, respectively.

(continued)

Box 7.1 (continued)

The amount of heat stored for a temperature rise of 20 K is:

$$\Delta Q = \Delta T(B \cdot C_{Mo} + m_w \cdot C_{Mw}) = 20(2000 \cdot 1.92 + 4667 \cdot 4.18)$$
$$= 466961 \ \text{J m}^{-2} = 0.47 \ \text{MJ m}^{-2}$$

The average heat flux for 9 h will be obtained by dividing 0.47 10^6 J m^{-2} by the duration (9 × 3600 s) which yields 14.4 W m^{-2}, which is very small (about 2 %) as compared to typical values of solar irradiance under those conditions (600–800 W m^{-2}).

Box 7.2 Analyzing the Effect of a Black Plastic on the Energy Balance of Bare Soil

The plastic sheet creates a barrier that suppresses evaporation (LE = 0) so all the energy is spent in G and H. A small variation in R_n may be expected as the albedo is reduced and long wave loss may increase when the plastic gets hot.

The partitioning between H and G will depend on the contact between the plastic sheet and the soil as any air layer between them will reduce flux into the soil. On the other hand, aerodynamic resistance is reduced as the temperature profile over the hot plastic is very unstable. Therefore, sensible heat flux is enhanced.

In summary, covering the soil with black plastic suppresses LE and reduces the G/H ratio, which promotes a higher temperature of the aerial environment.

7.3 Relative Importance of the Components of the Energy Balance

As water availability is the main factor determining LE, two extreme conditions can be distinguished:

(a) Humid/well watered areas where water availability does not limit evaporation. Most of the net radiation is used in LE. It is the case of large water bodies (seas, lakes), wetlands, large irrigation schemes with abundant water or any area after widespread rainfall.
(b) Dry/arid environments where no water is available: LE is negligible and therefore net radiation is partitioned only into heating the air and the soil.

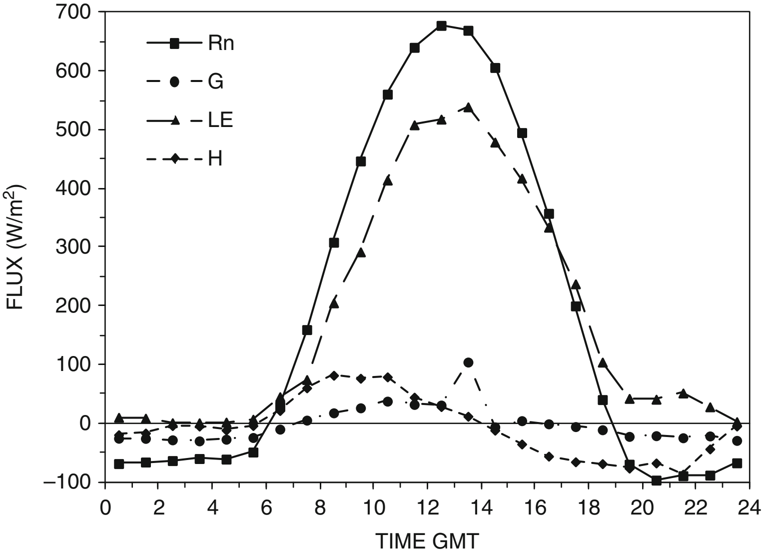

Fig. 7.1 Energy balance components over an irrigated cotton crop. Cordoba (Spain). June 27, 2003. For the 24-h period the total fluxes were $R_n = 15.9$, $G = -0.2$, $LE = 15.7$ and $H = -0.6$ MJ m^{-2} day^{-1}

A special case is that of the oasis, a small well watered area surrounded by arid lands. Here horizontal transport of sensible heat from the arid surrounding area enhances LE in the oasis, so it may exceed R_n. This process of horizontal transport of energy from dry to wet areas is called advection.

The energy balance of crops is usually between the two extremes (wet-desert) depending on the availability of water and the presence of vegetation (this issue will be further explored in Chap. 9). Four different situations are analyzed below.

Figure 7.1 represents the daily time course of R_n, LE, H and G on an irrigated cotton field measured on June 2003 in Cordoba (Spain). This would be a typical well watered environment. The R_n presents typical values of clear days at this time of the year in Cordoba. Most of the energy is spent in LE which is less than R_n during the morning and higher during the afternoon (advection). The sensible heat flux is small and reaches its maximum during the morning. From 14:00 the H flux is reversed, being then directed towards the surface. The soil is heated for most of the daytime, although G is very small as the crop covers the soil almost completely. The balance for 24 h indicates that net radiation was invested mostly in evaporation. In this case the heating of the air and the soil in the daytime period is offset by their cooling during the night.

A case of water stressed crops is represented in Fig. 7.2 for a wheat crop in spring (around flowering) after a very dry winter in Cordoba (Spain). The soil was very dry and consequently, crop transpiration was very low. As a result, latent heat flux is very small during most of the day while H and G use most of the energy during the

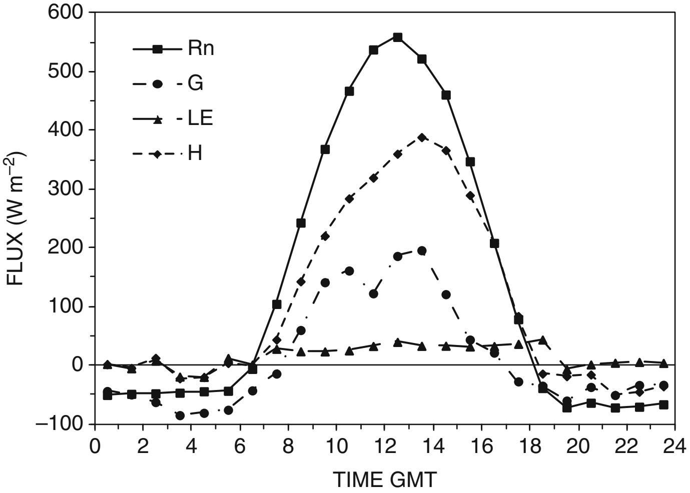

Fig. 7.2 Energy balance components on a severely stressed wheat crop. Cordoba (Spain). April 19, 1999. For the 24-h period the total fluxes were $R_n = 11.6$, $G = 1.2$, $LE = 1.4$ and $H = 9$ MJ m^{-2} day^{-1}

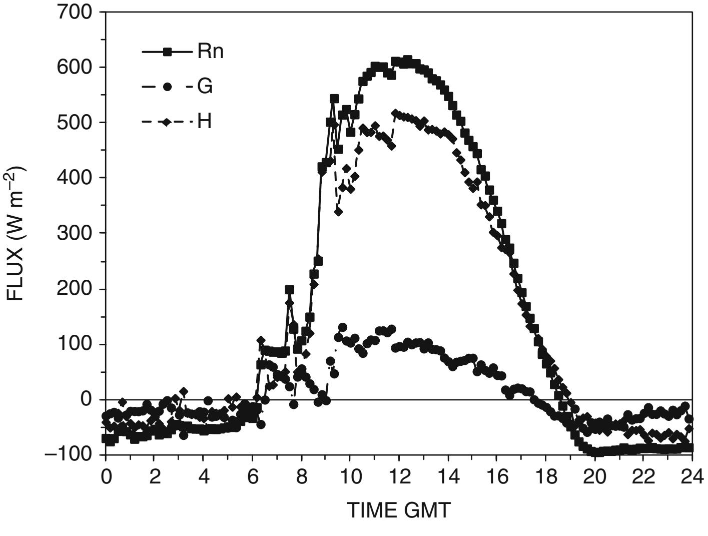

Fig. 7.3 Energy balance components on wheat stubble. Cordoba (Spain). June 17, 1995. For the 24-h period the total fluxes were $R_n = 13.7$, $G = 1.3$ and $H = 12.4$ MJ m^{-2} day^{-1}

daytime. For the period of 24 h, the percentages of energy invested in LE, H and G are 12 %, 78 % and 10 %, respectively.

Contrasting with the well watered crop is the case of wheat stubble shown in Fig. 7.3. Around the measurement date (June 17), extraterrestrial solar radiation

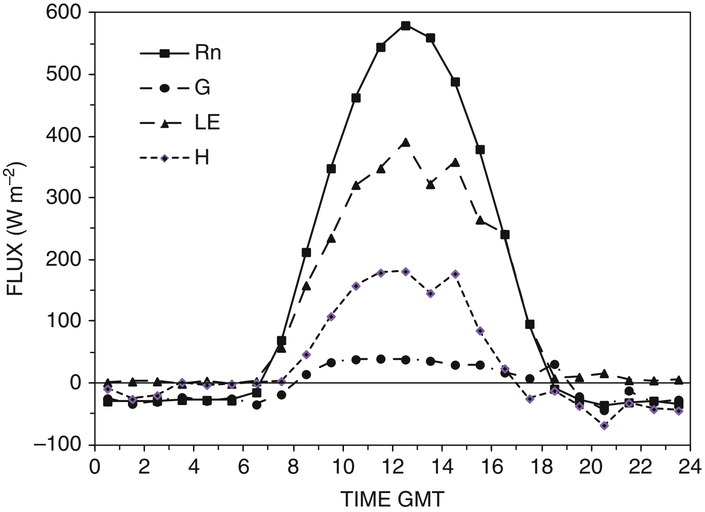

Fig. 7.4 Energy balance components in an olive grove. Agricultural Research Center of Cordoba (Spain). September 8, 1997. For the 24-h period the total fluxes were $R_n = 13.1$, $G = -0.1$, $LE = 10.3$ and $H = 2.9$ MJm^{-2} day^{-1}

peaks in the northern hemisphere. However, the maximum R_n is slightly lower than in the case of Fig. 7.1, which is explained by the high albedo of stubble and straw covering the soil. The availability of water in this case is zero (the crop had extracted all soil water) which explains the absence of LE. The sensible heat flux parallels R_n throughout the day, peaking at around noon. The soil heat flux is now larger than for cotton and decreases during the afternoon. Considering the 24-h period 90 % of the energy is spent in heating the air and 10 % in heating the soil. Note that the straw and stubble covering the soil serve as a thermal insulation.

Finally, Fig. 7.4 presents an intermediate case between the wet and dry cases. It is a drip irrigated olive orchard at Cordoba where the trees cover only a fraction of the ground. At the time of the measurements the tree canopy represented 40 % ground cover and the soil surface was dry. In the daytime the three fluxes (LE, H and G) are important but LE predominates (Fig. 7.4). The H flux peaks at noon and is small at night. G presents a pattern similar to the above cases: the maximum occurs at noon, because at that time the percentage of soil exposed to direct radiation is maximum. For the period of 24 h the percentages of energy invested in LE and H are 79 % and 21 %, respectively, while G gets no share.

We have seen that the relative importance of the components of the energy balance varies throughout the day and that when summed for 24-h periods, G is usually small compared to H and LE, whose relative magnitudes depend on the availability of water (or presence of vegetation) on the soil surface. The impact of the fluxes on the oscillations of air and soil temperature depends on the absolute value of H and G. The difference between the maximum and the minimum temperature will be greater when positive fluxes are higher and negative fluxes are smaller.

Table 7.1 Annual energy (MJ/m^2) available at different levels and losses (partitioning of energy) at each stage for an irrigated olive orchard with 40 % ground cover in Cordoba (Spain)

	Available energy	Losses	
	MJ/m^2	MJ/m^2	
		Reflection	Emission
Solar radiation	5975	1100	2065
		LE	H
Net radiation	2810	1570	1124
		Respiration	
Energy photosynthesis	40	20	
		Vegetative	
Energy fixed	20	8	
		Residues	
Energy harvested	12	5	
Energy in olive oil	7		

The partitioning of energy for annual periods is also governed by the availability of water. Table 7.1 shows the values of energy available at different levels and the losses (partitioning of energy) at each stage for an irrigated olive orchard with 40 % ground cover in Cordoba (Spain). Starting from an incoming solar radiation of around 6000 MJ m^{-2}, the energy produced by the crop as oil is equivalent to 7 MJ m^{-2} as oil (2000 kg oil ha^{-1}). About 50 % of incoming radiation is lost by reflection and emission of long wave radiation. Then net radiation is allocated to evaporation (56 %), heating of the atmosphere (40 %) and photosynthesis (only 4 %). Note that the soil heating component is zero for annual periods as long as the mean soil temperature does not change in the long run. Around 50 % of energy converted by photosynthesis is lost as respiration, leaving another 50 % fixed in tree biomass (shoots, roots and fruits). Only 60 % of fixed energy is harvested. After extraction of the oil, the energy captured is just 7 MJ m^{-2}. This low apparent efficiency does not take into account other energy inputs required for the production of olives (machinery, fertilizers, pumping of irrigation water). In the same environment, an intensive, irrigated wheat-maize rotation in about the same period (as a double crop, maize planted after wheat is harvested) could yield up to 19,000 kg $ha^{-1}$of grain total, which would be equivalent to about 26 MJ m^{-2}, still a very small fraction of the incoming solar radiation of 6000 MJ m^{-2}.

7.4 Energy Requirements in Farming

The energy balance of a field may be also analyzed in terms of the energy requirements associated to the different agricultural practices and the final energy stored in crop products. Energy requirements may be direct (fuel used, energy spent in pumping water) or indirect (energy spent in production of inputs, machinery or

Table 7.2 Classification of types of energy requirements for agricultural operations

Operation	Direct		Indirect	
	Fixed	Variable	Fixed	Variable
Sowing	Fuel		Machine, tractor	Seed, pesticide, fertilizer
Tillage	Fuel		Tools, tractor	
Irrigation		Fuel or electric energy for pumping	Irrigation system	Desalination, transport
Pesticide application	Fuel		Machine, tractor	Pesticide
Harvest	Fuel		Machine	
Processing		Fuel or electric energy	Machine	

equipment). Each category may be also divided in a variable component (being proportional to input rate) and a fixed component (not dependent on input rate). Therefore:

$$E_{req} = E_{dir\ fix} + E_{dir\ var} + E_{ind\ fix} + E_{ind\ var} \tag{7.2}$$

Table 7.2 summarizes the types of energy inputs associated to different farm operations. For instance, the application of a pesticide requires a fixed direct input of energy to run the tractor, a fixed indirect input associated to tractor and machine manufacturing and maintenance and a variable indirect input, that of manufacturing the pesticide, that depends on the dose applied.

Table 7.3 shows some energy coefficients which are useful for calculating the energy requirements of the farm. In Table 7.4 representative values are given for different operations including both direct and indirect energy requirements. The actual values for specific operations will be discussed in more detail in Chap. 17.

The energy requirement (MJ ha^{-1} year^{-1}) for irrigation may be calculated as:

$$E_{irrig} = \rho_{water}\ g\ 10^{-6} \frac{I}{\mu_p \mu_m} (H_{lift} + 1.2\ H_{op}) + E_{ind\ fix} + E_{ind\ var} \tag{7.3}$$

where:

ρ_{water}: density of water (10^3 kg m^{-3})
g: acceleration of gravity (9.81 m s^{-2})
10^{-6} is used to convert from J to MJ
I: seasonal applied irrigation (m^3 ha^{-1})
μ_p: pump efficiency (typically between 0.6 and 0.8)
μ_m: motor efficiency, which we may assume 0.4 for diesel and 0.9 for electric engines
H_{lift}: the energy required to lift water from the water source (m). It is roughly equal to water table depth for ground water and negligible for surface water sources.

Table 7.3 Energy coefficients for different inputs used in crop production

Input	Observations	Energy coefficient	Units
Human labor	Embodied energy	100–1000	MJ/day/person
Gasoline	Energy content	38	MJ/L
Diesel	Energy content	39	MJ/L
Ethanol	Energy content	22	MJ/L
Coal	Energy content	17–30	MJ/kg
Wood	Energy content	18–23	MJ/kg
Tractors	Manufacture and transport	87	MJ/kg
Implements	Manufacture and transport	70	MJ/kg
Pesticides	Manufacture and transport	358	MJ/kg
N fertilizer	Manufacture and transport	77	MJ/kg N
P fertilizer	Manufacture and transport	37	MJ/kg P
K fertilizer	Manufacture and transport	17	MJ/kg K
Anhydrous ammonia	Manufacture and transport	60	MJ/kg N
Ammonium nitrate	Manufacture and transport	85	MJ/kg N
Urea (solid)	Manufacture and transport	80	MJ/kg N
Drying grain		6.4–10	MJ/kg water
Transport	By truck	6.3	MJ/t/km
Water	Desalinization sea water	9.0–13.0	MJ/m3
Water	Desalinization brackish water	3.6–10	MJ/m3
Primary tillage	Total	1200	MJ/ha
Secondary tillage	Total	300	MJ/ha
Spray pesticide	Total (excluding pesticide)	90	MJ/ha
Spread fertilizer	Total (excluding fertilizer)	90	MJ/ha
Sowing	Total (excluding seeds)	340	MJ/ha
Harvest cereals and legumes	Total	1200	MJ/ha
Harvest tubers and roots	Total	2200	MJ/ha

Table 7.4 Energy requirements of different agricultural operations

	Total energy (excluding labor)
	MJ/ha
Primary tillage	1200
Secondary tillage	300
Spray pesticide	90
Spread fertilizer	90
Sowing	340
Harvest cereals and legumes	1200
Harvest tubers and roots	2200

These values include both direct and indirect energy requirements and are only indicative of the order of magnitude

H_{op}: operating pressure of the irrigation method (m). We may use typical values of 10–25 m for drip and 30–40 m for sprinklers. The coefficient 1.2 is based on the assumption that 20 % additional energy is required to keep enough pressure in the whole network.

$E_{ind\ fix}$: Energy spent in the manufacturing and installation of the irrigation system divided by its life span. We may use values of 7000–9000 MJ ha^{-1} $year^{-1}$ for sprinkler and 13,000 MJ ha^{-1} $year^{-1}$ for drip irrigation. For surface irrigation we should add here the energy required for land levelling and for shaping the ridges.

$E_{ind\ var}$: Energy spent in desalination (if needed) and in delivering the water to the farm, which is proportional to the amount of irrigation applied:

$$E_{ind\ var} = c_w\, I \tag{7.4}$$

where c_w is the energy spent per volume unit of water. Therefore, we can calculate the energy requirement for irrigation as the sum of two terms, one variable and one fixed:

$$E_{irrig} = \left(\frac{H_{lift} + 1.2\, H_{op}}{102\mu_p\, \mu_m} + c_w\right) I + E_{ind\, fix} \tag{7.5}$$

The energy requirement of fertilizer application (MJ ha^{-1} $year^{-1}$) is calculated as:

$$E_{fert} = n_f A + N_a c_N + P_a c_P + K_a c_K + E_{ind} \tag{7.6}$$

where

n_f: is the number of applications of fertilizer
A: is the energy consumption as fuel in each application (MJ ha^{-1})
N_a, P_a, K_a: amounts of N, P and K (kg ha^{-1} $year^{-1}$) applied
c_N, c_P, c_K: energy required for producing and transporting the fertilizers (MJ/kg N, MJ/kg P, MJ/kg K)
E_{ind}: Energy spent in the manufacturing, repair and maintenance of the fertilizer spreader or injector divided by its life span.

The energy spent in human labor is not easy to calculate. An average human being needs between 10 and 15 MJ day^{-1} of energy as food, but we need to add the energy required for humans to live which depends strongly on the standards of living so we may finally arrive to a wide range of values of the so-called embodied energy (100–1000 MJ $day^{-1}person^{-1}$). For calculation purposes, we may take the minimum value when almost all the operations are performed with human labor and the maximum when machines are used for all operations.

Example 7.1 The average needs of human labor for manual harvesting of wheat (yield of 6 t/ha) is around 1000 h/ha, while using just machinery it is reduced to 2 h/ha. Assuming working days of 8 h, the energy requirements of manual harvest are 12,500 MJ/ha. If we use a combine, the energy requirements would be the sum of a human component (2 h/8 h/day × 1000 MJ day^{-1} person^{-1}) and a machine component (1200 MJ/ha, Table 7.3), which gives 1450 MJ/ha. Not surprisingly, the energy requirement of manual harvesting is much higher as humans are not as efficient as machines for performing physical work.

7.5 Farm Energy Outputs and Efficiency

The energy outputs of a farm may be computed according to different criteria. We usually consider only the energy contained in all materials exported from the farm, so the energy content of crop residues is ignored (unless they are sold for feed outside the farm) and so is the energy stored in soil organic matter. On the other hand, the energy content of a given material varies according to the use of the energy. We use values of gross energy which are close to the combustion energy of the material. Table 7.5 shows typical values of gross energy in crop products and crop residues. Apart from the composition of dry matter,an important factor in evaluating the energy content of biomass is its water content. The Heating Value (HV, MJ/kg fresh biomass) is calculated as:

$$HV = (1 - w)HCB - 2.45\, w \tag{7.7}$$

where w is the water content of biomass (g water/g fresh biomass).

Table 7.5 Energy content in agricultural products and residues

		Energy content (HCB,MJ/kg DM)	
Crop	Use	Harvested product	Residues
Cereals	Grain	18–19	15.5–18.5
	Forage	18–19	
Legumes	Seed	19–20	18–19
	Forage	18–19	
Soybean	Seed	23.6	19
Cotton	Fiber+seed	23.8	19
Oil crops	Seed	26–29	18.3–18.8
Sugar beet	Root without crown	17	16.7
Tuber and root crops	Tubers, roots	17	18–20

Crop species have been grouped whenever possible: Grain cereals (wheat, barley, rye, maize, millets, sorghum, rice, triticale), forage cereals (maize, sorghum), seed legumes (bean, cowpea, faba bean, lentil, pea, peanut, chickpea), forage legumes (clover, alfalfa), oil crops (safflower, rapeseed, sunflower, flax), tuber and root crops (potato, cassava, yam, sweet potato). The total energy output will be the product of yield and the energy content of the harvested product

Example 7.2 Rainfed wheat is grown as monoculture in a farm producing (dry matter) 2500 kg grain/ha and 3750 kg straw/ha. The total energy requirements are 14,779 MJ/ha (3400 for operations, 9613 for fertilizer, 1050 for seed and 716 for pesticides). If both grain and straw are exported the output is 110,000 MJ/ha and the ratio output/input is 7.4. If only the grain is exported the output/input ratio is 3.1. In both cases, the energy balance of farming is positive (more energy produced than consumed).

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Chapter 8
The Water Budget

Francisco J. Villalobos, Luciano Mateos, Francisco Orgaz, and Elias Fereres

Abstract The components of the water balance (infiltration, deep percolation, evaporation from the soil surface, etc.) determine the amount of water available to the crop. Water flow in the soil occurs following the gradient of water potential and can be analyzed by the Richards equation, but there are simpler alternative methodologies to quantify the water balance components. Deep percolation can be estimated based on soil properties and water content above Field Capacity, depending also on soil evaporation and transpiration. Runoff is calculated based on the Curve Number and the amount of precipitation. For monthly values, effective rainfall can be calculated by the methods of FAO and SCS.

8.1 Introduction

The functioning of terrestrial ecosystems depends largely on the inputs and outputs of water, which determine the quantity and quality of water available for life on earth. The availability of water is considered the main limiting factor of the productivity of agricultural systems. Of all uses of water diverted by man, agriculture is the main consumer of water, on the average consuming two thirds of total globally, and in most countries of the arid regions irrigation consumes more than 80 % of the developed water. Therefore, it is essential to understand and quantify the dynamics of the flows in and out of the agricultural system, that is, to calculate the water balance components that determine the availability of water for crops and, where appropriate, to quantify irrigation needs.

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As described in Chap. 2, soils are comprised of solids, liquid, and gas, with typical fractions of 45–50 % of mineral material, 0–5 % of organic matter, and 50 % of pore space which allows the flow of water and gases. The porosity (volume fraction of pore space) is determined by the arrangement of the soil particles, being low when soil particles are very close together (e.g. compacted soil) and higher when soils have high organic matter. Typical values of porosity are in the range 0.35–0.50 in sandy soils and 0.40–0.60 in medium to fine-textured soils. Porosity usually decreases with soil depth because the subsoil tends to be more compacted than the topsoil. Soil bulk density (ρ_b) is a measure of the mass of soil per unit volume (solids + pore space) and is usually reported on an oven-dry basis (Chap. 2).

8.2 The Status of Water in the Soil: Water Content and Water Potential

The water content of the soil can be expressed in terms of volume (θ_v = volume of water/volume of soil) or mass (gravimetric, θ_g = mass of water/mass of dry soil). Both measurements are related through the soil bulk density so that $\theta = \rho_b\, \theta_g$. The amount of water (expressed in mm) in a soil depth Z (mm), i.e. the total soil water for that depth (TSW, mm) will be:

$$TSW = (1 - F_{VC})Z \cdot \theta \tag{8.1}$$

where F_{VC} is the volume fraction of coarse fragments (soil particles exceeding 2 mm in diameter) which can be estimated as a function of the mass fraction of coarse fragments (F_{MC}) as:

$$F_{VC} = \frac{F_{MC}\,\rho_b}{2.65 - F_{MC}\,(2.65 - \rho_b)} \tag{8.2}$$

where ρ_b has units of t m^{-3} and is calculated excluding coarse fragments. Note that 2.65 t m^{-3} is the average density of coarse soil fragments.

Example 8.1 A soil of 1 m depth has 30 % of coarse fragments (mass basis) and bulk density 1.4 t m^{-3}. If the water content is 0.2 m^3 m^{-3}.

$$F_{VC} = \frac{F_{MC}\rho_b}{2.65 - F_{MC}(2.65 - \rho_b)} = \frac{0.3 \cdot 1.4}{2.65 - 0.3\,(2.65 - 1.4)}$$
$$= 0.18\ \text{m}^3\ \text{m}^{-3}$$

$$TSW = (1 - F_{VC})Z \cdot \theta = (1 - 0.18)1000 \cdot 0.20 = 164\ \text{mm}$$

Water is held in the matrix of soil particles by adsorption and moves by capillarity in the pores. Water is always moving albeit very slowly when the soil is dry and thus it can be considered retained by the soil for many practical purposes. There are three water content values that characterize the soil water retention capacity:

- Permanent wilting point (PWP, also called Lower limit) (θ_{PWP}): the soil water content below which plant roots are unable to extract water.
- Field capacity (FC, also called drained upper Limit) (θ_{FC}): It is the value at which soil water content will stabilize after drainage (drainage continues but at a rate that may be considered negligible).
- Saturation (θ_{SAT}): This is the maximum soil water content that can be observed in the soil and is on average 85 % of the porosity (η). As the average density of the soil solid fraction is 2.65 t m^{-3}, we can calculate the porosity as a function of bulk density as $\eta = 1 - \rho_b/2.65$.

The state of water in the soil can be characterized as a function of its potential (Ψ), which is the potential energy per unit mass or volume and has units of pressure (1 J/kg = 1 kPa ≈ 0.1 m water column). The soil water potential is the sum of four components:

- Pressure potential (Ψ_p) which is the pressure exerted by a column of water above the point considered. In an unsaturated soil $\Psi_p = 0$.
- Gravitational potential (Ψ_g) is the potential energy of water due to its position in a gravitational field. It is calculated as g h where g is the gravitational constant (9.81 m/s^2) and h is the height above the arbitrary reference plane.
- Matric potential (Ψ_m) is caused by the attraction of the soil matrix and the water molecules. The relationship between matric potential and soil water content, $\Psi_m = f(\theta_v)$, is called the soil-water characteristic curve (Fig. 8.1). The matric potential is zero in saturated soil and becomes more negative as the soil dries.

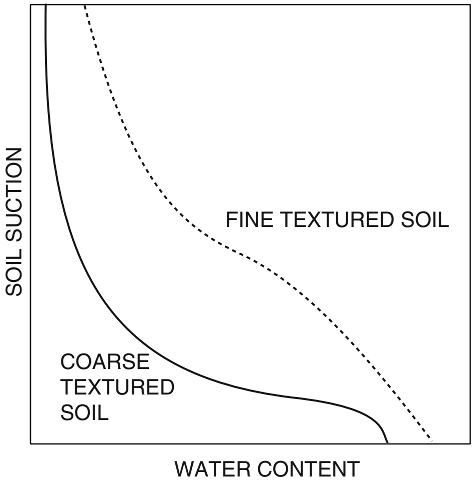


Fig. 8.1 Soil-water characteristic curves for a fine and a coarse texture soil

Campbell has proposed the following equation for computing the soil-water characteristic curve:

$$\Psi_m = \Psi_e \left(\frac{\theta_v}{\theta_{SAT}}\right)^{-b} \tag{8.3}$$

where Ψ_e is called the air entry water potential, b is an empirical parameter and θ_{SAT} is the saturation water content. The values of Ψ_e and b for different soil textures are presented in Table 8.1.

- Osmotic potential (Ψ_o) is due to the presence of salts in the soil solution. This potential is zero for pure water and becomes more negative as the concentration of salts increases. An approximate relationship between Ψ_o (kPa) and the salt concentration (C_s, g m^{-3}) is:

$$\Psi_o = -0.05625\, C_s \tag{8.4}$$

Example 8.2 The soil characteristic curve of a Sandy loam soil is given by

$$\Psi_m = -0.152\, \theta^{-3.1} (\text{kPa})$$

We will calculate water potential for this soil at 1 m depth if the water content is 0.2 $m^3\ m^{-3}$ and the salt concentration in the soil solution is 64 g/m^3. We fix the reference level on the soil surface. Therefore:

$$\begin{aligned}\Psi &= \Psi_m + \Psi_g + \Psi_o = -0.152\ \ 0.2^{-3.1} - 9.81 \times 1 - 0.05625 \times 64 \\ &= -22.3 - 9.8 - 3.6 = -35.7\ \ \text{kPa}\end{aligned}$$

which is equivalent to −0.036 MPa or −0.36 bar.

Example 8.3 A water table is located at a depth of 1 m in the soil of example 8.2. What would be the water content at the soil surface under conditions of hydraulic equilibrium if the osmotic potential does not change with depth?

If we take the soil surface as reference level, the water potential at the water table will be:

$$\Psi = \Psi_m + \Psi_g + \Psi_o = 0 - 1 \times 9.81 + \Psi_o = -9.81 + \Psi_o (\text{kPa})$$

The water potential at the soil surface will have the same value. If osmotic potential is the same at the reference level and at the water table, the matric potential at the surface will be:

(continued)

Example 8.3 (continued)

$$\Psi_{\mathrm{m\,surface}} = -9.81 + \Psi_{\mathrm{o\,water\,table}} - \Psi_{\mathrm{o\ surface}} = -9.81\,\mathrm{kPa}$$

According to the characteristic curve:

$$\Psi_{\mathrm{m}} = -0.152\ \theta^{-3.1}$$

$$\theta = -\left(\frac{0.152}{\Psi_m}\right)^{1/3.1} = \left(\frac{0.152}{-9.81}\right)^{1/3.1} = 0.26\mathrm{m}^3\ \ \mathrm{m}^{-3}$$

8.3 Water Flow in the Soil

In the simplest case we consider one-dimensional (vertical) water flow in the soil that obeys Darcy's law:

$$J_w = -K(\Psi_m)\frac{d\,\Psi}{dz} \tag{8.5}$$

where $K(\Psi_m)$ is the hydraulic conductivity which is a function of matric potential and J_w is water flow ($kg/m^2/s$). At saturation (zero matric potential) K reaches its maximum value called the saturated hydraulic conductivity (K_s). The components of the water potential to be considered are the matric and gravitational potentials. Then, the equation above is equivalent to:

$$J_w = -K(\Psi_m)\frac{d\Psi_m}{dz} - K(\Psi_m)\frac{d\Psi_g}{dz} = -K(\Psi_m)\left(\frac{d\Psi_m}{dz} + g\right) \tag{8.6}$$

The hydraulic conductivity may be computed as:

$$K(\theta) = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{8.7}$$

or

$$K(\Psi_m) = K_s\left(\frac{\Psi_e}{\Psi_m}\right)^{2+3/b} \tag{8.8}$$

where the parameters have already been defined and given in Table 8.1.

Table 8.1 Physical properties of soils with different texture

	Silt	Clay	Ψ_e	b	K_s	Bulk dens	Porosity	θ_{PWP}	θ_{FC}	θ_{SAT}
Texture	Fraction		J/kg		$\times 10^{-6}$ kg s m^{-3}	t/m^3	Fraction	m^3/m^3	m^3/m^3	m^3/m^3
Sand	0.05	0.03	−0.7	1.7	5800	1.68	0.37	0.03	0.09	0.23
Loamy sand	0.12	0.07	−0.9	2.1	1700	1.64	0.38	0.06	0.13	0.26
Sandy loam	0.25	0.1	−1.5	3.1	720	1.56	0.41	0.1	0.21	0.31
Loam	0.4	0.18	−1.1	4.5	370	1.43	0.46	0.12	0.27	0.37
Silt loam	0.65	0.15	−2.1	4.7	190	1.41	0.47	0.13	0.33	0.40
Sandy clay	0.13	0.27	−2.8	4	120	1.4	0.47	0.15	0.26	0.37
Clay loam	0.34	0.34	−2.6	5.2	64	1.31	0.51	0.2	0.32	0.41
Silty clay	0.58	0.33	−3.3	6.6	42	1.27	0.52	0.20	0.37	0.45
Sandy clay	0.07	0.4	−2.9	6	33	1.33	0.50	0.21	0.34	0.42
Silty clay	0.45	0.45	−3.4	7.9	25	1.23	0.54	0.21	0.39	0.46
Clay	0.2	0.6	−3.7	7.6	17	1.21	0.54	0.21	0.4	0.47

8.4 The Water Budget

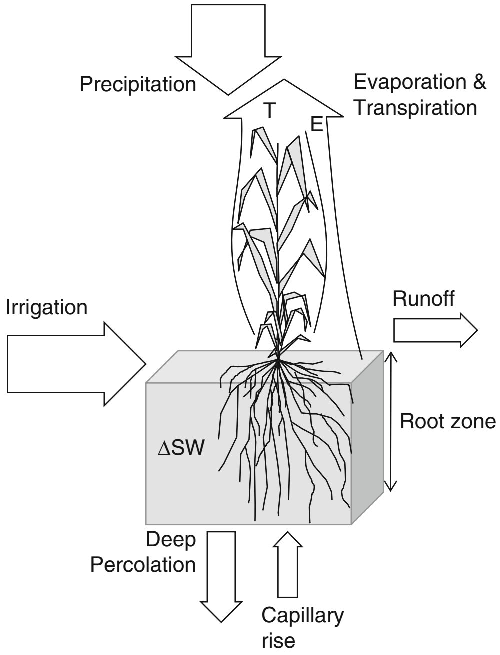
Figure 8.2 shows a schematic diagram of the water balance of a field. We may write the mass conservation equation for water inputs and outputs from that field during a period to calculate the increment in total soil water content in the crop root zone (TSWC):

$$\Delta \mathrm{TSWC} = \mathrm{P} + \mathrm{I} - \mathrm{E_s} - \mathrm{E_p} - \mathrm{SR} - \mathrm{DP} + \mathrm{WTC} \tag{8.9}$$

where P is precipitation, I is applied irrigation, E_s is evaporation from the soil surface, E_p is transpiration, SR is surface runoff, i.e. water not infiltrated, DP is deep percolation and WTC is upward water flow from the water table. For Irrigation Scheduling it is better to express the amount of soil water as a deficit (Soil Water Deficit, SWD), which is the amount of water required to bring the soil to FC or the upper limit.

The water balance may be computed for different time periods (hour, day, decade, months). We will focus first on several methods to calculate it for daily values.

Fig. 8.2 Diagram of the water balance components of a field



8.5 Infiltration

The rate at which water enters the soil through its surface (infiltration rate) is reduced with time, until a relatively constant value is reached, which depends on the soil (Fig. 8.3), being higher for sandy soils and lower for clay soils. The initial infiltration rate is inversely proportional to the initial water content. This is because the water potential gradient between the water and the soil is greater if the latter is drier (since the matric potential is more negative). The water that does not infiltrate, stays on the surface and moves to the lower parts running off the field. In Sect. 8.7 we will revise a methodology for evaluating the amount of runoff.

8.6 Deep Percolation

There are different approaches to compute the amount of water that moves out below the crop root zone. The method presented here requires knowing the values of soil depth (Z, mm), and the soil water content values at field capacity and at saturation. Additionally it requires a dimensionless parameter (SWCON) which is the fraction of water lost by percolation in 1 day in relation to the amount of soil water which exceeds field capacity. The amount of water that exceeds the saturation water content is considered instantly lost by deep percolation.

Suppose that on a given day an amount of water P_I (mm) has infiltrated into the soil. The amount of water that can be stored in the short term (SWCC) may be calculated as:

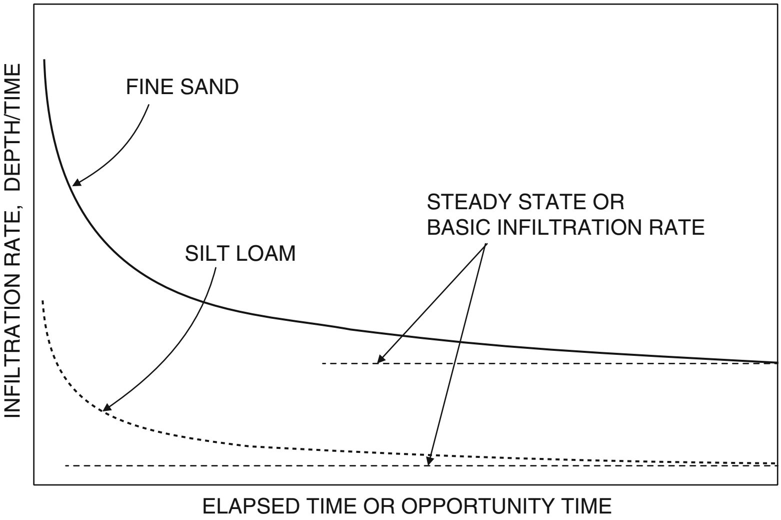


Fig. 8.3 Infiltration rate for two soils differing in saturated hydraulic conductivity

$$\mathrm{SWCC} = (\theta_{\mathrm{SAT}} - \theta)\mathrm{Z} \tag{8.10}$$

where θ is the average water content in the soil. If P_I is higher than SWCC the excess is lost by deep percolation on the same day. If the water content, after adding infiltrated water, does not exceed Field Capacity then it is assumed that there is no percolation. If the water content is between field capacity and saturation then percolation is calculated as:

$$\mathrm{DP} = \mathrm{SWCON}\ \ \mathrm{Z}\ (\theta - \theta_{\mathrm{FC}}) \tag{8.11}$$

Some models of this type have assumed that SWCON = 1, that is, all water that exceeds the upper limit is instantly lost. Such simplification may be valid in very permeable soils or fallow situations or early crop stages. However, if SWCON is less than 1 and the crop is extracting water from the soil, plant roots can extract some of the water that exceeds the upper limit, which will not be lost by percolation. When there is no crop or it has just been planted, deep percolation estimates are less sensitive to the SWCON value. Ritchie has suggested SWCON values for different types of soil:

Clay soil (very slow to moderately slow drainage): 0.01–0.25
Medium textured soils (moderate to moderately rapid drainage): 0.40–0.65
Sandy soils (fast to very rapid drainage): 0.75–0.85

Example 8.4 We will calculate deep percolation for a maize crop growing on a loam soil 1000 mm depth with the following parameters:

$$\theta_{\mathrm{PWP}} = 0.10\ \mathrm{m}^3\ \mathrm{m}^{-3},\ \theta_{\mathrm{FC}} = 0.25\ \mathrm{m}^3\ \mathrm{m}^{-3},\ \theta_{\mathrm{SAT}} = 0.35\ \mathrm{m}^3\ \mathrm{m}^{-3},$$
$$\mathrm{SWCON} = 0.4$$

The soil starts with a soil water content $\theta = 0.30\ \mathrm{m}^3\ \mathrm{m}^{-3}$. A rainfall of 45 mm has fallen and 5 mm have not infiltrated.

Total water infiltrated will be:

$$\mathrm{P_I} = 45 - 5 = 40\,\mathrm{mm}$$

Short term storage is given by:

$$\mathrm{SWCC} = \mathrm{Z}(\theta_s - \theta) = 1000(0.35 - 0.30) = 50\,\mathrm{mm}$$

which is greater than total infiltration. Therefore 40 mm will be stored in the short term. Soil water content increases to:

(continued)

Example 8.4 (continued)

$$\theta = \theta + 40/1000 = 0.30 + 0.04 = 0.34 \ \mathrm{m^3\ m^{-3}}$$

which is higher than θ_{FC}. Therefore some deep percolation will occur:

$$\mathrm{DP = SWCON \cdot Z(}\theta - \theta_{\mathrm{FC}}) = 0.4 \cdot 1000(0.34 - 0.25) = 36 \ \mathrm{mm}$$

In the previous example we applied Eq. 8.11 to a single day. But we can extend this analysis to the days after the rainfall event to calculate the total DP. We consider a soil of depth Z (mm) with an initial water content θ_i, that loses water by evaporation from the soil and crop transpiration at a rate equal to ET (mm/day) (see Chap. 9 for more detail). After rainfall, an amount P_I (mm) has infiltrated, so that the water content is now: $\theta_i + P_I/Z$, which is greater than θ_{FC} (otherwise there would be no percolation). We start from the differential equation describing the variation of water content:

$$\frac{d\theta}{dt} = SWCON \ (\theta - \theta_{FC}) - \frac{ET}{Z} \tag{8.12}$$

And, after integrating:

$$\theta = \theta_{FC} + \frac{\left[SWCON \left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) + \frac{ET}{Z}\right] e^{-SWCON\ t} - ET/Z}{SWCON} \tag{8.13}$$

Equation 8.13 may be used to calculate the soil water content at time t (days after rainfall) as a function of SWCON and ET. This equation may also be used to calculate the time it takes to reach Field Capacity:

$$t_{FC} = \frac{ln\left(1 + \frac{SWCON\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right)}{ET/Z}\right)}{SWCON} \tag{8.14}$$

During that time, a total of t_{FC}·ET will be lost by evaporation from the soil and the plants, so we may deduce the total percolation from rainfall until time t_{FC}, when the soil water content returns to Field Capacity:

$$\sum_{1}^{t_{FC}} DP = Z \ \left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) - t_{FC} \ ET \tag{8.15}$$

This equation shows that evaporation losses partly counterbalance percolation losses, as shown in the example below.

Example 8.5 Let's consider a loam soil 1 m (1000 mm) deep with a water content of 0.23 m/m. A total of 50 mm infiltrates into the soil. We will calculate percolation if: (a) ET = 1 mm/day, (b) ET = 8 mm/day. These values are typical of soil covered by vegetation in winter and summer, respectively, in the South of Spain.

Soil data given: $\theta_{FC} = 0.25$, SWCON = 0.6

(a) ET = 1 mm/day

$$t_{FC} = \frac{ln\left(1 + \frac{0.6\,\left(0.23+\frac{50}{1000}-0.25\right)}{1/1000}\right)}{0.6} = 4.91 \text{ days}$$

$$\sum_{1}^{t_{FC}} DP = Z\left(\theta_i + \frac{P_I}{Z} - \theta_{FC}\right) - t_{FC}\,ET$$

$$= 1000\left(0.23 + \frac{50}{1000} - 0.25\right) - 4.91 \cdot 1 = 25.1 \quad \text{mm}$$

(b) ET = 8 mm/day

$$t_{FC} = \frac{ln\left(1 + \frac{0.6\,\left(0.23+\frac{50}{1000}-0.25\right)}{8/1000}\right)}{0.6} = 1.96 \text{ days}$$

$$\sum_{1}^{t_{FC}} DP = 1000\left(0.23 + \frac{50}{1000} - 0.25\right) - 1.96 \cdot 8 = 14.3 \quad \text{mm}$$

8.7 Surface Runoff

The main factors that determine surface runoff are rainfall intensity, soil type, vegetation type, topography and surface roughness. In the method of the Soil Conservation Service (US-SCS) all these factors are combined into a single factor, called "runoff curve number" (CN) which is proportional to runoff potential.

To calculate the CN, soils are classified into four hydrologic groups from low to high runoff potential:

(A) Low runoff potential. These are soils with high infiltration rate when wet. It is generally the case of sandy or gravely soils, deep and well drained.

(B) Soils with moderate infiltration rate when wet, average depth and medium texture.

(C) Soils with low infiltration rates when wetted. These soils are of fine texture or have a horizon that hinders the drainage.
(D) High runoff potential. Includes soils with very low infiltration rates when wet, such as expansive clay soils, soils with high water table, soils with a clay layer near the surface and shallow soils over impervious materials.

In addition to soil characteristics, in the calculation of CN, the hydrological condition of the field is considered, which can be good or bad depending on slope and cultural practices. Table 8.2 shows the CN values based on hydrologic condition and soil group, for different types of crops and conservation practices. The CN value shown in Table 8.2 implies average conditions of soil moisture when precipitation occurs (Antecedent Moisture Condition AMC 2) and is called CN2. CN values that correspond to low AMC (AMC 1; CN1) or High (AMC 3; CN3) are calculated by the following equations:

Table 8.2 Runoff curve number (CN) for different soils and cover types

Cover type	Treatment	Hydrologic condition	Soil hydrological group			
			A	B	C	D
Fallow	Bare soil crop residue (CR)	–	77	86	91	94
		Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR and CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C and CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured and terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR.	Poor	65	76	84	88
		Good	63	75	83	87
	SR+ CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C&CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80

(continued)

Table 8.2 (continued)

			Soil hydrological group			
Cover type	Treatment	Hydrologic condition	A	B	C	D
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80
Pasture, grassland, or range-continuous grazing		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
Meadow – continuous grass, protected mowed for hay			30	58	71	78
Brush – weed-grass mixture		Poor	48	67	77	83
		Fair	35	56	70	77
		Good	30	48	65	73
Woods-grass combination (orchard)		Poor	57	73	82	86
		Fair	43	65	76	82
		Good	32	58	72	79
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	30	55	70	77

$$CN_1 = CN_2 - 20\,\frac{100 - CN_2}{100 - CN_2 \quad + CN_2 e^{2.533-0.0636\,(100-\,CN_2)}} \tag{8.16}$$

$$CN_3 = \; CN_2 \; e^{0.00673\,(100-CN_2)} \tag{8.17}$$

The values of CN1 or CN3 cannot exceed 100. For values of soil water content other than dry (CN1) or saturated soil (CN3), the curve number can be calculated as a function of soil water content in the upper soil layer:

(a) If soil water content is higher than Field Capacity:

$$\mathrm{CN} = \mathrm{CN2} + (\mathrm{CN3} - \mathrm{CN2})(\theta - \theta_{\mathrm{FC}})/(\theta_{\mathrm{SAT}} - \theta_{\mathrm{PWP}}) \tag{8.18}$$

(b) If soil water content is lower than Field Capacity:

$$\mathrm{CN} = \mathrm{CN1} + (\mathrm{CN2} - \mathrm{CN1})(\theta - \theta_{\mathrm{PWP}})/(\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}) \tag{8.19}$$

Once CN is known we calculate the maximum water depth (SMX, mm) that may be infiltrated or stored above the soil surface:

$$SMX = 254\left(\frac{100}{CN} - 1\right) \tag{8.20}$$

If daily rainfall (P) is lower than 0.2 SMX, runoff is zero. Otherwise, runoff (SR, mm) is calculated as:

$$SR = \frac{(P - 0.2\,SMX)^2}{P + 0.8\,SMX} \tag{8.21}$$

Example 8.6 We have a sunflower crop growing on a deep medium texture soil with almost zero slope. A rain event of 40 mm occurs when the soil is almost saturated

(a) The soil can be included in the B type, and the hydrologic condition is good due to the absence of slope. In Table 8.2 we choose a value of CN2 = 78.

(b) As the soil is wet we calculate CN3 = 90 using Eq. 8.15 and assign CN = 90.

(c) We calculate SMX:

$$SMX = 254\left(\frac{100}{90} - 1\right) = 28 \quad \text{mm}$$

(d) We compare 20 % of SMX (5.6 mm) with rainfall (40 mm). As P > 0.2 SMX then runoff will occur:

$$SR = \frac{(40 - 0.2 \times 28)^2}{40 + 0.8 \times 28} = 19 \;\; \text{mm}$$

In this case almost 50 % of rainfall would have infiltrated.

8.8 Effective Rainfall

Effective rainfall (P_e) is the fraction of total precipitation during a specific time period that is not lost by runoff or percolation and thus is stored in the crop root zone. It is a broad concept, sometimes used to characterize the seasonal or monthly water balance or to assess the disposition of a rainfall event. A number of methods for calculating effective rainfall for a monthly period have been proposed. These methods have been developed for monthly periods and should not be used for shorter time intervals. In any case they can only provide rough estimates as they ignore key factors like soil properties or the actual rainfall distribution within the month.

8.8.1 FAO Method

This method has been the result of a study conducted by FAO in arid and sub-humid areas. The equation was developed to estimate the monthly effective rainfall (P_e) that is exceeded in 80 % of the years, and is used for irrigation system design. Effective rainfall is estimated by the following equations:

$$P_e = 0.6P - 10 \qquad \text{if } P < 70 \text{ mm} \tag{8.22a}$$

$$P_e = 0.8P - 24 \qquad \text{if } P > 70 \text{ mm} \tag{8.22b}$$

8.8.2 USDA-Soil Conservation Service Method

In this method, in addition to rainfall, crop evapotranspiration (ET) and soil water deficit before irrigation are taken into account according to:

$$P_e = f(SWD)\left[1.25P^{0.824} - 2.93\right]10^{0.001\ ET} \tag{8.23}$$

$$f(SWD) = 0.53 + 0.0116\,SWD - 8.94\,10^{-5}SWD^2 + 2.32\,10^{-7}SWD^3 \tag{8.24}$$

where SWD (mm) is the soil water deficit just before irrigation and ET is given in mm/month.

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Chapter 9
The Components of Evapotranspiration

Francisco J. Villalobos, Luca Testi, and Elias Fereres

Abstract Evapotranspiration is the sum of evaporation from the soil surface and the plant surfaces, and transpiration. The evaporation from the soil in agronomy follows a two-stage process depending if the soil surface is wet after a rain or irrigation or has already dried up. When the soil surface is wet the rate of evaporation is potentially very high; that's why the rainfall frequency is the main driver of the soil evaporation, especially at low ground cover. The core model to quantify the process of evaporation is the combination equation, later applied to crop canopies and for computing plant transpiration known as the Penman-Monteith equation. This equation has two resistance variables (the aerodynamic and canopy resistance) which are hard to quantify as they are constantly changing with the physical environment and the plant physiological state. The Penman-Monteith equation is the established method to analyze the evaporation processes in plants and stands and it has been thoroughly verified. The transpiration of trees is heavily dependent on canopy conductance and scales up well with the ground cover or the fraction of intercepted radiation.

9.1 Introduction

Evaporation from vegetated surfaces (or evapotranspiration, as it combines evaporation from soils and transpiration from plants) is the main component of water loss from terrestrial ecosystems so its quantification is of great importance in hydrology, agronomy and related sciences. Moreover in agronomy, evaporation is usually directly proportional to crop productivity, as discussed in Chap. 14.

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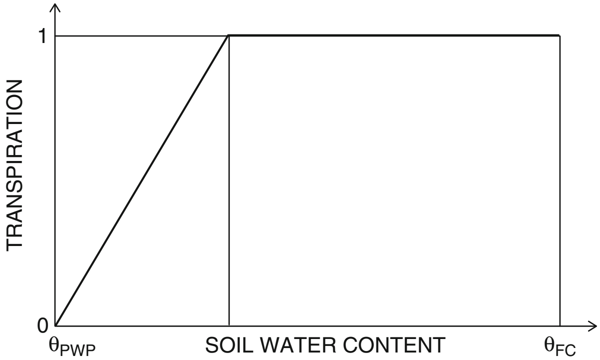

Fig. 9.1 Effect of soil water content on transpiration or evapotranspiration

Evapotranspiration (ET) is the sum of direct evaporation from the soil surface (E_s), plant transpiration (E_p) and direct evaporation from plant surfaces (E_{ps}):

$$ET = E_s + E_p + E_{ps} \tag{9.1}$$

Strictly transpiration is the water vapor flow through the stomata of plants. For this flow to occur, evaporation must take place in the substomatal cavities. If the canopy surface is dry, $E_{ps} = 0$, so that:

$$ET = E_s + E_p \tag{9.2}$$

Maximum transpiration (and ET) occurs when soil water is not limiting root water uptake, which usually happens for soil water content above one third of available soil water (Fig. 9.1).

9.2 Measurement of Evapotranspiration

Crop ET can be measured directly by determining the mass of water lost from a vegetated surface or estimated indirectly. Direct ET measurement is done in weighing lysimeters which are large containers open at the top to enclose a volume of soil whose mass can be measured accurately and where plants are grown. Lysimeters are placed in the middle of large fields to ensure that the microclimate experienced by the plants inside them is the same as that of the surrounding plants. They are large in size and are deep enough so that root systems are not limited by the lysimeter walls. For example, at the Agricultural Research Center of Cordoba (Spain) two weighing lysimeters were installed in 1987 with an area of 6 m^2 each and a depth of 1.5 m. The measurement systems are accurate enough to register water losses equivalent to the ET of short sub-hourly periods (5–10 min).

Estimates of ET and fluxes of other scalars (e.g. canopy photosynthesis) may be obtained using micrometeorological methods (Box 9.1).

The simplest method for estimating ET is the water balance, which requires the estimation of the water balance components, so that ET is obtained by difference. From Eq. 8.3 in Chap. 8:

$$ET = P + I - SR - DP + WTC - \Delta TSWC \tag{9.3}$$

Example 9.1 Soil water content measurements were taken of a 1-m deep soil under a soybean crop on two dates (August 11 and August 19). The average soil water content was 0.22 (August 11) and 0.175 $\mathrm{cm}^3\ \mathrm{cm}^{-3}$ (August 19). In that period there has been a rain episode of 20 mm. Assuming no runoff, no deep percolation and that the water table is too deep to contribute water to the root zone through capillary rise, we can calculate the ET for the period as the difference between rainfall and the increase in total soil water content:

$$ET = P - \Delta TSWC$$

The soil water content in the first date will be:

$$\mathrm{TSWC(11Aug)} = 0.22 \times 1000 = 220\,\mathrm{mm}$$

Analogously we calculate the water content in the second date, resulting in TSWC (19 Aug) = 175 mm.

The increase will be:

$$\Delta\mathrm{TSWC} = \mathrm{TSWC\ (19\ Aug)} - \mathrm{TSWC\ (11\ Aug)} = 175\text{–}220 = -45\ \mathrm{mm}$$

And so the ET will be:

$$\mathrm{ET} = 20 + 45 = 65\ \ \mathrm{mm}$$

Box 9.1 Micrometeorological Methods

Measurements of meteorological variables close to the canopy allow the estimation of the components of the energy balance. For instance by measuring net radiation, soil heat flux and the gradients of temperature and vapor pressure above the canopy it is possible to estimate latent heat flux, using the so called Bowen Ratio method.

If instead of measuring the gradients we use an infrared thermometer to get canopy temperature we can calculate sensible heat flux and thus deduce latent heat flux.

(continued)

Box 9.1 (continued)

A more sophisticated approach is the eddy covariance method. It is based on high frequency measurements of scalars (temperature, absolute humidity, CO_2 concentration) and vertical wind velocity. The covariance of any scalar and vertical wind speed (w) provides a measure of the flux of the scalar. For instance the covariance of temperature and w is directly proportional to sensible heat flux, while that of water vapor concentration and w leads to latent heat flux. Note that this technique may be applied to measure the flux of any chemical (e.g. ammonia) provided that we have the proper instrument for measuring its concentration.

9.3 Evaporation from the Soil Surface

Philip described the evaporation from a bare soil surface (E_s) after wetting, as a three-stage process. In the first stage (energy limited) the soil surface is wet and the hydraulic conductivity is high, so that the evaporation rate is only limited by the amount of energy available for evaporation at the surface. In this case the evaporation is approximately equal to the evaporation from a short grass field which is defined in Chap. 10 as the reference evapotranspiration ET_0. This stage continues until a certain amount of water has evaporated (U_e) that depends on soil type, ranging from 5–6 mm (well drained soils) to 12–14 mm (heavy clay soils).

When the second (soil limited) stage begins, the soil hydraulic conductivity has been reduced to values which limit the water flow to the soil surface from the deeper soil layers. During this phase E_s is decreasing as a function of the square root of time since the start of the second phase (t):

$$E_s = c_e\left(\sqrt{t} - \sqrt{t-1}\right) \tag{9.4}$$

where c_e is a constant that depends on the soil type, although its value is usually close to 3.5 mm $day^{-0.5}$.

The third stage described by Philip corresponds to extremely dry soil in which water is transported to the soil surface as water vapor and the evaporation is extremely low. For practical purposes in agronomy we can calculate E_s considering only the first two phases.

Therefore, the evaporation of a soil depends primarily on the availability of energy at its surface and on the water content of the upper soil layers (down to about 30 cm). Thus, when the soil is thoroughly wet, E_s is similar to the evaporation from a full cover crop, and can be assumed equal to ET_0. By contrast, when the soil surface is dry, E_s is reduced to very low values (Fig. 9.2).

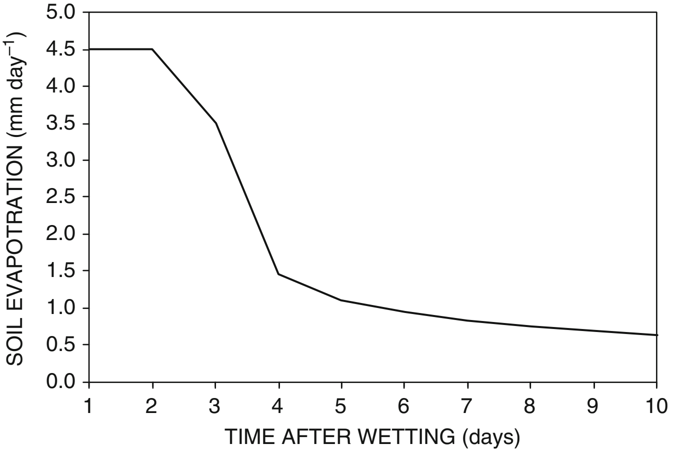

Fig. 9.2 Soil evaporation rate after soil wetting. Reference ET is 4.5 mm/day. The parameter U_e is 9 mm

If the soil is partly covered by a crop canopy or by crop residues, the amount of energy reaching the soil surface is reduced, and so will be E_s for the first stage (E_{s1}):

$$E_{s1} = ET_0(1 - f_{PI}) \tag{9.5}$$

where f_{PI} is the fraction of radiation intercepted that does not reach the soil surface.

Example 9.2 Rain has fallen and wetted a bare soil thoroughly. The soil parameter for evaporation during the first stage (energy limited) is $U_e = 9$ mm and ET_0 is 4.5 mm/day.

In this case the first stage (E_s equal to ET_0) will last 2 days as it is the time required to evaporate 9 mm:

$$U_e/ET_0 = (9\ \text{mm})/(4.5\ \text{mm/day}) = 2\ \text{days}$$

Therefore $E_s(1) = E_s(2) = 4.5$ mm/day

The second stage of E_s starts on the third day thus, taking c_e as 3.5 mm/day$^{0.5}$:

$$E_s(3) = 3.5(1^{0.5} - (1 - 0)^{0.5}) = 3.50\ \text{mm/day}$$

$$E_s(4) = 3.5\left(2^{0.5} - (2 - 1)^{0.5}\right) = 1.45\ \text{mm/day, and so on.}$$

(continued)

Example 9.2 (continued)

If the same situation occurred in an olive orchard intercepting 40 % of radiation ($f_{PI} = 0.4$) then evaporation in stage 1 would be:

$$E_{s1} = ET_0\,(1 - f_{PI}) = 4.5 \cdot (1\ -\ 0.4) = 2.7\ \ \text{mm/day}$$

In this case the first stage will last 3.3 days (it may be rounded to 3). On the fourth day the second stage will start so:

$$E_s(4) = 3.5\left(1^{0.5} - (1-0)^{0.5}\right) = 3.50\ \ \text{mm/day}$$

$$E_s(5) = 3.5\left(2^{0.5} - (2-1)^{0.5}\right) = 1.45\ \text{mm/day},\ \text{and so on.}$$

According to the two stage model of evaporation, the average E_s for a given period (month, year) will be proportional to the frequency of wetting. If wetting events have an average duration of WD, and the average interval between two consecutive events is WI, we may calculate the average daily E_s using the equations for evaporation in stage 1 for WD-0.5 days and the two equations (stage 1 and stage 2) for WI − WD + 0.5 days, assuming that on day WD the rainfall stops in the middle of the day.

The average soil evaporation for the period will be:

$$E_{sm} = \frac{(WD - 0.5)\,ET_0 + \ \ U_e + c_e\ \sqrt{WI - (WD - 0.5) - \frac{U_e}{ET_0} - t'}}{WI} \tag{9.6}$$

where $t' = (c_e/ET_0)^2$ if $c_e > ET_0$. Otherwise $t' = 0$. Please note that the square root function in Eq. 9.6 is valid only for positive values. A negative value would indicate that the soil stays in first stage evaporation so its average evaporation rate is equivalent to ET_0.

Example 9.3 A farmer has sown a summer crop during June in southern Italy ($ET_0 = 6$ mm/day). To ensure crop emergence, irrigations are applied every 5 days (WI = 5 days, WD = 1 day). The soil has a parameter for first stage $U_e = 9$ mm and $c_e = 3.5$ mm $\text{day}^{-0.5}$. Calculate the average evaporation for the period.

Applying Eq. 9.6:

$$E_{sm} = \frac{0.5 \times 6 + 9 + 3.5\sqrt{5 - 0.5 - 9/6}}{5} = 3.6\ \ \text{mm/d}$$

Example 9.4 The average number of rainy days in Cordoba (Spain) during March (ET_0= 3 mm/day) is 9.3. In principle, this would imply that on average a rainfall event would occur every 3.3 days. However, rainy days tend to cluster, to occur in consecutive days. According to Villalobos and Fereres the average interval between two consecutive rainy spells may be estimated as:

$$WI = \frac{1}{0.75 f_w (1 - f_w)} \tag{9.7}$$

where f_w is the mean frequency of rainy days. In the case of Cordoba $f_w = 9.3/31 = 0.3$, thus WI = 6.3 days.

And each period of 6.3 days would be composed of 1.9 rainy days (30 % of 6.3 days) and 4.4 dry days. Now taking WI = 6.3 days and WD = 1.9 days we may apply Eq. 9.6 (we will assume a soil with the parameter for first stage $U_e = 6$ mm and $c_e = 3.5\ \mathrm{mm}^{-0.5}$) to calculate the average soil evaporation during March:

$$E_{sm} = \frac{(1.9 - 0.5) \times 3 + 6 + 3.5\sqrt{6.3 - (1.9 - 0.5) - 6/3}}{6.3} = 2.6\ \ \mathrm{mm/d}$$

9.4 Analysis of Evapotranspiration with the Penman-Monteith Equation

The first formulation of a combination equation to calculate evaporation is due to Penman in 1948, who combined the energy balance equation with those of latent heat and sensible heat fluxes. Similar solutions were proposed by Ferguson in Australia and Budyko in Russia. The most widespread formulation of the combination equation is due to Monteith that started from the following equations:

the energy balance (Chap. 7):

$$R_n - G = LE + H \tag{9.8}$$

Latent heat flux (Chap. 5):

$$LE = \frac{\rho C_p}{\gamma} \frac{(e_{sc} - e_a)}{(r_c + r_a)} \tag{9.9}$$

Sensible heat flux (Chap. 5):

$$H = \rho C_p \frac{(T_c - T_a)}{r_a} \tag{9.10}$$

In this method, the slope of the saturation vapor pressure function versus temperature (Δ, kPa K^{-1}) is approximated as:

$$\Delta = \frac{e_{sc} - e_s}{T_c - T_a} \tag{9.11}$$

where e_{sc} is the saturation vapor pressure at canopy temperature (T_c) and e_s is the saturation vapor pressure at air temperature (T_a). Therefore:

$$e_{sc} = e_s + \Delta(T_c - T_a) \tag{9.12}$$

Now adding and subtracting e_s in part of Eq. 9.9 and using Eq. 9.12:

$$\begin{aligned} e_{sc} - e_a &= e_{sc} - e_a + e_s - e_s = \Delta(T_c - T_a) + e_s - e_a \\ &= \Delta(T_c - T_a) + VPD \end{aligned} \tag{9.13}$$

So Eq. 9.9 can be written as:

$$LE = \frac{\rho C_p}{\gamma} \frac{\Delta(T_c - T_a) + VPD}{(r_c + r_a)} \tag{9.14}$$

From Eqs. 9.10 and 9.8 we can write the term Δ (T_c – T_a) as:

$$\Delta(T_c - T_a) = \frac{\Delta \; r_a H}{\rho C_p} = \frac{\Delta \; r_a(Rn - G - LE)}{\rho \; Cp} \tag{9.15}$$

Which placed in Eq. 9.14, allows solving for LE, leading to the Penman-Monteith equation:

$$LE = \frac{\Delta(R_n - G) + \frac{\rho \, C_p}{r_a} \; VPD}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{9.16}$$

The Penman-Monteith equation indicates that crop evaporation depends on meteorological (radiation, temperature, humidity, wind speed) and crop factors (r_c). In the case of r_a apart from canopy characteristics (height, leaf area) there is a dependence on meteorological conditions (wind speed).

This equation has the drawback of requiring information on canopy resistance (r_c, see Chap. 5) which in turn depends on different environmental factors such as temperature, radiation and Vapor Pressure Deficit (VPD). It has been found that in a large number of crop species, r_c is proportional to VPD. Thus, on one hand, a high VPD increases LE, but if r_c increases as well due to the high VPD, it contributes to reducing crop transpiration when evaporative demand is high.

The Penman-Monteith equation is very useful from a conceptual standpoint. For example, when the VPD tends to zero (extremely humid conditions) and the canopy resistance is small compared with the aerodynamic resistance (e.g. flat, smooth surfaces such as a short grass crop) evaporation tends to:

$$LE = \frac{\Delta(R_n - G)}{\Delta + \gamma} \tag{9.17}$$

This value has been termed "equilibrium evaporation" and corresponds also to the evaporation from a canopy that has a very high aerodynamic resistance. In cases like this evaporation is dependent only on radiation and temperature (as Δ depends on temperature). These conditions are found in short, smooth crop canopies where the humidity is high and the aerodynamic resistance is very high due to the absence of wind or in crops growing in greenhouses in still air.,.

The opposite case is that of very rough canopies and windy conditions (low r_a) with rather high canopy resistance (e.g. forests with variable tree heights and isolated trees with small leaves such as olives). In this case it is easy to demonstrate that evaporation (called "imposed evaporation") depends only on VPD and canopy resistance:

$$LE = \frac{\rho C_p}{\gamma} \frac{1}{r_c} VPD \tag{9.18}$$

These two extremes of equilibrium and imposed evaporation are said to correspond to uncoupled and coupled canopies in relation to the atmosphere. In a perfectly coupled canopy the absence of aerodynamic resistance makes transpiration highly responsive to changes in VPD. On the contrary, the uncoupled canopy (e.g. grass in the absence of wind) is somehow isolated from changes in atmospheric conditions above it. If stomata close then the reduced transpiration leads to higher canopy temperature which leads to increased transpiration (see Eq. 5.12 in Chap. 5). In the field, crop canopies are not perfectly coupled or uncoupled but somewhere in between. Those better coupled to the atmosphere (for example, tree crops) can exert more control of transpiration via stomata closure than those that are largely uncoupled such as smooth field crops.

9.5 Transpiration

The calculation of actual transpiration is difficult as it depends on meteorological (e.g. radiation) and plant factors, primarily through the response of stomata to the aerial environment but also including root system responses. For well-watered conditions, a very simple approach may be followed. For a given condition the transpiration coefficient, that is the ratio transpiration/ET_0, is proportional to the fraction of intercepted radiation, so transpiration (E_p, mm day^{-1}) can be calculated as:

$$E_p = f_{PI}\ K_{tf}\ ET_0 \tag{9.19}$$

where f_{PI} is the fraction of radiation intercepted, K_{tf} is the transpiration ratio for full interception, which is close to 1 for most herbaceous and evergreen tree crops and between 1.2 and 1.8 for deciduous tree crops (Table 9.1).

For isolated trees, Eq. 9.19 becomes:

$$E_{p\ tree} = RR_i\ K_{tf}\ ET_0 \tag{9.20}$$

where $E_{p\ tree}$ is tree transpiration (L day^{-1} tree^{-1}) and RR_i is the relative radiation interception (the ratio between total intercepted radiation and incoming radiation; see Chap. 3).

Example 9.5 In Example 3.5, we calculated the relative interception of a small olive tree with radius 0.5 m in Cordoba, Spain on 21 March as $RR_i = 0.69\ m^2$.

If ET_0 is 3 mm day^{-1}, calculate tree transpiration.

$$E_{p\ tree} = RR_i K_{tf} ET_0 = 0.69 \cdot 1 \cdot 3 = 2.07\ \ \mathrm{L\,day^{-1}}$$

Villalobos et al. (2013) proposed a more detailed model for calculating the transpiration of orchard canopies This model considers a daily “bulk” canopy conductance (G_c), i.e. the inverse of the canopy resistance for the whole stand, a parameter that is related to VPD and to the radiation intercepted by the canopies as:

$$G_c = \alpha \frac{Q R_s}{a + bVPD} \tag{9.21}$$

where Q is the fraction of radiation intercepted by the canopy (see Chap. 3), R_s is the daily solar radiation (MJ m^{-2} day^{-1}), VPD is the vapor pressure deficit (kPa), α is a generic coefficient and a and b are empirical coefficients which vary with the tree species (see Table 9.1). As $r_c = 1/G_c$, we can use the Penman-Monteith equation (Eq. 9.16) to calculate the transpiration of the stand. As orchard canopies are generally well coupled to the atmosphere,, similar results may be obtained using the “imposed” evaporation equation (Eq. 9.18), which is much more practical as it does not require knowledge of the aerodynamic resistance, r_a. The transpiration (in mm day^{-1}) can thus be calculated as:

$$E_p = 37.08 \cdot 10^3 \frac{Q\ R_s}{a + b\ \ VPD} \frac{VPD}{P_{at}} \tag{9.22}$$

Table 9.1 Empirical coefficients to calculate bulk canopy conductance of some cultivated tree species

Species	a (μE mol^{-1})	b (μE mol^{-1} kPa^{-1})	K_{tf}
Orange	1002	1666	0.8
Walnut	1287	673	1.4
Apple	442	911	1.8
Olive	1211	1447	1.1
Apricot	452	2050	
Peach	333	633	1.8
Pistachio	359	624	1.9
Almond			1.25

where P_{at} is the atmospheric pressure (kPa). The coefficient 37.08 10^3 is used to convert the units to mm day^{-1}. This model has been developed and tested in semi-arid climates, i.e. when the transpiration is primarily regulated by the evaporative demand of the atmosphere rather than by solar radiation only.

Example 9.6 An intensive olive orchard at an altitude of 100 m a.s.l. intercepts 52 % of the incident daily radiation. Let's calculate its transpiration on a sunny day with daily total solar radiation of 27.6 MJ m^2 day^{-1} and average VPD of 2.8 kPa. Assume an atmospheric pressure of 101 kPa.

Using Eq. 9.24 with the coefficients of Table 9.1 for olive (a = 1211 μE mol^{-1} and b = 1447 μE mol^{-1}kPa^{-1}),

$$E_p = 37.08\ 10^3 \frac{0.52 \cdot 27.6 \quad \cdot 2.8}{(1211 + 1447 \cdot 2.8) \cdot 100.1} = 2.83 \ \text{mm} \ \text{day}^{-1}$$

9.6 Evaporation from Wetted Canopies

When the plant is wet (for example, immediately after a rainfall event) the water film and droplets covering the foliage will eventually evaporate directly into the atmosphere. Note that this evaporation flux is neither transpiration nor evaporation from the soil, although the water involved is still coming from the rain or irrigation: it should then be evaluated and considered as part of the evapotranspiration flux (see Eq. 9.1) to correctly assess the evaporation component of the water budget.

Although the direct evaporation flux from wetted canopies is often overlooked, it may be appreciable when frequent rains wet dense canopies with high LAI, which can intercept a significant amount of rain. The maximum capacity of rainfall interception by agricultural species with full ground cover is around 0.25 mm per unit of LAI, i.e. a wheat canopy with LAI = 4 can intercepted 1 mm of rain. Another issue is when mechanically moved sprinkler irrigation systems (center pivots) irrigate very frequently and a significant part of the application is intercepted by a full canopy before it infiltrates in the soil. In all cases, the direct evaporation is the

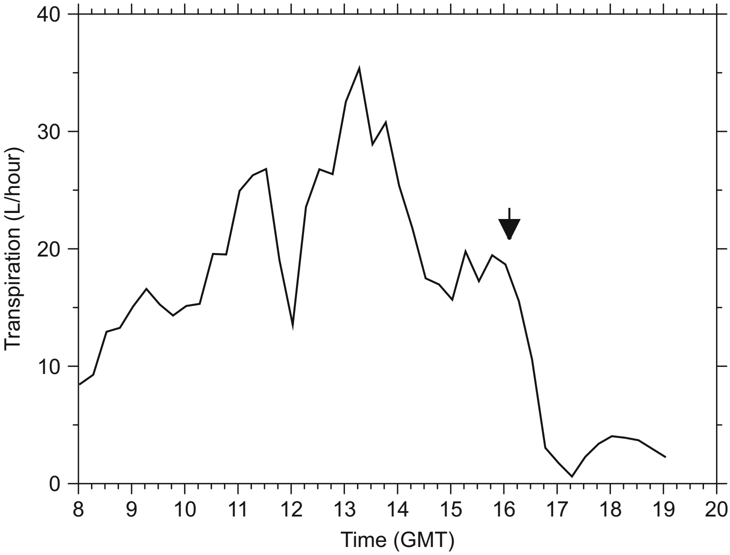

Fig. 9.3 Time course of transpiration of a walnut tree in Cordoba (Spain) on June 5, 2009. Rain started at 16:20 (*vertical arrow*) and lasted 1 h

main process to be evaluated in order to assess the canopy wetness duration after a rainfall. This knowledge is important because the time interval that a canopy stays wet is strongly related with the chances of infection by many fungal diseases; furthermore, during that interval the transpiration rate is nil (see Fig. 9.3), so no water is actually extracted from the soil by the roots with the associated reduction in soil water and nutrient uptake. To calculate the evaporation of wet canopies, the Penman-Monteith equation may be used assuming zero canopy resistance.

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Chapter 10
Calculation of Evapotranspiration and Crop Water Requirements

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Abstract Reference ET (ET_0) is defined as the ET of short grass with full soil cover, and an unlimited supply of water and nutrients. In the absence of water deficit, the ET of any crop may be calculated as the product K_c x ET_0, where K_c is the crop coefficient, which depends on crop related factors (leaf area, roughness) and ET_0, the reference ET (grass), which is a function of climatic variables (radiation, temperature, humidity and wind speed). The main equation for calculating ET_0 is the Penman-Monteith-FAO, although the Hargreaves equation can be used when only air temperature data are available. K_c is calculated by the method proposed by FAO which uses linear functions between the initial, maximum and harvest dates of the cycle. The initial K_c depends on the frequency of soil wetting and ET_0. The maximum values of K_c of annual crops and deciduous fruit trees are typically between 1.0 and 1.3 (median 1.2). The crop irrigation water requirement is the difference between ET and the effective rainfall, although the role of stored soil water as a contributor to meeting the ET demand may be important in some situations to reduce the dimensions (and investment) of the irrigation network.

10.1 Introduction

The ET in the absence of water stress is usually calculated as the product:

$$ET = K_c \, ET_0 \tag{10.1}$$

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where K_c is a crop coefficient, which depends on factors related to the crop (leaf area, roughness, crop management) and ET_0 is the reference ET, by definition, the ET of a well-irrigated short grass surface, which is ideally only a function of climatic variables (radiation, temperature, humidity and wind speed). This expression is always valid unless water stress reduces ET, which generally occurs when 65–80 % of the extractable soil water is depleted. Below this value the K_c decreases linearly to 0 when it reaches the Permanent Wilting Point (Fig. 9.1).

The usual method of calculating crop ET is to calculate ET_0 based on meteorological data and apply a variable K_c that changes with crop development stage. Numerous methods have been proposed for estimating ET_0 (e.g. Penman-FAO) or the K_c (e.g. FAO) which will be discussed below.

10.2 Reference ET

Reference ET (ET_0) is defined as the ET of short (8–15 cm height) grass with full soil cover, and a good supply of water and nutrients. The concept of ET_0 came to replace the term "potential ET" used widely in the past but lacking a precise definition.

In some areas, networks of automatic weather stations provide daily information via Internet which usually would allow applying combination formulas based on the Penman-Monteith equation. However, in many world areas there is a dearth of agrometeorological data which limits the use of the most precise methods.

If only maximum and minimum temperature data are available the equation of Hargreaves (see 10.2.1) provides a good approximation in many areas. In some cases evaporation pans are available on the farm and provide another estimate of ET_0, as shown in Appendix 10.1.

The annual time course of ET_0 follows a pattern similar to that of solar radiation. As an example, Fig. 10.1 shows the daily ET_0 calculated by the Penman-Monteith equation in Santaella (southern Spain, semi-arid Mediterranean climate), typical of mid-latitudes. The mean values range from 1 mm/day during the winter to 7 mm/day during the summer. The average annual total ET_0 is 1278 mm.

10.2.1 Method of Hargreaves

In 1985 Hargreaves and Samani proposed a simple equation for estimating ET_0 (in mm/day):

$$ET_0 = 5.5210^{-3} K_{RS} R_A (T_{avg} + 17.8)\sqrt{T_{max} - T_{min}} \tag{10.2}$$

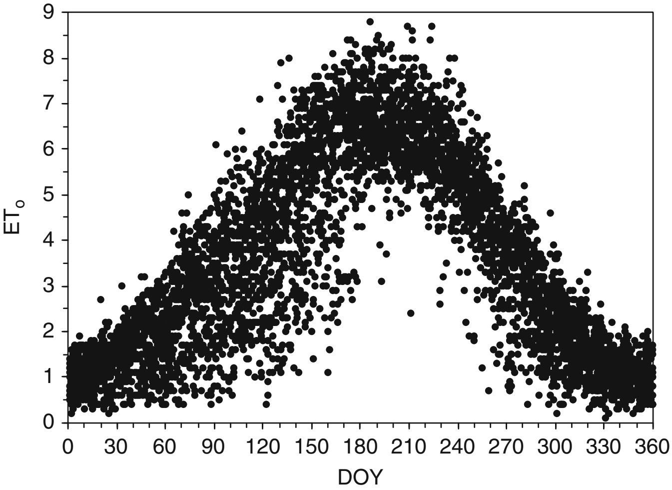


Fig. 10.1 Annual time course of reference ET calculated using the method of Penman-Monteith-FAO for Santaella (Spain) from 2000 to 2013

where R_A is extraterrestrial radiation (MJ m^{-2} day^{-1}), and T_{avg}, T_{max} and T_{min} are the average, maximum and minimum air temperatures (°C), respectively, while K_{RS} is another coefficient already defined in Chap. 3 on solar radiation (Eq. 3.7). Usually, the values of K_{RS} vary between 0.16 and 0.19 for interior and coastal locations, respectively. This equation has shown good performance for different areas despite being based only on measured air temperature. This is because it includes a term associated with the potential radiation of the location, by considering the extraterrestrial radiation and a variable related to the degree of cloudiness (the amplitude of air temperature). Thus, in very cloudy days there is little heating during the day (low solar radiation) and little cooling during the night (clouds reduce long wave radiation loss). Therefore the maximum and minimum temperatures will not differ much. By contrast, in clear days the greater warming during the day and the increased cooling at night lead to a greater difference between the maximum and minimum temperatures. The Hargreaves method may be less reliable when applied in areas with little daily temperature oscillation or where the temperature amplitude is influenced by factors not related to solar radiation, e.g. the presence of massive water bodies (coastal regions).

10.2.2 Penman-Monteith-FAO Method

This equation has become the standard for ET_0 calculation as proposed by FAO. Applying the Penman-Monteith equation (Eq. 9.16) to a hypothetical grass canopy of height 0.12 m and canopy resistance 69 s m^{-1} we can deduce the ET_0 (mm day^{-1}) for 24-h periods as:

$$ET_0 = \frac{\Delta R_n + 0.5\ VPD \cdot U_2}{2.45[\Delta + 0.067(1 + 0.33U_2)]} \tag{10.3}$$

where Δ (kPa K^{-1}) is the slope of the saturation vapor pressure function versus temperature (Eq. 9.13), R_n is the net radiation (MJ m^{-2} day^{-1}), VPD is vapor pressure deficit (kPa) and U_2 is wind speed at 2-m height (m s^{-1}).

The value of Δ (kPa K^{-1}) can be calculated as:

$$\Delta = \frac{4098 e_s}{[237.3 + T]^2} \tag{10.4}$$

where T is air temperature (°C) and e_s is the saturation vapor pressure (kPa) which is a function of temperature (Eq. 5.2).

10.3 Crop Coefficients

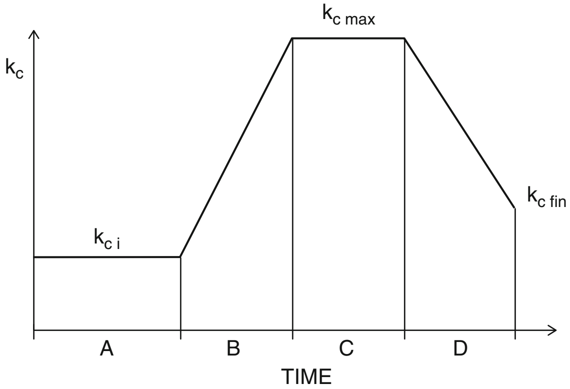
The crop coefficient is a parameter that reflects the specific features of the crop as they affect ET, such as leaf area, height, fraction of ground cover, etc. Its value is determined experimentally as:

$$K_c = \frac{ET}{ET_0} \tag{10.5}$$

In irrigated crops K_c depends primarily on the fraction of ground cover, and, if the latter is low, it depends on the water content of the soil surface as it determines the rate of soil evaporation (see 9.3). Thus, when the crop has not emerged yet, the K_c of a bare dry soil may be as low as 0.1, but if the soil surface is wet, the K_c increases to values close to 1. When the crop completely covers the ground, the K_c becomes almost independent of the water content of the soil surface, and usually exceeds 1 (1.05–1.30), with a typical value of 1.20.

In some cases the latent heat flux exceeds the net radiation, that is, an amount of sensible heat is used to evaporate water. This phenomenon typically occurs due to the movement of masses of hot, dry air from dry areas surrounding a wet area where water is available for evaporation (oasis effect). We may distinguish the clothesline effect when advection occurs at the field level, and is characterized by sensible heat input decreasing from the edge of the plot inwards. At a smaller scale (micro-advection) there is a sensible heat flux transported from dry soil to the surrounding plants. In the event that an isolated irrigated field is surrounded by dry land (fallow, stubble, dry crops) the clothesline effect provides additional energy for ET so that the crop coefficient may be much greater than the values indicated previously. This

Fig. 10.2 Crop coefficient curve for an annual crop according to the FAO approach. The duration of the four phases is 40, 30, 30 and 30 days, respectively



enhancement will be greater for small plots with tall plants, but there is no reliable model to quantify exactly the K_c in these situations. Some authors suggest that the extreme value of K_c for isolated irrigated plots may be as high as 2.5, but this value should be considered a hypothetical limit that is reached only under infrequent extreme conditions and for a limited time.

The K_c is not constant during the season but changes with the ground cover, the plant height, the soil surface wetting and plant aging. The most widespread method for estimating the value of the crop coefficient at any time of the growing season is the one proposed by FAO (Doorenbos and Pruitt 1977). This method represents the K_c curve as a set of straight lines. To define the curve it is necessary to know in advance the length of phases A, B, C and D, and the value of K_c at three points (K_{c1}, K_{c2} and K_{c3}). The initial phase (A) ends when the crop reaches 20 % of ground cover, while the rapid growth phase (B) ends when ground cover is 70–80 %, which usually corresponds to values of Leaf Area Index around 2.5–3.0. Figure 10.2 shows an example of a curve of K_c for annual crops in which the phase durations are 40, 30, 30 and 30 days, and the crop coefficients which define the curve are 0.3, 1.2 and 0.5. Table 10.1 shows the values of K_{c2} (maximum) and K_{c3} (final) for a number of crops and Appendix 10.3 presents a more complete list.

Although the methodology proposed by FAO allows fitting the crop coefficient to specific climatic conditions, in Table 10.1 we show the intervals of K_c that we believe may hold for temperate areas. Moreover, Table 10.1 also shows indicative values of the phase durations for different species. These durations should be taken merely as examples, since the actual duration depends on many factors (climate zone, cultivar, date of sowing or bud burst in tree crops, climatic conditions of the year, etc.). The main driving factor for changes in the duration of crop stages is temperature, which may change from year to year or if sowing date is changed. For actual irrigation scheduling, the K_c curve should always be obtained using on-season information on the phases (beginning and duration) obtained from empirical observations in the field.

The K_c in the initial phase (K_{c1}) is a function of the frequency of rain and irrigation and ET_0 during that period because most of the ET of a crop during this

Table 10.1 Durations of phases of growth cycle (FAO method) and crop coefficients in phase C (mid) and at harvest (end) for different crop species

Crop species	Date of start of crop cycle (N hemisphere)	Stage duration (days)				Kc mid	Kc end
		A	B	C	D		
Alfalfa (hay)	Mar–Oct[a]	5	10–20	10	5–10	0.9–1.15[b]	0.90
Barley	Nov–Mar	20–40	25–30	40–65	20–40	1.15	0.2–0.4
Bean (phaseolus) (dry seed)	May–Jun	15–25	25–30	30–40	20	1.15	0.30
Citrus (70 % CC)*	Jan	60	90	120	95	0.65	0.75
Coffee						0.95	0.95
Cotton	Mar–May; Sept	30–45	50–90	45–60	45–55	1.15–1.25	0.4–0.7
Grapes (table or raisins)	Mar–May	20	40–50	75–120	20–60	0.85	0.45
Grapes (wine)	April	30	60	40	80	0.70	0.45
Lettuce	Nov–April	20–35	30–50	15–45	10	1.00–1.05	0.95
Maize (grain)	Mar–Jun	20–30	35–50	40–60	30–50	1.20	0.35–0.6
Millet	Apr–Jun	15–20	25–30	40–55	25–35	1.00	0.30
Olives (60 % CC)*	Mar	30	90	60	95	0.70	0.70
Palm trees						1.00	1.00
Peas (dry harv.)	Mar–May	15–35	25–30	30–35	30	1.15	0.30
Pome fruits, cherries (60–70 % CC)*	Mar	20–30	50–70	90–130	30–60	1.10	0.75
Potato	Nov–Jan; Apr–May	25–45	30–35	40–70	20–30	1.15–1.25	0.7–0.8
Rapeseed, Canola	Nov–Dec	25–40	35–40	60–70	30–35	1.10	0.35
Rice	May (Medit.); May–Dec (tropics)	30	30	60–80	30–40	1.20	0.9–0.6
Sorghum (grain)	Apr–Jun	20	35	40–45	30	1.00–1.10	0.55
Soybean	May–Jun; Dec (tropics)	15–20	15–35	40–75	15–30	1.15	0.50

Stone fruits (60–70 % CC)*	Mar	21–30	51–70	91–130	31–60	1.10	0.65
Sugar beet	Nov–June	25–50	30–75	50–100	10–65	1.20	0.70
Sugar cane (ratoon)		25–35	70–105	135–210	50–70	1.25	0.75
Sugar cane (virgin)		35–75	60–105	190–330	120–210	1.25	0.75
Sunflower	Feb–May	25–45	35–40	45–60	25	1.20	0.35–0.5
Tea						1.00	1.00
Tomato	Jan–May	30–35	40–45	40–70	25–30	1.15–1.25[c]	0.7–0.9
Wheat (winter)	Oct–Dec	20–30	60–140	40–70	30	1.15	0.25–0.4

Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). For some crops the final Kc shows a wide interval, as its value depends on crop use (fresh or dry). This Table should be used with caution as the actual duration of phases may change for different regions, cultivars and weather conditions of each year

*When cover crop or weeds are present add 0.2 to the crop coefficient. If canopy cover (CC) is lower than the value indicated in the table (CC′) then $K_c = 0.15 + CC\,(K_c' - 0.15)/CC'$ where K_c' is the value shown

[a] For the first cut cycle use durations twice the values shown

[b] Lower value is the seasonal average; higher value is at full cover-before cutting

[c] When cultivated on stalks, the Kc mid should be increased by 0.05–0.1

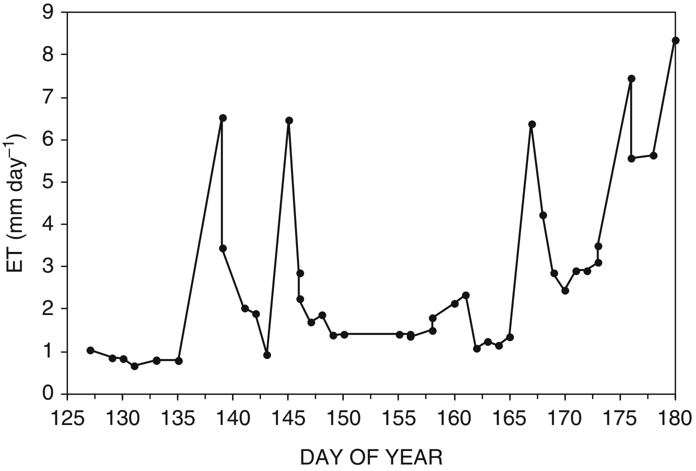


Fig. 10.3 Evapotranspiration of a cotton crop in Cordoba (Spain) for stages A and B. Inter-row tillage was performed on DOY 156 which caused an increase in soil evaporation

phase is direct evaporation from the soil surface. Bare soil evaporation is approximately equal to the ET_0 while the soil surface is wet (energy-limited or first stage evaporation, see Sect. 9.3). As the soil dries the soil hydraulic conductivity decreases (soil limited or second stage). The importance of E_s in determining the initial K_c is manifested in significant variations of ET in the early stages of the crop cycle associated with the occurrence of rainfall or irrigation (Fig. 10.3). Doorenbos and Pruitt (1977) proposed a method of calculating the K_c in the initial development stage (until the onset of rapid crop growth, K_{c1}) which was summarized in the following equations by Allen et al. (1998):

For WI <4 days:

$$K_{c1} = (1.286 - 0.27\ \ln WI) exp[(-0.01 - 0.042 \ln WI) ET_{01}] \tag{10.6a}$$

For WI >4 days:

$$K_{c1} = \frac{2}{(WI)^{0.49}}\ exp[(-0.02 - 0.04 \ln WI) ET_{01}] \tag{10.6b}$$

where WI is the interval between irrigations or rainfall events during the initial stage and ET_{01} is the average ET_0 during the initial stage (mm/day). If we consider the effect of rainfall major errors may arise if we assume that rainy days are evenly distributed over the period (Villalobos and Fereres 1989. Transactions of ASAE, 32 (1):181–188.), thus a correction should be applied to calculate the interval between rainfall events (see Example 9.4). It is important to calculate the initial K_c accurately because errors in the initial K_c translate into errors in K_c during the rapid growth period (phase B) as this is determined by interpolation between the values of K_{c1} and K_{c2}.

If real time information on ground cover fraction (f_{GC}) is available we can assign values of K_c by considering the proportionality between them. In arid and semiarid areas:

$$K_c = K_{c1} + f_{GC} \frac{K_{c2} - K_{c1}}{f_{GC2}} \tag{10.7}$$

where f_{GC2} is the ground cover fraction associated to K_{c2} ($f_{GC2} = 1$ for full cover crops).

The method described above for calculating crop coefficients is valid for well-watered plants, and would thus be valid for irrigated crops or for periods in rainfed crops where water does not limit ET. For rainfed or deficit irrigated conditions the crop reduces its transpiration as soil water is depleted below a threshold (water stress). Consequently, the K_c is reduced. A very simple model for estimating the K_c as a function of soil water would be:

$$K_c = K_c^* \frac{3(\theta - \theta_{PWP})}{(\theta_{FC} - \theta_{PWP})} \tag{10.8}$$

where K_c^* is the crop coefficient with no water stress and θ is the average volumetric soil water content. This equation is valid for θ lower than θ_{PWP} + $(\theta_{FC} - \theta_{PWP})/3$. If θ is higher, then the K_c is not reduced, which implies that crops can use around two third of extractable water without having a reduction in ET.

10.4 Crop Coefficients of Perennial Species

Forage crops and pastures have a variable K_c depending on management (cutting frequency, maximum LAI). For instance alfalfa has an average seasonal K_c close to 1, oscillating between 0.6 after cutting then increasing to 1.2 before the next cut.

For fruit trees evaporation from the soil may play an important role throughout the cycle depending on the fraction of the soil which is exposed to solar radiation. Where the tree canopies are small, the Kc will be higher during periods with high rainfall frequency. The contribution of tree transpiration is proportional to ground cover and will be nil during the winter season in deciduous fruit trees, contrary to evergreen fruit trees (olive, citrus) that keep their leaf area during the whole year. In these evergreen species under mild Mediterranean climates, the K_c could be maximum in winter (high soil evaporation due to high frequency of rain) and minimum during summer (low soil evaporation, high stomatal resistance in response to high VPD) (Fig. 10.4).

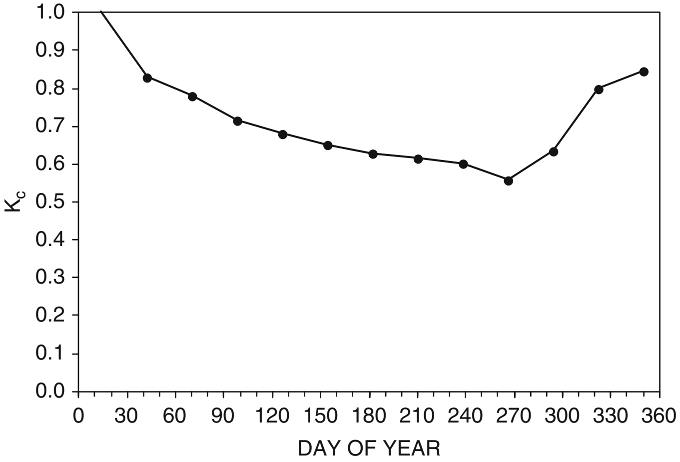


Fig. 10.4 Average crop coefficient for an olive orchard with 40 % ground cover in Cordoba (Spain) in 2001 and 2002. The data have been grouped in 4-week periods

10.5 Evapotranspiration in Greenhouses

The evapotranspiration inside greenhouses is usually lower than in the open field because the shelter cover reduces the incoming radiation, the driving force of ET and turbulence. Specific methods have been developed to evaluate the ET of screened or sheltered crops. In sophisticated greenhouses such as those used for production of high-value crops or for ornamental horticulture, with climatic control (heating/cooling, supplemental light, etc.) data from sensors are available for using complex transpiration models in short time steps (e.g. 10-min). Furthermore, intelligent use of sensors may provide indirect estimates of greenhouse ET. For instance, measurements of air flow into the greenhouse (Q_{in}, $m^3\ s^{-1}$) along with sensors of temperature and air vapor pressure in air going in (T_{in}, e_{in}) and out (T_{out}, e_{out}) allow calculating ET of a greenhouse (mm/h) of surface area A_g (m^2) as:

$$ET = \frac{Q_{in}}{A_g}\frac{3600}{0.4615}\left(\frac{e_{out}}{T_{out}} - \frac{e_{in}}{T_{in}}\right) \tag{10.9}$$

where temperatures are given in K and vapor pressures in kPa.

A different case is that of unheated greenhouses with passive ventilation, typically with plastic covers, such as those in the Mediterranean coast of Almeria (Spain) and other mild climate areas. The conditions inside the greenhouse are characterized by reduced turbulence, higher humidity and higher temperature that the outside. This in theory leads to equilibrium ET (see Eq. 9.17), i.e. ET is governed by radiation, a situation which has been confirmed empirically leading to an equation for reference evapotranspiration (ET_0, mm day^{-1}) of the form:

$$ET_0 = \frac{1}{2.45} 0.7 \frac{\Delta}{\Delta + \gamma} R_{si} \tag{10.10}$$

where R_{si} (MJ m^{-2} day^{-1}) is the solar radiation inside the greenhouse, which can also be estimated from the solar radiation measured in the open if the transmissivity of the cover (τ_{gc}) is known ($R_{si} = \tau_{gc}$ R_s). For instance, transmissivity of polyethylene film of 0.2 mm is around 0.7.

Once the reference ET is known inside the greenhouse, calculation of ET requires a crop coefficient, which is usually somewhat higher (10–20 %) than that of crops grown outside. For instance, measurements of K_c values of greenhouse tomatoes have reached 1.4 while those in open fields seldom exceed 1.2.

10.6 Calculation of Maximum ET for Designing Irrigation Systems

The ET of a given crop in a location can vary from year to year depending on weather conditions. To design irrigation systems it would be desirable to have historical series of ET (and precipitation) to determine the water requirements at different levels of probability. Often we only have the average values of crop ET, which obviously will be exceeded in some years. Doorenbos and Pruitt (1977) proposed an adjustment method for calculating the ET which corresponds to a probability level of 75 % (ET_{75}, which will be exceeded only 25 % of the years) as a function of the average ET (ET_{avg}) and the mean irrigation applied (I_a). The method is shown in Fig. 10.5, where four different climate types are considered. Each line can be calculated as:

$$\frac{ET_{75}}{ET_{avg}} = C - 0.06\,(C - 1)\,\sqrt{I_a} \tag{10.11}$$

where the mean irrigation applied is given in mm and the coefficient C is 1.21, 1.49, 1.33 and 1.43, for types 1, 2, 3 and 4, respectively.

Note that, ideally, the system should be designed to supply the peak or maximum ET level corresponding to the period of highest ET of the crop mix of the farm rotation or of the irrigated area. The decision to determine the size of the irrigation network is basically economic, as reducing the flow rate below the maximum requirements of the extreme year and highest demanding crop of the rotation will require less capital investment but will increase the risks of crop water deficits in some years. Also, if the system is dimensioned for annual crops of low requirements

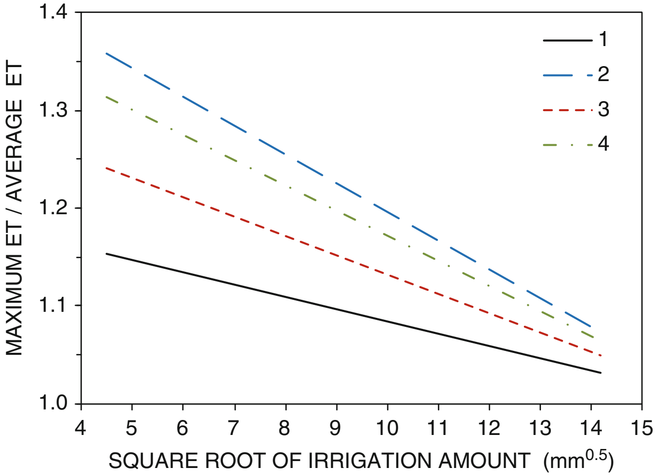


Fig. 10.5 Ratio of 75 % probability ET and average ET as a function of the square root of mean irrigation applied in each irrigation event. Four climate types are considered. (1) Arid and semi-arid with clear skies during summer. (2) Continental climates in mid latitudes and sub-humid climates with variable cloudiness. (3) Mid latitude continental climates with ET up to 5 mm/day. (4) Mid latitude continental climates with ET up to 10 mm/day

(for example, winter cereals), its conversion to summer crops or perennials is not possible without leaving some of the land unirrigated.

Example 10.1 We will calculate the ET of maize during August ($K_c = 1.2$) in Evora, Portugal ($ET_0 = 7.0$ mm/day) and Paris, France ($ET_0 = 4.0$ mm/day) for 75 % probability assuming that irrigation doses of 60 mm are applied.

We calculate the average ET for both locations:

$$\text{Evora. ET} = 1.2 \times 7.0 = 8.4 \text{ mm day}^{-1}$$
$$\text{Paris. ET} = 1.2 \times 4.0 = 4.8 \text{ mm day}^{-1}$$

Evora has a semiarid climate so it corresponds to type 1 (Fig. 10.5). Paris has a subhumid climate during summer (type 2). Applying Eq. 10.11 for Evora (C = 1.21):

$$\frac{ET_{75}}{ET_{avg}} = 1.21 - 0.06\,(1.21 - 1)\,\sqrt{60} = \ 1.11$$

For Paris C = 1.49 so:

(continued)

Example 10.1 (continued)

$$\frac{ET_{75}}{ET_{avg}} = 1.49 - 0.06\,(1.49 - 1)\,\sqrt{60} = \ 1.26$$

Therefore the values of ET_{75} for the two locations will be:

Evora: $ET_{75} = 1.10 \times 8.4 = 9.2$ mm/day
Paris: $ET_{75} = 1.26 \times 4.8 = 6.0$ mm/day

10.7 Calculation of Crop Water Requirements

Crop irrigation water requirement is the amount of water to be supplied to maintain a maximum level of ET, and can be calculated invoking water balance (Chap. 8) as the difference between the ET (the potential value, without restrictions of any kind) and water supplied by rainfall or extracted from the soil during a given period of time:

$$IWR_n = \ ET \ - \ P_e - \ (-\Delta TSWC) = \ ET \ - \ P_e \ + \ \Delta TSWC \tag{10.12}$$

Note that the extraction of water from the soil is expressed as increase in the total soil water content with a negative sign. In this equation P_e is effective precipitation, i.e. precipitation not lost by runoff or deep percolation (see Chap. 8).

We can distinguish between net and gross water requirement. In the first case we refer to the amount of water required assuming no losses during irrigation and perfect uniformity in the spatial distribution of irrigation water. In almost all cases these assumptions are not met and we are forced to apply more water than the actual crop water consumption (Chap. 19). The total amount to apply including excess water is the gross irrigation water requirement (GIWR = net requirement/application efficiency).

The calculation of IWR may be performed for different time intervals (weeks, months) and for different spatial scales (field, farm, irrigation scheme). The first step is always computing IWR of each field and then obtaining the weighted average using the fractions of area as weights.

The term related to soil water storage is frequently omitted in the calculations which may lead to large overestimations of IWR in some cases. The soil water stored at sowing depends on the recharge during the fallow period since the harvest of the previous crop. This can be calculated by adding effective precipitation and discounting soil evaporation (Eq. 9.6) during fallow. This value should not exceed the soil water storage capacity (Chap. 8). Stored soil water is seen in irrigated agriculture as an insurance against irrigation system failures and extremely high ET periods, thus keeping a moderately high level of soil water stored during much of the irrigation season reduces risks. However, by the end of the season soil water content may be nearly depleted, thus it is possible to use a large fraction of stored soil water (e.g. 80–90 %) which should be discounted from the requirements of the final period (see Chap. 20 on irrigation scheduling).

After calculating IWR for each crop of the farm we calculate the average farm IWR as:

$$IWR_{farm} = \sum_{1}^{n} IWR_i \cdot s_i \tag{10.13}$$

where n is the number of crops, and IWR_i and s_i are irrigation water requirement and fraction of farm area of crop i, respectively.

Appendix 10.1: Class A Evaporation Pan

A relatively simple way to obtain ET_0 is to empirically observe the evaporation from a free water surface in a standardized device and then apply some empirical relationships to convert the direct evaporation of water to that of a grass surface. This method became quite popular in the past because it does not require meteorological measurements taken in expensive weather stations, thus is affordable for farmers even in undeveloped countries. However, the corrections to apply depend also on the micrometeorology of the place where the device is installed.

The most popular model of these devices is the standard National Weather Service Class A type evaporation pan which has a diameter of 1.21 m and height 0.254 m.

It is normally installed on a wooden platform set on the ground. The pan is filled with water to within 6 cm of the top and exposed to represent an open body of water. The evaporation rate is measured as the difference in water level between consecutive measurements.

Then, reference ET may be calculated as:

$$ET_0 = K_p E_{pan} \tag{A10.1.1}$$

where E_{pan} is the measured pan evaporation (mm/day) and K_p is the pan coefficient which is in the range 0.35–0.85 with an average value of 0.75. The actual value will depend on the surroundings of the pan, on relative humidity and on wind speed. According to FAO manual 24, if the pan is surrounded by crops, the pan coefficient for the class A may be calculated as:

$$\begin{aligned} K_p = {} & 0.108 - 0.0286\,U + 0.0422\ln(X) + 0.1434\ln(RH) \\ & - 0.000631\,[\ln(X)]^2\ln(RH) \end{aligned} \tag{A10.1.2}$$

where U is wind speed (m/s) at 2-m height, X is the distance (m) covered with crops around the pan and RH is mean relative humidity.

If the pan is located on a dry location (bare soil, stubble) the pan coefficient is calculated as:

$$K_p = 0.61 + RH\,(0.00341 - 0.000162\,U) + U\,\left[0.00327\ln(X) - 9.59\;10^{-6}\,X\right] + [4.459 + \ln(U)]\left[-0.0106\ln(X) + 0.00063\,[\ln(X)]^2 - 0.00289\,U\right] \tag{A10.1.3}$$

A simpler formula may be applied to both cases:

$$K_p = 0.85\,exp\left(-0.15\,\frac{2.45\;\cdot Epan}{R_n}\right) \tag{A10.1.4}$$

where R_n is calculated net radiation (MJ m^{-2} day^{-1}).

Appendix 10.2: Calculating Crop Coefficients Following the Model of Ritchie's

As a crop grows, intercepted radiation increases and so does energy available for transpiration. At the same time energy available for evaporation at the soil surface decreases. In 1972 Professor Joe T. Ritchie proposed a model for calculating the ET of crops by computing separately transpiration and evaporation from the soil surface (Ritchie 1972). Using this model the K_c may be calculated as a function of ground cover and soil wetting frequency.

Model results are summarized in Eq. A10.2.1 where K_c is a function of ET_0, the interval between rain events or irrigations (WI) and the fraction of ground covered by the crop (f_{GC}). The lower values of K_c logically occur when WI is large and the ET_0 is high, if f_{GC} is very small. In contrast when f_{GC} is high K_c varies little with ET_0 and WI.

$$K_c = 0.14 + 1.08 f_{gc} + \frac{13.3 - 5.2 f_{gc}}{WI\;ET_0} \tag{A10.2.1}$$

Example A10.1 A garlic crop in March has a ground cover of 0.3. The last rain occurred 7 days ago. Since then, the average ET_0 has been 3.5 mm/day. Let's calculate the K_c during that period.

$$K_c = 0.14 + 1.08 \times 0.3 + \frac{13.3 - 5.2 \times 0.3}{7 \times 3.5} = 0.14 + 0.32 + 0.48$$
$$= 0.94$$

Appendix 10.3: Crop Coefficients, Root Depth and Factor for Allowable Depletion

Crop coefficients in phase C (mid) and at harvest (end) for different crop species. Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). For some crops the final Kc shows a wide interval, as its value depends on crop use (fresh or dry). Values of maximum crop height, maximum root depth and a coefficient for calculating allowable depletion (Chapter 20) are also shown

Crop species					
Cereals and pseudocereals	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Barley	1.15	0.2–0.4	1	1.0–1.5	0.09
Maize (grain) (field corn)	1.2	0.35–0.60	2	1.0–1.7	0.09
Maize, sweet (sweet corn)	1.15	1.0–1.05	1.5	0.8–1.2	0.10
Millet	1	0.3	1.5	1.0–2.0	0.09
Oats	1.15	0.2–0.4	1	1.0–1.5	0.09
Rice	1.2	0.90–0.60	1	0.5–1.0	0.16
Rye	1.15	0.2–0.4	1	0.9–2.3	0.08
Sorghum (grain)	1.00–1.10	0.55	1.0–2.0	1.0–2.0	0.09
Sorghum (sweet)	1.1–1.2	1.05	2.0–4.0	1.0–2.0	0.10
Wheat (spring)	1.15	0.25–0.4	1	1.0–1.5	0.09
Wheat (winter)	1.15	0.25–0.4	1	1.5–1.8	0.09
Forages	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Alfalfa Hay	0.9–1.15[a]	0.9	0.7	1.0–2.0	0.09
Bermuda hay	1	0.85	0.35	1.0–1.5	0.09
Bermuda (spring crop for seed)	0.9	0.65	0.4	1.0–1.5	0.08
Clover hay, berseem	0.9	0.85	0.6	0.6–0.9	0.10
Rye grass hay	1.05	1	0.3	0.6–1.0	0.08
Sudan grass hay (annual)	0.9	0.85	1.2	1.0–1.5	0.09

(continued)

Crop species					
Pasture (rotated grazing)	0.85–1.05	0.85	0.15–0.30	0.5–1.5	0.08
Pasture (extensive grazing)	0.75	0.75	0.1	0.5–1.5	0.08
Turf grass (cool season)	0.95	0.95	0.1	0.5–1.0	0.12
Turf grass (warm season)	0.85	0.85	0.1	0.5–1.0	0.10
Fruit trees, trees and shrubs	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Almonds (70 % CC)*	1.1–1.2	0.65	5	1.0–2.0	0.12
Apple (60–70 % CC)*	1.1	0.75	4	1.0–2.0	0.10
Apricot (60–70 % CC)*	1.1	0.65	3	1.0–2.0	0.10
Avocado (70 % CC)*	0.85	0.75	3	0.5–1.0	0.06
Banana (year 1)	1.1	1	3	0.5–0.9	0.13
Banana (year 2)	1.2	1.1	4	0.5–0.9	0.13
Berries (bushes)	1.05	0.5	1.5	0.6–1.2	0.10
Cacao	1.05	1.05	3	0.7–1.0	0.14
Citrus (70 % CC)*	0.65	0.75	3.0–4.0	1.0–1.5	0.10
Cherry (60–70 % CC)*	1.1	0.75	4	1.0–2.0	0.10
Coffee	0.95	0.95	2.0–3.0	0.9–1.5	0.12
Conifers	0.9–1	0.9–1	10	1.0–1.5	0.06
Grapevine (table or raisin)	0.85	0.45	2	1.0–2.0	0.13
Grapevine (wine)	0.7	0.45	1.5–2	1.0–2.0	0.11
Kiwi	1.05	1.05	3	0.7–1.3	0.13
Olives (60 % CC)*	0.7	0.7	5–7	1.2–1.7	0.07
Palm (date)	0.95	0.95	8	1.5–2.5	0.10
Palm tres	1	1	8	0.7–1.1	0.07
Peach (60–70 % CC)*	1.1	0.65	3	1.0–2.0	0.10
Pear (60–70 % CC)*	1.1	0.75	4	1.0–2.0	0.10
Pineapple	0.3	0.3	0.6–1.2	0.3–0.6	0.10
Pistachio (60–70 % CC)*	1.1	0.45	3–6	1.0–1.5	0.12
Plum (60–70 % CC)*	1.1	0.65	3	1.0–2.0	0.10
Rubber trees	1	1	10	1.0–1.5	0.12
Tea (non-shaded)	1	1	1.5	0.9–1.5	0.12
Tea (shaded)	1.15	1.15	2	0.9–1.5	0.11
Walnut (70 % CC)*	1.1	0.65	4–5	1.7–2.4	0.10
Horticultural crops	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Artichokes	1	0.95	0.7	0.6–0.9	0.11
Asparagus	1	0.3	0.2–0.8	1.2–1.8	0.11
Bean (green)	1.1	0.95	1.5	0.5–0.7	0.11
Beet (table)	1.1	0.95	0.2	0.6–1.0	0.10

(continued)

Crop species					
Broccoli	1.05	0.95	0.3	0.4–0.6	0.11
Brussel sprouts	1.05	0.95	0.4	0.4–0.6	0.11
Cabbage	1–1.1	0.9–1	0.4	0.5–0.8	0.11
Carrots	1.05	0.95	0.3	0.5–1.0	0.13
Cauliflower	1.05	0.95	0.4	0.4–0.7	0.11
Celery	1.05	1	0.6	0.3–0.5	0.16
Cucumber	1	0.75–0.9	0.3	0.7–1.2	0.10
Egg plant	1.05	0.9	0.8	0.7–1.2	0.11
Fababean (fresh)	1.1	0.9		0.5–0.7	0.11
Lettuce	1–1.05	0.95	0.3	0.3–0.5	0.14
Melon	1.05–1.1	0.7–0.75	0.4	0.8–1.5	0.12
Melon (cantaloupe)	0.85	0.6	0.3	0.9–1.5	0.11
Mint	1.15	1.1	0.6–0.8	0.4–0.8	0.12
Peas (fresh)	1.2	1	0.7	0.6–1.0	0.13
Pepper	1.05–1.15	0.70–0.90	0.7	0.5–1.0	0.14
Pumpkin, winter squash	1	0.8	0.4	1.0–1.5	0.13
Radish	0.9	0.85	0.3	0.3–0.5	0.14
Spinach	1	0.95	0.3	0.3–0.5	0.16
Squash, zucchini	0.95–1.0	0.75–0.9	0.3	0.6–1.0	0.10
Strawberries	0.85	0.75	0.2	0.2–0.3	0.16
Tomato	1.15–1.25[b]	0.70–0.90	0.6	0.7–1.5	0.12
Watermelon	1	0.75	0.4	0.8–1.5	0.12
Legumes	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Beans (Phaseolus)	1.1–1.25	0.3–0.9	0.4	0.6–0.9	0.11
Beans (lima)	1.1	0.5	0.5	0.8–1.2	0.11
Chick pea	1	0.35	0.4	0.6–1.0	0.10
Fababean (broad bean)	1.15–1.25	0.3–1.1	0.8	0.5–0.7	0.11
Green gram and cowpeas	1.05	0.3–0.6	0.4	0.6–1.0	0.11
Groundnut (peanut)	1.15	0.6	0.4	0.5–1.0	0.10
Lentil	1.1–1.2	0.3–0.5	0.5	0.6–0.8	0.10
Peas	1.15	0.3–1.1	0.5	0.6–1.0	0.12
Soybeans	1.15–1.25	0.5	0.5–1.0	0.6–1.3	0.10
Roots, tubers and bulbs	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Cassava (year 1)	0.8	0.3	1	0.5–0.8	0.13
Cassava (year 2)	1.1	0.5	1.5	0.7–1.0	0.12
Garlic	1–1.2	0.7–1.05	0.5	0.3–0.5	0.14
Onions	1–1.1	0.75–1	0.3–0.5	0.5–0.8	0.14
Parsnip	1.05	0.95	0.4	0.5–1.0	0.12
Potato	1.15–1.25	0.70–0.80	0.6	0.4–0.6	0.13
Sugar beet	1.2	0.7	0.5	0.7–1.2	0.09

(continued)

Crop species					
Sweet potato	1.15	0.65	0.4	1.0–1.5	0.10
Turnip (and Rutabaga)	1.1	0.95	0.6	0.5–1.0	0.10
Sugar, oil and fiber crops	**Kc mid**	**Kc end**	**Max. crop height (m)**	**Max. root depth (m)**	**F_{AD}**
Cotton	1.15–1.25	0.4–0.7	1.2–1.5	1.0–1.7	0.07
Castorbean (Ricinus)	1.15	0.55	0.3	1.0–2.0	0.10
Flax	1.1	0.25	1.2	1.0–1.5	0.10
Hops	1.05	0.85	5	1.2	0.10
Rapeseed, canola	1.1	0.35	0.6	1.0–1.5	0.08
Safflower	1.1	0.25	0.8	1.0–2.0	0.08
Sesame	1.1	0.25	1	1.0–1.5	0.08
Sisal	0.4–0.7	0.4–0.7	1.5	0.5–1.0	0.04
Sugar cane	1.25	0.75	3	1.2–2.0	0.07
Sunflower	1.2	0.35–0.5	2	0.8–1.5	0.11
Tobacco	1.15	0.8	1.5–2.0	0.8	0.10

[a] Lower value is the seasonal average; higher value is at full cover-before cutting

[b] When cultivated on stalks, the Kc mid should be increased by 0.05–0.1

*When cover crop or weeds are present add 0.2 to the crop coefficient. If canopy cover (CC) is lower than the value indicated in the table (CC′) then $K_c = 0.15 + CC\ (K_c{}' - 0.15)/CC'$ where $K_c{}'$ is the value shown.

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Part II
Crop Productivity

Chapter 11
Crop Development and Growth

Victor O. Sadras, Francisco J. Villalobos, and Elias Fereres

Abstract Growth of crops, plants or plant parts is defined as the irreversible increase in size whereas development is the continuous change in plant form and function with characteristic transition phases. Growth is primarily associated with capture and allocation of resources whereas development is mostly related to non-resource environmental cues such as temperature, photoperiod and light quality. We separate development and growth conceptually, but both types of processes are closely linked. Thermal time and variations of thermal time corrected to account for photoperiod and vernalization are useful to model crop phenological development. Crop development, in particular the time of flowering, is one of the most important traits for crop adaptation. Breeders, agronomists and growers understand the importance of matching the pattern of phenological development to their particular environments, and use a combination of genetic and agronomic tools to manipulate development. Crop growth depends on the capacity of the canopy to capture CO_2 and radiation, the capacity of the root system to capture water and nutrients from soil, and the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into dry matter. Stresses such as water deficits or soil compaction reduce growth by reducing the amount of resources captured by the crop, by reducing the efficiency in the use of resources or both.

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11.1 Introduction

Growth of crops, plants or plant parts is defined as the irreversible increase in size whereas development is the continuous change in plant form and function with characteristic transition phases. The expansion of a leaf or the accumulation of crop biomass are typically growth processes whereas the transition from a vegetative meristem, producing leaves, to a reproductive meristem producing flowers is a characteristic developmental process. We distinguish morphological development (e.g. appearance of successive structures in the plant) from phenological or phasic development which deals with the duration of the different phases of the crop cycle.

The distinction between growth and development is important for two reasons. First, growth is primarily associated with capture and allocation of resources whereas development is mostly related to non-resource environmental clues such as temperature, photoperiod and light quality. Second, the physiological processes involved are different, as discussed in this chapter. Whereas we separate growth and development conceptually, organs, plants and crops grow and develop simultaneously, and for many agronomically important traits the limits between growth and development are blurred. For example, a wheat grain grows, i.e. it expands in volume and gains mass, and also develops, e.g. leaf and root primordia are differentiated in the embryo. Developmental biology (Box 11.1) and crop growth analysis are thus distinct perspectives underpinning the investigation of development and growth. In this chapter, we outline agronomically important aspects of these processes.

Box 11.1 Developmental Biology

The fundamental question of developmental biology is this: how do different cellular phenotypes emerge from cells which share a common set of genes? A typical flowering plant has 30 different cell types, whereas a typical vertebrate has about 120 cell types. All this diversity has to be explained in terms of differential gene expression, as the 30 or so cell types in a plant share the same genome – genetically, the cells of the wheat root endodermis and the mesophyll cells in the flag leaf of the same plant are essentially identical. Likewise, your neurons and liver cells are genetically identical, but their shape and physiology are obviously different. For readers interested in this question, we recommend the book of Mary Jane West-Eberhard: Developmental plasticity and evolution (Oxford University Press, 2003).

Some examples demonstrate the practical implications of understanding the process of cell differentiation. Stem cells, which are undifferentiated cells with potential to generate any cell type, present animal and human health with potential opportunities for new therapies. Short time between generations is one of the cornerstones of successful plant breeding programs. Making use of advanced knowledge of cell differentiation and tissue culture, breeders can

(continued)

Box 11.1 (continued)

currently grow up to six generations of chickpeas in a single year. Likewise, tissue culture exploiting the principles of cell differentiation is a rapid, effective and cheap method to generate virus-free seedlings of high value in horticulture.

11.2 Phenological Development

Scales have been devised to characterise phenological development in annual and perennial crops. They are based on the concept of pheno-stage; major pheno-stages in annual crops include

1. Sowing
2. Germination
3. Emergence
4. Juvenile Phase/Initiation of leaves
5. Floral initiation (formation of primordia of reproductive structures)
6. Flowering
7. Physiological maturity
8. Harvest maturity

The case of perennial species is more complex. Trees stay in juvenile phase, thus not flowering, for several years after seed germination. However, most trees of agricultural interest are not propagated by seeds but vegetatively from cuttings that are rooted in nurseries. In this case the cutting may not be juvenile which reduces the time until flowering. In some tree species, the growth of the main stem beyond a certain length accelerates the end of the juvenile period. Once the juvenile phase is over, the tree will follow annual cycles that resemble those of an annual plant, following two possible strategies:

(a) Deciduous species: Most fruit trees and vines belong to this category. All the leaves fall in autumn-winter in response to cold temperatures and/or short photoperiod. Buds stay dormant during winter and usually require low temperatures for an extended period (chilling requirement) until they respond to warm temperature and bud break occurs. After that vegetative and reproductive growth will occur with a degree of overlap that depends on the species. For instance, flowering may occur before leaf growth starts (stone fruits, e.g. peach) or later (pome fruits e.g. apple), while harvest may occur in early to midsummer (several months before leaf fall, e.g. cherry) or in late summer or start of autumn (e.g. apple).

(b) Evergreen species: They include citrus spp., olive and tropical fruit trees (e.g. mango). Leaves stay in the tree for long periods (2–3 years). In some cases (e.g. olive) the tree stay dormant (no vegetative growth) during winter and resume growth in the spring.

The period between two phenostages constitutes a phenophase; we can be interested, for example, in the phase sowing-emergence or emergence-flowering. Some of these phases are well-defined biologically, for example the phase between floral initiation and flowering. Other phases are not defined biologically but with agronomic criteria; for example the phase from physiological maturity, when grain reaches its maximum dry matter, to harvest maturity, when grains reach a moisture content suitable for mechanical harvest. Harvest maturity of wine grapes is defined by oenological criteria, including sugar concentration and acidity, and complementary traits such as colour and aromas. Sugar:acid ratio is an important trait for the decision of harvest in most fruit crops.

The duration of the cycle of different crops is shown in Appendix 11.1.

All phenophases are responsive to temperature, which is the main environmental influence on development (Box 11.2). The phase sowing-emergence can also be influenced by the content of water and oxygen in the soil. In some species, photoperiod also affects the duration of some phenophases. Some species and phases are also responsive to low temperature in a process called vernalisation. Here we outline the effects of mean temperature, low temperature (vernalisation) and photoperiod on phenological development.

Box 11.2. Phenology and Global Warming

Phenological shifts are the most conspicuous biological signal of global warming. Using a systematic phenological network data set of more than 125,000 observational series of 542 plant and 19 animal species in 21 -European countries between 1971 and 2000, it was found that 78 % of all leafing, flowering and fruiting records advanced (30 % significantly) and 3 % were significantly delayed.

The consequences of warming for agriculture are many fold and varied. At high latitudes, warming is extending the window for cropping, with overall positive implications for crop production. In China and USA, milder winters are allowing for earlier crop sowing, which combined with new varieties and practices is improving crop production. Climate projections and modelling indicate that Finland's crop productivity by 2050 would be close to the current productivity in Denmark. In 2000, the EU has accepted Denmark as a wine producing country, and the Association of Danish Winegrowers now counts more than 1400 members. In temperate environments like the Pampas, warming over the last few decades has shortened the season of wheat crops, allowing for early sowing and higher yield of soybean in wheat/soybean double cropping. In temperate and subtropical environments, warming is shortening the season of crops, with potential for yield reduction in the absence of adaptive practices. Increasing frequency and incidence of heat

(continued)

Box 11.2 (continued)

waves may reduce both yield and quality of crops. Thus, the outcomes of warming are complex and varied, particularly when warming interacts with changes in rainfall, but a good deal of crop responses to warming are related to phenological changes.

Another interesting consequence of warming is the decoupling of processes, from ecosystems to molecules. In the last five decades, the productivity of Northern Sea fisheries has declined. The main reason is that warming has "decoupled" the phenology of the components of the trophic web. This means that for example, predators and preys which were phenologically synchronized before are now out of phase, with direct consequences for the structure and function of the whole ecosystem. In red grapevine varieties, warming is decoupling sugars and anthocyanins. This means that fruit reaches sugar maturity with less pigmentation; growers have therefore two choices. They can wait longer to harvest, hence allowing for color to develop; this leads to undesirably high sugar and alcohol concentration. Or they can harvest at the right sugar level, and deal with lack of color in the winery. The process of decoupling is therefore an agronomically important aspect of warming, which is related to developmental and growth processes.

11.2.1 Effects of Daily Mean Temperature

Figure 11.1 shows the relationship between the daily rate of phenological development (R, unit: day^{-1}) and daily mean temperature (T, unit: °C). The daily rate of development is the inverse of the duration of the phenophase (D, unit: day); for example if it takes 10 days to complete the phase sowing-emergence, the daily rate of development is 0.1 day^{-1}. The rate of development increases linearly with temperature between the base (T_b) and optimum temperature (T_o), and decreases between the optimum and maximum temperature (T_m) for development. These

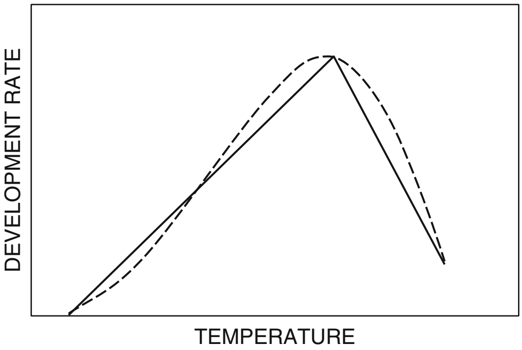

Fig. 11.1 Responses of development rate to temperature. The *dashed line* represents the actual response while the *solid line* is a linear approximation

three parameters, T_b, T_o, and T_m constitute the “cardinal” temperatures for development, and depend on the species and phenological phase.

The daily rate of development is assumed to be zero (i.e. the plant does not develop) if the mean temperature is below T_b or above T_m. The concept of "thermal time" (also called degree days or heat units) is useful to predict the duration of a phase for different temperatures. Thermal time (TT, unit: °Cd) is defined as the sum of daily mean temperature (T, °C), above the base temperature, from the beginning to the end of the phase; for example for the phase sowing-emergence:

$$\mathrm{TT} = \sum\nolimits_{sowing}^{emergence} (\mathrm{T} - T_b) \tag{11.1}$$

and the daily rate of development when the daily mean temperature is between T_b and T_o is

$$\mathrm{R} = 1/\mathrm{D} = (\mathrm{T} - \mathrm{T_b})/\mathrm{TT} \tag{11.2a}$$

The duration of a phase can thus be calculated if we know the daily mean temperature, the base temperature and the thermal time required to complete the phase:

$$\mathrm{D} = \mathrm{TT}/(\mathrm{T} - \mathrm{T_b}) \tag{11.2b}$$

Table 16.1 in Chap. 16 shows T_b and TT for the phase sowing-emergence for a number of crops. With adequate supply of water and oxygen, the thermal time required to complete the phase is approximately constant. Thus, we can predict that wheat will take approximately 11 days to emerge at mean temperature of 10 °C [$\mathrm{D} = 110/(10 - 0)$] and 7 days if mean temperature is 15 °C [$\mathrm{D} = 110/(15 - 0)$].

Base temperatures have physiological and ecological meaning, as they reflect differences between species and stages, and contribute to the coupling of organisms in trophic webs. For example, the base temperature for the sowing-emergence phase is much lower for winter crops than for spring-sown crops (Table 16.1). Base temperatures normally decline from early to late stages in summer crops, e.g. for sunflower and soybean, and increase from early to late stages in winter crops such as wheat. The thermal time model applies not only to plants but also to other organisms including insects which are – like plants – unable to regulate body temperature. The base temperature for the emergence of bollworms after overwintering in the soil is very close to the base temperature for the sowing-emergence phase of cotton; this coincidence of base temperatures ensures that a new generation of bollworm emerges in synchrony with a suitable food source.

The thermal time model (Eq. 11.2a, 11.2b) is a simplification of a more complex response of development to temperature, as it rests on the assumption of a linear relationship between the rate of development and temperature. However, above the optimum temperature, the rate of development declines with increasing temperature, until a maximum temperature (T_m) is reached (Fig. 11.1). For some phenostages, particularly those related with reproduction, development is also responsive to vernalisation and photoperiod. In these cases, the thermal time required to complete the phase is not constant, but influenced by low temperatures and day length.

11.2.2 Vernalisation and Photoperiod

Annual crops have specific windows of development when grain number, the main yield component, is most affected by environmental stresses such as frost, heat and water stress (Fig. 11.2). These windows vary, but are more or less centered on flowering in most crops. For this reason, mechanisms have evolved that reduce the probability of coincidence of extreme stress and the most sensitive developmental stages. These mechanisms are based on two environmental cues: vernalisation and photoperiod. Flowering time is indeed one of the most important traits for crop adaptation to particular environments in agricultural systems. Consider for example wheat in a Mediterranean region. If it flowers too early, a significant frost risk would reduce seed production in a number of seasons. If it flowers too late, frost risk is reduced at the expense of increased risk of heat and water stress. Early wheat varieties introduced to Australia reached flowering at 125 days after sowing, hence exposing the sensitive reproductive window to high frequency of heat and water stress. Recognising this problem, breeders selected for shorter season varieties, which were better adapted to their environments. Where compared under the same conditions, the time from sowing to anthesis was 119 for cultivars released earlier than 1950 and 108 for cultivars developed later. Rainfed sunflower in southern Spain grows on stored soil water that is depleted during the growing season. In these

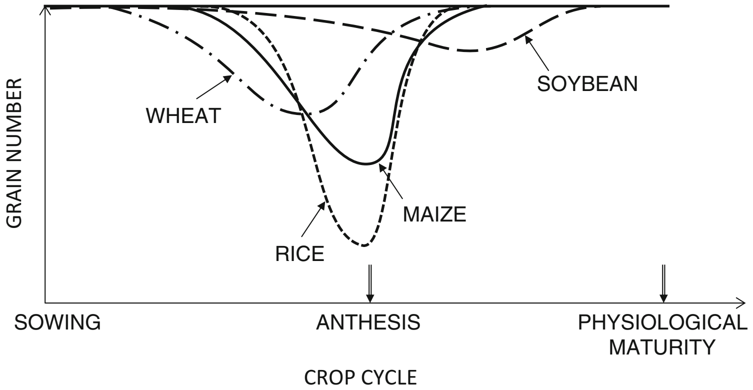

Fig. 11.2 Critical period for grain number determination, the main yield component of annual crops. Grain number is presented in an arbitrary scale where the *vertical line* represents 100 %, of the grain number in unstressed controls. Deviations from this line represent reductions due to stress in different periods of the crop cycle (Source: Calviño and Monzon (2014) in Sadras and Calderini and Hsiao TC 1982. In: Drought resistance of crops with emphasis on rice. IRRI, Los Baños, Manila, Philippines. p 39–52)

environments, hybrids with very long cycle may deplete soil water reserves during a long vegetative stage thus suffering a stronger water deficit during grain filling than short-cycle hybrids. To manipulate the timing of key phenological events, plant breeders make use of fundamental genetic understanding including the manipulation of vernalisation and photoperiod genes in selecting varieties adapted to particular environments. To manipulate the timing of key phenological events, growers combine two practices: cultivar selection and sowing date.

Vernalisation is a response to low temperatures necessary for some plants to become competent for the transition to the reproductive phase. The plant apex may sense vernalising temperatures from seed imbibition, throughout the vegetative phase. Vernalisation requirements are characteristic of temperate crops such as wheat, barley, Brassicas and field pea. In many of these species, 'winter' types require vernalisation whereas, 'spring' types have little or no vernalisation requirements. For instance, for winter wheat, temperatures between 0 and 8 °C are the most effective, although vernalisation happens with temperatures up to 15 °C. Vernalisation may be reversed by high temperatures (usually >20 °C), in a process known as 'devernalization'. In some species, vernalization combines with photoperiod to modulate time of flowering.

Vernalization is also important in horticultural crops. In biennial plants such as sugar beet and carrot, vernalisation modulates the development of flower buds in the second year of growth. In proteranthous perennials (i.e. those that flower before leafing) vernalisation modulates flowering time. In horticulture, the vernalisation requirement is also known as "chilling hours", which is the time below a species-specific base temperature. Understanding vernalisation requirements is important to determine the geographical limits and risks of growing particular crops. Apple trees for example, have a high vernalisation requirement, hence they cannot be grown successfully in warm-winter environments where these requirements are not met. Almond trees have a relatively low vernalisation requirement, and this implies the risk of early flowering with subsequent yield losses due to frost. Breeders have selected horticultural perennials with a broad range of vernalisation requirements to extend their cropping areas and reduce risks of crop failure.

Virtually in all plant species photoperiod sensitive genotypes can be found, or rather, genotypes sensitive to the duration of the night. Gardner and Allard classified annual species into two categories: long-day plants and short-day plants. The short-day plants accelerate their development (shorten the time to flowering) when the days are short, while long-day plants develop faster if the days are long.

Small grains (wheat, barley, oats and rye) are long-day species, while maize, rice, sorghum and soybeans are short-day species. However, within each species there is often a great variability in sensitivity to photoperiod. In general photoperiod response is quantitative, i.e. development rate increases or decreases with the photoperiod but never becomes zero, which would be a qualitative response. By manipulating photoperiod genes in soybean, varieties have been developed that can be grown between high latitudes in the northern hemisphere to the tropics; a classification system of maturity types, with 00 the shortest (90 days) and VIII the longest season (190 days) shows the wide range of phenological patterns in soybean.

11.3 Morphological Development

The architecture of the plant is under genetic control, and is modulated by environmental factors including temperature, photoperiod, and light-quality. Agronomically, the architecture of the crop is important because it influences traits such as lodging, harvestability, competition with weeds, responses to herbivory and distribution of light and chemicals in the canopy profile. The introduction of semi-dwarf genes in rice and wheat has lead to significant improvements in crop production, and part of the success of these semi-dwarf crops is related to their improved architecture, which allows for higher nutrient inputs with reduced lodging risk. The node where the first pod is set is an important trait of grain legumes, as genotypes with pods too close to the ground cannot be harvested effectively.

Plants have numerous meristems (buds) which can follow one of three fates: they can remain dormant, they can activate to produce vegetative structures, or they can become reproductive structures. Different species combine different strategies of meristem allocation, and these strategies involve trade-offs. For example, the adaptation of grasses to browsing, and their exploitation in agriculture, is directly related to their underground, dormant meristems that allow re-growth after grazing. Plants with profuse branching or tillering are more able to fill gaps originated, for example, from failures in sowing or damage by pests or diseases. As an example of trade-off, strong apical dominance, whereby most lateral buds are dormant, favours growth in height, competition for light, and capacity to recover after herbivory, at the expense of limited capacity for growth and reproduction, and constrains to expand into neighbouring gaps.

Interactions between neighbouring plants influence the morphology of individual plants, and the final architecture of the crop. Part of these interactions are mediated by the ability of plants to sense changes in the quantity, quality and direction of light, which in turn trigger developmental responses called photomorphogenesis. The main groups of photoreceptors involved in plant photomorphogenesis are the red (R)/far-red (FR) light-absorbing phytochromes and the blue/UV-A light-absorbing cryptochromes and phototropins. As the green tissue of plants differentially reflects and absorbs light of different wavelengths, plants are able to detect the presence of neighbours by detecting changes in the spectral composition of light, and in particular, reductions in the R/FR ratio. Typically, a shade-avoidant plant responds to neighbours by extending internodes, increasing stem:leaf ratio, reducing activation of lateral buds, producing more erect shoots and in some cases advancing the time of flowering. In some weeds, germination can be triggered by changes in the R/FR ratio associated with soil cultivation. Light signals interacting with the central circadian oscillator, enable plants to monitor photoperiod and adjust the timing of the transition from vegetative to reproductive development (Sect. 11.2.2).

The successive appearance of plant leaves is an important component of morphological development. In general, the thermal time between the appearance of two consecutive leaves, known as phyllochron, is constant. For example, wheat has a phyllochron around 100 °C d with a base temperature of 0 °C. In sunflower the phyllochron is around 20 °C d with a base temperature of 4 °C.

11.4 Growth

Box 11.3 outlines the methods used to quantify crop growth. Crop growth depends on the capacity of the canopy to capture CO_2 and radiation, the capacity of the root system to capture water and nutrients from soil, and the efficiency of the crop to transform resources (water, nutrients, radiation, carbon dioxide) into biomass (Fig. 11.3). The right half in Fig. 11.3 highlight how environmental factors, such as ambient temperature or soil salinity, modulate the rate of capture of resources and the efficiency in the transformation of resources in plant biomass. Other chapters deal in detail with the capture and efficiency in the use of radiation (Chap. 13), water (Chap. 14) and nutrients (Chaps. 24, 25, and 26).

The capture and efficiency in the use of resources changes with the stage of phenological development. The growth of a typical annual crop is characterised with a sigmoid curve (Fig. 11.4) with three phases. First, in a lag-phase, plants grow slowly, as they mostly depend on seed reserves, whereas small root and canopy systems constrain their capacity to capture resources. Many practices (e.g. sowing date, fertiliser) seek to reduce the duration of this lag-phase, also known as "period lost to growth". Second, the growth increases rapidly to reach a linear phase when sufficiently large canopy and root system allow for a high capacity to capture resources. Third, crop growth slows down as both canopy and root systems age, entering a senescence phase in parallel to the accumulation of carbon and nitrogen in reproductive organs. The senescence of leaves and roots is genetically driven in a

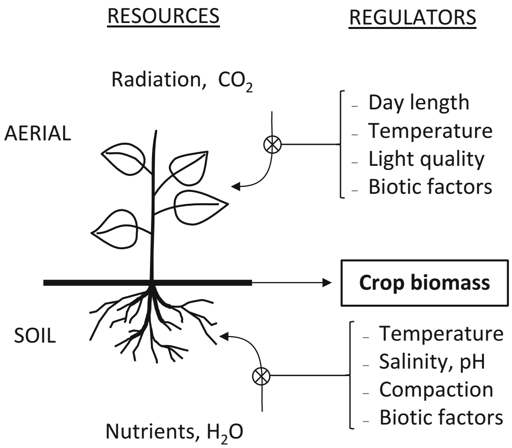

Fig. 11.3 Crop growth depends on the ability of crops to capture above-ground and soil resources, and on the capacity of crops to transform these resources into biomass (Adapted from Sadras and McDonald 2012)

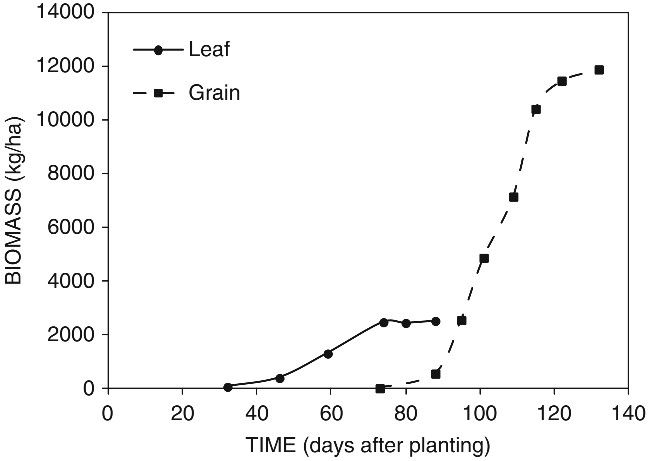

Fig. 11.4 Time course of biomass of leaves and grain of a maize crop in Florida (Data taken from DSSAT 4.6, experiment UFGA8201MZ)

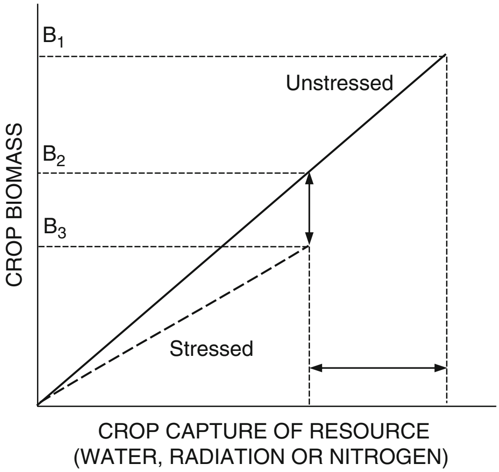

Fig. 11.5 Crop biomass increases with increasing capture of resources, primarily water, radiation and nitrogen. Maximum crop biomass is shown as B_1. Stress reduces crop growth by reducing capture of resources (*horizontal arrow*) resulting in B_2, reducing production per unit resource (*vertical arrow*) or both, which leads to B_3

process known as monocarpic senescence, whereas stresses such as shortage of water or nutrients may accelerate the process.

Figure 11.5 illustrates the relationship between crop growth and capture of resources in crops with favorable and stressful conditions. As the season progresses and roots and canopies expand, the crop captures more soil and above-ground resources. A straight line represents increasing growth with increasing resource capture. Stresses such as deficit of nutrients or soil compaction reduce growth through two processes: reducing the amount of resources captured by the crop (horizontal arrow in Fig. 11.5, and b) reducing the efficiency in the use of resources.

The vertical arrow in Fig. 11.5 indicates the reduction in growth for the same amount of resource captured; this means lower efficiency.

In general shortage of resources (water or nutrient deficits) and soil constraints (compaction, salinity) reduce crop growth by reducing capture of resources, rather than affecting the efficiency in the use of resources.

Ambient temperature influences growth directly, by changing the rate of processes such as cell division, leaf expansion and crop photosynthesis, and indirectly by affecting phenological development and the duration of key phenophases, as discussed before. Within agronomically sensible ranges, the main effect of temperature on crop production is related to the modulation of phenological development. In temperate environments, late sowing shifts the crop cycle to warmer conditions, development proceeds faster, the period available to capture resources and growth is reduced, and biomass at maturity is normally lower. Figure 11.6 illustrates the interplay between development and growth in faba bean crops sown between October (autumn) and early May (spring) in Lugo, Spain. As the sowing is delayed, both temperature and photoperiod increase. This shortens the phenophases of the crop, resulting in a reduction of crop cycle from 209 to 87 days. With shorter cycle duration, the peak leaf area is reduced, the amount of radiation captured by the crop is reduced and the final production of biomass is also reduced. Hence, the effects of temperature and photoperiod on development (cycle length) have a dominant role in seasonal growth. Of interest, the first sowing date does not conform to this pattern. For the earliest sowing, the crop has the longest cycle duration and the highest capture of radiation as expected; therefore it should also have the highest biomass. However, it has the lowest biomass. The explanation is that the extremely

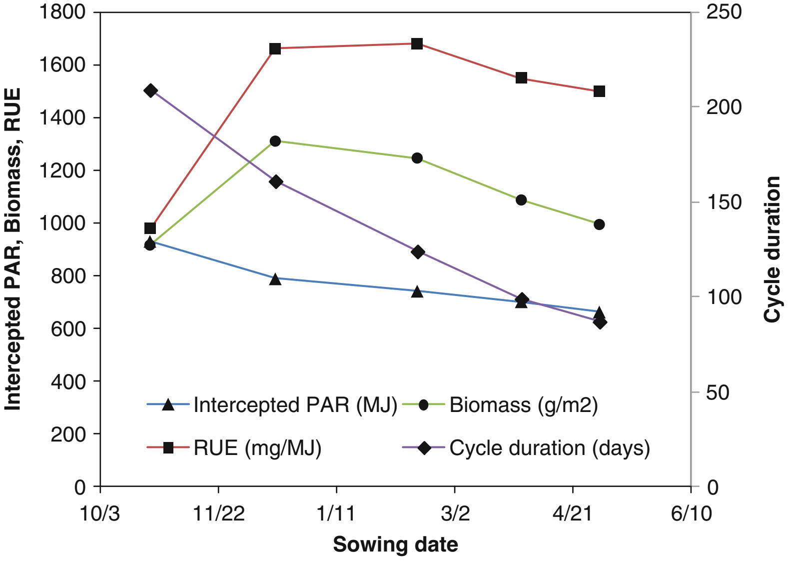

Fig. 11.6 Effect of sowing date on crop duration (time sowing maturity), intercepted PAR, RUE and biomass production of Vicia faba (Adapted from Confalone et al. (2010) Field Crops Res 115, 140–148)

low temperature in the earliest sowing reduced the photosynthetic efficiency of the crop. In this case, the physiological response (photosynthesis) was stronger than the developmental response.

Box 11.3 Quantification of Crop Growth

Depending on the objectives of measurements, we could be interested in describing growth in terms of crop height, leaf surface area, fruit volume, or grain mass. As crop growth depends on capture of resources, and this is in turn related to the size of the canopy and root system, we often use the leaf area index (LAI, m^2 leaf/m^2 ground) to measure the size of the canopy and the rooting depth and density characterized as Root Length Density (L_v, m root/m^3 soil) to quantify the size of the root system. LAI is the ratio of leaf area (assuming single-sided leaves) and ground area, and L_v is the length of roots per unit of soil volume. For many agronomic applications, shoot mass is measured by taking crop samples (e.g. 1 m^2 of crop cut to ground level), which are dried to constant weight to express the dry matter in g/m^2 or kg/ha; this measure of dry matter is also called biomass. Periodic sampling of biomass combined with periodic measurements of radiation interception, nutrient uptake and evapotranspiration allows calculating the efficiency in the use of radiation, nutrients and water as illustrated in Fig. 11.5.

Indirect methods are also used for quantifying biomass or LAI. For trees empirical relationships between biomass and trunk diameter have been widely used. Transmittance of PAR or reflectance of radiation in different wavelengths (e.g. red and far red) (see Chap. 3) may be related to LAI and are the base of most indirect methods for non-destructive measurement of LAI.

Appendix 11.1

Durations of phases of growth cycle (FAO method) for different crop species and climatic areas. A: sowing to 20 % ground cover, B: 20 % to 80 % ground cover, C: 80 % ground cover to start of leaf senescence, D: start of senescence to harvest

			Duration of crop stage (days)				
Crop species	Climate	Sowing date	A	B	C	D	Total
Horticultural crops							
Artichoke (year 1)	M	April	40	40	250	30	360
Artichoke (year 2)	M	May	20	25	250	30	325
Asparagus	M-warm winter	Feb	50	30	100	50	230
Asparagus	M	Feb	90	30	200	45	365
Beets (table)	M	Apr/May	15	25	20	10	70

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Broccoli	A	Sept	35	45	40	15	135
Brussel sprouts	M	Feb/April	20–25	30–35	20–25	10	80–95
Cabbage	A, M	Sept	40	60	50	15	165
Cabagge	M	Feb/April	20–25	30–35	20–25	10	80–95
Melon (Cantaloupe)	M-warm winter	Jan	30	45	35	10	120
Melon (Cantaloupe)	M	Aug	10	60	25	25	120
Carrots	A	Oct/Jan	20	30	40	20	110
Carrots	M	Feb/Mar	30	40	60	20	150
Carrots	A	Oct	30	50	90	30	200
Cauliflower	A	Sept	35	50	40	15	140
Celery	SA	Oct/Jan	25–30	40–55	95–105	20	180–210
Celery	M	April	25	40	45	15	125
Cucumber	A	May–August	20	30	40	15	105
Cucumber	A-warm winter	Nov/Feb	25	35	50	20	130
Egg plant	A	October	30	40	40	20	130
Egg plant	M	May/June	30	45	40	25	40
Lettuce	M	April	20	30	15	10	75
Lettuce	M	Nov/Jan	30	40	25	10	105
Lettuce	A	Oct/Nov	25	35	30	10	100
Lettuce	M	Feb	35	50	45	10	140
Melon	M	March/May	25–30	30–35	40–50	20–30	120–140
Melon	A	Aug	15	40	65	15	135
Melon	A	Dec/Jan	30	45	65	20	160
Onion (dry harvest)	M	April	15	25	70	40	150
Onion (dry harvest)	A	Oct/Jan	20	35	110	45	210
Onion (green harvest)	M	April/May	25	30	10	5	70
Onion (green harvest)	A	October	20	45	20	10	95
Pepper	T & M	April/June	30	35	40	20	125
Pepper	A	October	30	40	110	30	210
Pumpkin, Winter squash	M	Mar, Aug	20	30	30	20	100
Pumpkin, Winter squash	T	June	25	35	35	25	120
Radish	M, T	Mar/Apr	5	10	15	5	35
Radish	A	Winter	10	10	15	5	40
Spinach	M	Apr; Sep/Oct	20	20	20	5	65
Spinach	A	November	20	30	40	10	100

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Squash, Zucchini	M, A	Apr; Dec.	25	35	25	15	100
Squash, Zucchini	M,T	May/June	20	30	25	15	90
Tomato	A	January	25–30	40	40–70	30	135–155
Tomato	M	Apr/May	35	40	50	30	155
Tomato	A	Oct/Nov	35	45	70	30	180
Water melon	M	April	20	30	30	30	110
Water melon	A	May/Aug	10	20	20	30	80
Roots, tubers and bulbs							
Cassava (year 1)	T	Rainy season	20	40	90	60	210
Cassava (year 2)	T		150	40	110	60	360
Potato	SA	Jan/Nov	25	30	40	30	125
Potato	C	April/May	25–30	30–35	45–50	30	130–145
Potato	C	Apr/May	45	30	70	20	165
Potato	A	Dec	30	35	50	25	140
Sweet potato	M	April	20	30	60	40	150
Sweet potato	T	Rainy seas.	15	30	50	30	125
Sugarbeet	M	March/April	25–30	35–45	50–80	20–50	160–180
Sugarbeet	M	Oct/Nov	45	75	80	30	230
Sugarbeet	A	Sept/Nov	25–35	60–65	70–100	40–65	205–255
Sugarbeet	C	April	50	40	50	40	180
Legumes							
Beans (Phaseoulus) (green)	M	Feb/Mar	20	30	30	10	90
Beans (Phaseoulus) (green)	M, A	Aug/Sep	15	25	25	10	75
Beans (Phaseoulus) (dry seed)	C	May/June	20–25	25–30	30–40	20	100–110
Beans (Phaseoulus) (dry seed)	M	June	15	25	35	20	95
Faba bean, broad bean (green)	C, M	Mar/May	15–20	25–30	35	15	90–100
Faba bean, broad bean (green)	C, M	Oct	90	45	40	0	175
Faba bean, broad bean (dry seed)	C, M	Nov	90	45	40	60	235
Green gram, cowpeas	M	March	20	30	30	20	110
Groundnut (peanut)	T	Dry season	25	35	45	25	130
Groundnut (peanut)	C, high latitude	Spring	35	35	35	35	140

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Groundnut (peanut)	M	May/June	35	45	35	25	140
Lentil	C	April	20	30	60	40	150
Lentil	A	Oct/Nov	25	35	70	40	170
Peas	C	May	15	25	35	15	90
Peas	C, M	Nov, Mar–Apr	20–35	25–30	30–35	15–20	100–110
Soybeans	T	Dec	15	15	40	15	85
Soybeans	C, high latitude	May	20	25–35	60–75	25–30	140–150
Sugar, oil and fiber crops							
Castor beans	SA	March	25	40	65	50	180
Castor beans	T	Nov.	20	40	50	25	135
Cotton	M, A	Mar–May (M), Sept. (A)	30	50	50–65	45–55	180–195
Cotton	A	Mar	45	90	45	45	225
Flax	C	April	25	35	50	40	150
Flax	A	October	30	40	100	50	220
Hops	C	April	25	40	80	10	155
Safflower	M, A, SA	March/April	20–25	35	45–55	25–40	125–145
Safflower	A	Oct/Nov	35	55	60	40	190
Sesame	C	June	20	30	40	20	100
Sugarcane, virgin	T, low latitude		35	60	190	120	405
Sugarcane, virgin	T		50	70	220	140	480
Sugarcane, virgin	Pacific		75	105	330	210	720
Sugarcane, ratoon	T, low latitude		25	70	135	50	280
Sugarcane, ratoon	T		30	50	180	60	320
Sugarcane, ratoon	Pacific		35	105	210	70	420
Sunflower	M	April/May	25	35	45	25	130
Sunflower	M warm winter	Feb	45	40	60	25	170
Cereals and pseudocereals							
Barley, oats, wheat (spring types)	Central India	November	15	25	50	30	120
Barley, oats, wheat (spring types)	Mid latitude	March/Apr	20–40	25–30	40–60	20–30	130–135
Barley, oats, wheat (spring types)	East Africa	July	15	30	65	40	150

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Barley, oats, wheat (spring types)	C	Nov	40	60	60	40	200
Barley, oats, wheat (spring types)	M	Dec	20	50	60	30	160
Winter wheat	M warm winter	December	20	60	70	30	180
Winter wheat	M	November	30	140	40	30	240
Winter wheat	C	October	160	75	75	25	335
Grains (small)	M	March–April	20	30	60	40	150
Grains (small)	A	Oct/Nov	25	35	65	40	165
Maize (grain)	A	Dec/Jan	25	40	45	30	140
Maize (grain)	T	June	20	35	40	30	125
Maize (grain)	C (dry, cool)	October	20	35	40	30	125
Maize (grain)	M, C	March–April	30	40	50	30–50	150–170
Maize (sweet)	T	March	20	20	30	10	80
Maize (sweet)	M	May/June	20	25	25	10	80
Maize (sweet)	A	Oct/Dec	20	30	40	10	100
Maize (sweet)	C	April	30	30	30	103	110
Maize (sweet)	M warm winter	Jan	20	40	70	10	140
Millet	A	June	15	25	40	25	105
Millet	C	April	20	30	55	35	140
Sorghum (grain)	C, M	May/June	20	35	40	30	130
Sorghum (grain)	A	Mar/April	20	35	45	30	140
Rice	T, M	Dec; May	30	30	60	30	150
Rice	T	May	30	30	80	40	180
Forages							
Alfalfa*	frost free period		10	30	–	–	Variable
Alfalfa*	M	Mar	5	10	10	5	30
Alfalfa*	C	Jun	5	20	10	10	45
Bermuda (for seed)	A	March	10	25	35	35	105
Bermuda (for hay)	A	–	10	15	75	35	135
Grass Pasture	Frost free period		10	20	–	–	Variable
Sudangrass (first cutting cycle)	A	Apr	25	25	15	10	75
Sudangrass (other cutting cycles)	A	June	3	15	12	7	37

(continued)

Crop species	Climate	Sowing date	Duration of crop stage (days)				
			A	B	C	D	Total
Fruit trees, vines and shrubs							
Banana (year 1)	M	Mar	120	90	120	60	390
Banana (year 2)	M	Feb	120	60	180	5	365
Citrus	M	Jan	60	90	120	95	365
Deciduous orchard	C high latitude	March	20	70	90	30	210
Deciduous orchard	M,C low latitude	March	20–30	50–70	120–130	30	240–270
Grapes	Low latitude	April	20	40	120	60	240
Grapes	M, C mid latitude	Mar/April	20–30	50–60	40–75	60–80	205–210
Grapes	High latitude	May	20	50	90	20	180
Olives	M	March	30	90	60	95	365
Pineapple	T		60	120	600	10	790
Pistachios	M	Feb	20	60	30	40	150
Walnut	C high lat	April	20	10	130	30	190

Adapted from Doorenbos and Pruitt (1977) and Allen et al. (1998). This Table should be used with caution as the actual duration of phases may change for different regions, cultivars and weather conditions of each year

*For the first cut cycle use durations twice the values shown

Cimates: *M* Mediterranean, *A* arid, *SA* semi-arid, *C* continental, *T* tropical

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Chapter 12
Plant Density and Competition

Francisco J. Villalobos, Victor O. Sadras, and Elias Fereres

Abstract Crops respond to planting density modifying the characteristics of individual plants by changing the number and size of their organs. The density response can be described mathematically by the "Law of Reciprocal Yield". Under very high density mortality of individuals occurs and is often more pronounced when environmental conditions are more suitable (e.g. high fertility). Yield-density curves can be asymptotic or parabolic, although the latter may reflect the existence of an additional limiting factor (e.g. water or nutrients). In general the spatial variability in planting density leads to yield losses which are higher when the yield-density response is a parabolic curve.

12.1 Introduction

Plant population dynamics studies the temporal variation in the number of individuals and their attributes. These aspects are important to understand the productivity of crops, especially to evaluate the effect of planting density on yield. Population dynamics also helps us understand the weed-crop competition and the process of plant mortality, which may be critical for the establishment of annual crops or pasture maintenance.

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12.2 Density and Competition

A crop is a plant population with individuals of the same genotype and of similar age. The availability of resources changes in time and space and may limit crop growth and cause competition between neighboring plants. Unlike animals, higher plants show great plasticity in their growth and in their form, in response to the stress imposed by competition. Thus, the structure of individual plants is set to respond to competition stress by varying the rate of formation, growth or mortality of its organs (leaves, branches, stems, fruits, roots, etc.). The response may involve changes in the size of the individuals, in their shape or in the number of individuals.

The growth rate of a plant population is proportional to density in the early stages of development. This proportionality is later reduced as competition for resources among plants increases, and usually leads to a phase when crop growth rate is independent of the density. The higher the initial density, the sooner the competition for resources begins. Variations in initial density are therefore largely offset by variations in growth rates of individual plants. This has been verified for many species and has been called "law of constant final yield." This is true above a minimum plant population so there is enough opportunity to exploit all the resources. In other words, in its early stages of growth from seed, the biomass of a crop depends on the number of plants present, but over time, the supply of resources starts to control the rate of growth of individuals, until finally it is the limiting factor of productivity, regardless of the density. The population behaves as an integrated system in which the behavior of the individual plant is subordinated to the behavior of the population.

Any factor that reduces the rate of growth of the plants results in a delayed onset of competition and a reduction in its intensity. The relationship between yield per plant and density is often expressed by the following equation (called "reciprocal yield law"):

$$W = \frac{1}{b_1 + b_2 D_p} \tag{12.1}$$

where W is the dry mass per plant (g), D_p is the planting density (plants m^{-2}) and b_1 and b_2 are empirical coefficients. Crop biomass (B, g m^{-2}) is the product of mass per plant and planting density, and yield (Y) is the product of biomass and Harvest Index (Chap. 13) so:

$$Y = \frac{HI \cdot D_p}{b_1 + b_2 D_p} \tag{12.2}$$

The coefficient b_2 represents the inverse of the crop biomass (B) when the density is very high. If D_p tends to infinite in Eq. 12.2, $B \approx {b_2}^{-1}$

Coefficient b_1 represents the inverse of W when competition is absent, i.e. for very low density. If D_p is zero in Eq. 12.1, $W \approx {b_1}^{-1}$

Example 12.1 The maximum yield of sunflower for isolated plants of a particular cultivar is 500 g, and the maximum yield is 500 g m^{-2} when the density is very high. What is the expected yield if planting density is 5 plants m^{-2}?

$$B \approx 1/b_2 \text{ when } D_p \text{ is high} \rightarrow b_2 = 1/B = 1/500 = 0.002 \text{ m}^2/\text{g}$$

$$1/W \approx b_1 \text{ when } D_p \text{ is very small} \rightarrow b_1 = 1/W = 1/500 = 0.002 \text{ plants/g}$$

$$Yield = \frac{5}{0.002 + 0.002 \times 5} = 417 \text{ g m}^{-2}$$

12.3 Variability Between Plants and Hierarchy

The frequency distribution of weight per plant in a population under density stress is skewed, i.e. asymmetrical. The bias increases with both time and population density, as illustrated in Fig. 12.1 for sunflower. In a population in competition we thus find a large number of small individuals (low biomass per plant) and fewer large individuals. The place of an individual in the hierarchy of the population is determined primarily in the early stages of development. It has been shown experimentally that the amount of biomass produced by an individual in a population under competition is very closely related to the relative order of its appearance (emergence) in the population. The advantage of an early appearance must be related to an increased use of resources and the corresponding deprivation of resources for individuals that appear later. This implies that a likely source of

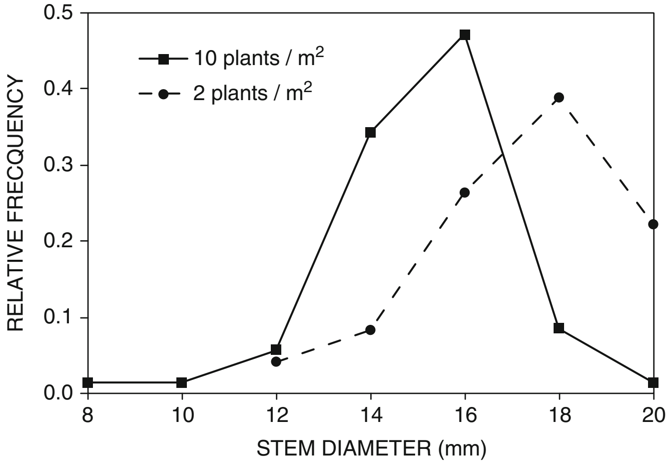


Fig. 12.1 Frequency distributions of stem diameter of sunflower plants at plant densities of 10 or 2 plants m^{-2}. Cordoba (Spain), 1994

variability of plant mass in the field is variability in time to emergence which in turn depends on the variation of soil properties (water content, thermal properties, compaction) and the sowing method.

In addition to heterogeneity of seedling emergence, herbivory, diseases and other sources of damage (e.g. hail) are agronomically important sources of crop heterogeneity. For example, insects feeding on the growing meristem of cotton slow down plant growth, as it takes time for activation of axillary buds that would re-initiate growth. This hiatus in growth of the damaged plant may favor the growth of undamaged neighbor plants. The yield per unit ground area of such heterogeneously damaged crops can be the same (compensation), higher (over-compensation) or smaller than in undamaged crops; the outcome depends on the gain in growth of the undamaged plant relative to the reduction of yield of the damaged neighbor. For instance, researchers in the UK observed how healthy potato plants next to diseased plants grew much bigger than those in uniformly healthy crops.

Insects, diseases or other agents that kill seedlings cause "gaps" in the crop. In the absence of compensatory capacity (when plant loss occurs very late or when it originates large gaps) yield would be reduced in proportion to the reduction of the plant stand. The relationship between yield and stand loss, however, demonstrates a compensatory mechanism which relates to the "relaxation" of competition and depends on the spatial distribution of plant loss and the time when it occurs (Fig. 12.2). In conclusion, crop heterogeneity often but not always reduces yield; the impact of heterogeneity depends on the size of the hierarchy or gap, their spatial distribution, the ability of plants for compensatory growth (e.g. tillering wheat

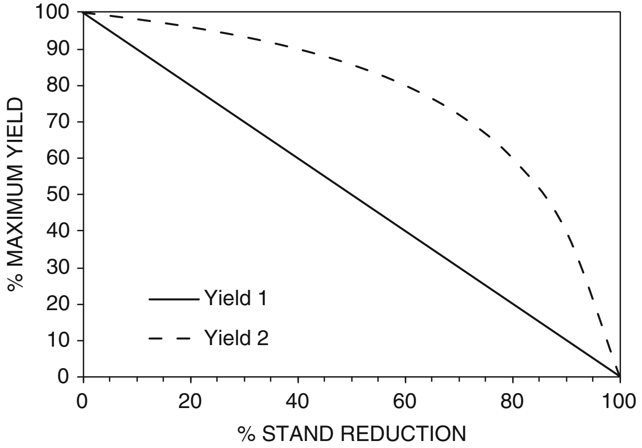


Fig. 12.2 Effects of plant stand loss on yield. The *continuous line* corresponds to stand loss occurring very late or when plant loss occurs in large patches so no compensatory growth is possible. The *dashed line* represents very early and random plant loss so maximum compensatory growth occurs

>uniculm sunflower), availability of resources and the time available for compensatory growth.

12.4 Density and Mortality

The high density tends to increase the risk of death of the individuals in the population although there are some examples of the opposed effect. The risk of mortality that increases with the density has regulatory properties, acting as a negative feedback on the size of the population. Various studies on "self-elimination" (density stress induced mortality) have shown that it occurs at high but not at low density, starts sooner with higher density and depends on environmental conditions.

In the years 1920–1930 Suskatschew studied the dynamics of self-elimination in populations of spruce near Saint Petersburg (Russia), finding that final plant density was higher in poor and shallow soils. In deeper soils he found lower densities of larger trees. This author then conducted an experiment with an annual plant (*Matricaria inodora*) using two levels of fertility and two densities, checking that mortality was higher with the highest density, and that the risk of death increased with higher fertility. This corroborated his observations in spruce forests. Fertilization apparently increased the growth rate of individuals thereby increasing the density stress and thus the mortality rate.

12.5 Mechanisms of Plant Competition

The density of plants in a crop determines the occurrence of numerous processes of interference between individual plants. As plant density is varied the environment of each plant is altered in terms of light intensity and quality and availability of resources (water, nutrients).

Thus, as plant density is higher, intercepted radiation and the availability of water and nutrients are reduced for each individual, which limits their ability to grow. Light quality is changed fundamentally in the relationship between red (670 nm) and far red radiation (760 nm) (ratio R: FR). On average, sunlight has a ratio R: FR of 1.15. As red is absorbed by pigments, light transmitted or reflected by vegetation has lower R: FR. For example, R:FR below crops may range from 0.1 to 0.5. As the density increases the ratio R:FR is reduced, and this reduction is detected by phytochromes, inducing morphological changes in many species (increased height growth, reduction in the formation of side branches or stems).

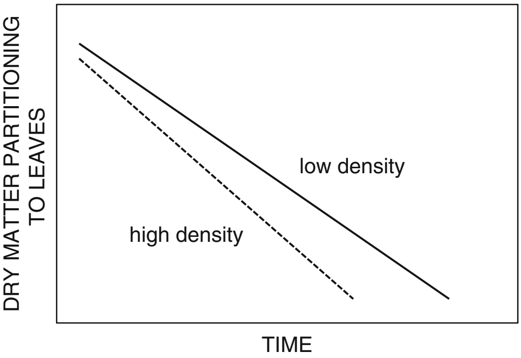


Fig. 12.3 Time course of dry matter partitioning for leaves in sunflower for low and high planting densities

The main crop responses to increased density are:

- Reduction of expansive growth and mass (per plant). Plant leaf area and thus radiation interception per plant are reduced.
- Increase or decrease in harvest index (in some species): For very low density, biomass per plant may be very large while seed growth is limited by the number of seeds and potential seed growth rate, implying a fall in HI. In other cases (e.g. maize) very high densities increase the percentage of sterile plants.
- Reduction of the number of seeds per plant and/or mass of single seeds.
- Changes in the distribution of dry matter among plant organs: increased allocation to stem and reduced allocation to leaves (Fig. 12.3). In general height increases while stem diameter decreases, which leads to a notable increase of its slenderness ratio and therefore a higher risk of lodging in adverse situations (for instance, strong winds).
- Depressed branching in dicots (e.g. soybean) and tillering in cereals.
- Acceleration of leaf senescence: In plants under high density leaf senescence starts sooner and the rate of senescence is higher, which seems to occur in response to very low levels of radiation.
- Changes in crop quality: In some cases quality may improve with high density (e.g. percentage of oil in sunflower seed) and in other cases it may decline (e.g. sunflower seed size for direct consumption). In general the size of harvestable organs is reduced as density increases (grains, tubers, bulbs, etc.).

12.6 Yield and Planting Density

Throughout the twentieth century great attention was paid to the relationships between plant density and crop yield. These relationships are important from the practical standpoint of defining if there is an optimum density.

Two types of relationships between yield and density are usually found: asymptotic and parabolic (Fig. 12.4). In the first type, yield increases with density, reaches a plateau and does not decrease for very high densities. This case is also found when

Fig. 12.4 Generic parabolic and asymptotic response curves of yield versus density

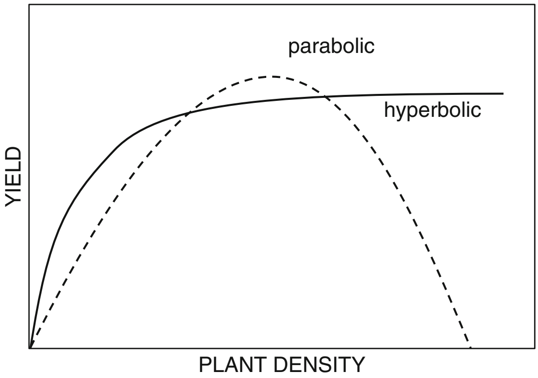
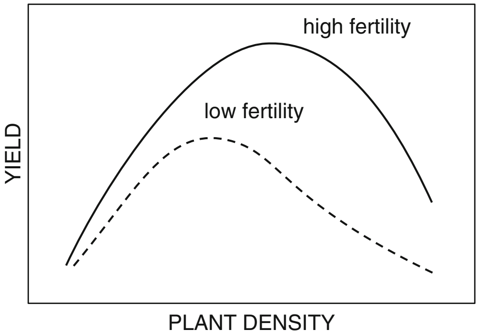


Fig. 12.5 Changes in parabolic response curves of yield versus density when resource availability is changed



we plot biomass versus density. In the parabolic case, yield reaches a maximum at a given density and decreases for densities above or below.

The biomass production of any crop follows an asymptotic relationship with density. This is the response predicted by the Reciprocal Yield Law (Eq. 12.2). In crops harvested for their seed it used to be common to observe a decrease in yield for high densities (parabolic response), which implies that the HI is reduced. This was due to a direct effect of density (e.g. barrenness in maize) or as a result of another limitation of resources such as water or nutrients. Thus, in situations of water deficit, the highest densities are at increased risk of not having sufficient water during grain filling. Evidence that a parabolic curve is the product of a limitation other than density may come from the observation that the density for maximum yield increases with increasing water or nutrient availability (Fig. 12.5). Additionally, within a species we can find various yield-density curves for the different cultivars, especially if they differ in cycle length. Very short cycles produce less biomass and yield at low densities. The maximum yield is achieved at higher density if the cycle is shorter than if it is long. A long cycle can fully exploit the available resources with low densities. It compensates the low plant density with a longer vegetative period which implies a higher growth potential for the single plants. This is illustrated in Fig. 12.6 for the case of two cultivars

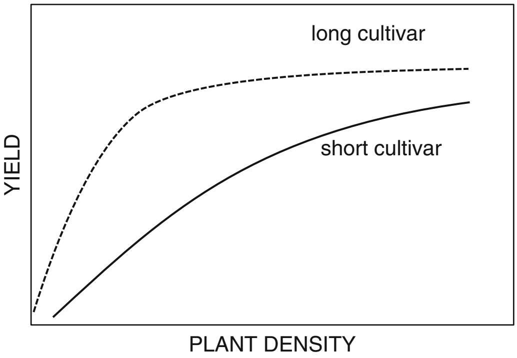


Fig. 12.6 Response of sunflower yield to density for short and long cycle genotypes

of sunflower in Cordoba, Spain. In winter cereals, plant breeders have incorporated substantial plasticity in the response to density, and yields are the same over a wide range of densities provided that resources are not limiting (fully irrigated and fertilized conditions). Even in maize, modern varieties are quite resistant to barreness and yields do not decline until very high densities are achieved (>150,000 plants/ha).

Using the Reciprocal Yield Law Eq. 12.1 we can deduce at what density a particular fraction of maximum biomass (r = B/Bmax) is achieved:

$$D_p(r) = \frac{r\, b_1}{(1-r)b_2} \tag{12.3}$$

Example 12.2 Two cultivars of sunflower differ in cycle. Under very low density the shorter cultivar produces 360 g/plant and the longer 1400 g/plant. In this environment maximum biomass production is 1200 g m^{-2} and 1600 g m^{-2}, for the short and the long cultivar, respectively. We will calculate the densities required for these varieties to reach 90 % of maximum biomass.

For both varieties:

$$\text{Short: } b_2 = 1/1200 = 8.33\ 10^{-4}\ \text{m}^2/\text{g}$$
$$\text{Long: } b_2 = 1/1600 = 6.25\ 10^{-4}\ \text{m}^2/\text{g}$$

Short cycle cultivar:

$$1/W \approx b_1 \text{ when } D_p \text{ is very small} \rightarrow b_1 = 1/W = 1/360$$
$$= 2.78\ 10^{-3}\ \text{plants/g}$$

(continued)

Example 12.2 (continued)

$$D_p(r) = \frac{r\,b_1}{(1-r)b_2} = \frac{0.9 \times 2.78\;10^{-3}}{(1-0.9)\;8.33\;10^{-4}} = 30\text{ plants m}^{-2}$$

Long cycle cultivar:

$$1/\mathrm{W} \approx \mathrm{b}_1 \;\text{ when } \mathrm{D}_\mathrm{p} \;\text{ is very small} \rightarrow \mathrm{b}_1 = 1/\mathrm{W} = 1/1400$$
$$= 7.14\;10^{-4}\;\text{ plants/g}$$

$$D_p(r) = \frac{rb_1}{(1-r)b_2} = \frac{0.9 \times 7.14\;10^{-4}}{(1-0.9)6.25\;10^{-4}} = 10\text{ plants m}^{-2}$$

We see that to achieve yields close to the maximum a much higher density is required for the short cultivar.

The yield-density relationships obtained experimentally should be used with caution because they depend on the limitations of water and nutrients and the cultivar considered. In any case it should be noted that there will be a minimum density which should be increased for short growing cycles. Furthermore, if water or nutrients are scarce, we must avoid high densities that could reduce the harvestable fraction of biomass and therefore yield. The high density may cause other undesirable effects such as increased risk of crop lodging by wind which may decrease yield dramatically.

Parabolic responses to density are also observed for some horticultural crops where the product price is closely related to the size of the harvestable organ (e.g. garlic, onion, carrot). High densities lead to smaller and therefore lower selling price, leading to yield-density curves of parabolic type, when we express the yield in income/ha.

The relationship between density and yield mentioned above are obtained in experimental plots in which the crop density is uniform across the plot. However in a commercial plot, plants are not distributed evenly across the field. There is a spatial variability in density so that there are areas where the density is high and areas where it is low. This may be due to variability in soil conditions (compaction, initial water), the presence of pests and soil diseases or poor seed distribution at sowing.

In general we may expect that the larger the variability in the density of plants the larger the decrease in yield. However, it depends strongly on the size of gaps and the possibility for compensation, as indicated in Sect. 12.3. The negative effect of variability should be more pronounced when the response is parabolic as both lower and higher densities reduce yield below the optimum. In this case if we cannot avoid a very high variability (soil or machinery problems, for example) we may reduce planting density below the theoretical optimum.

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Chapter 13
Radiation Interception, Radiation Use Efficiency and Crop Productivity

Victor O. Sadras, Francisco J. Villalobos, and Elias Fereres

Abstract Photosynthesis is the set of processes whereby radiant energy is converted and stored as chemical energy in most plants, algae and cyanobacteria. This process depends on radiation, temperature and CO_2 concentration. The maximum efficiency of the process is 6 % but it is usually well below. The leaf-level photosynthesis can be described mathematically, and this analysis can be extended to the calculation of crop photosynthesis, as a function of its leaf area index, the coefficient of extinction as a shortcut to represent canopy architecture, and leaf photosynthetic parameters.

The respiration of the crop can be decomposed into a maintenance component that is dependent on biomass and temperature, and a growth component which is proportional to gross photosynthesis.

Crop yield can be expressed as the product of three factors, the amount of intercepted radiation, radiation use efficiency (RUE) and harvest index (HI). RUE is smaller for C3 than C4 crops, and is smaller in crops with oil- and protein-rich seed in comparison to cereals. Radiation interception depends on incident radiation, leaf area index and the extinction coefficient accounting for canopy architecture. The HI depends on the species and its use. The main cause of genetic yield improvements in the past has been the increase in HI, which has been a remarkable success in the case of cereals; maize is the main expectation to this trend. In some cases, such as high-yielding wheat in northern Europe, HI is reaching a biophysical limit, hence further improvements in yield would require increasing RUE and biomass.

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13.1 Introduction

The input of energy to ecosystems is based on the process of photosynthesis by which sunlight is converted into chemical energy. Photosynthesis is the primary process in producing carbon compounds necessary for the construction and maintenance of crop biomass. Here, the focus is leaf-level photosynthesis with a brief scaling-up exercise to crop level photosynthesis, which links with crop traits developed in Chap. 3. When we measure the rate of CO_2 exchange of a single leaf, this rate is the net photosynthesis (P_n), which results from the total or gross photosynthesis (P_g) and respiration losses (R). We use a convention that fluxes from air to leaf are positive, whereas fluxes from leaf to air are negative. Emphasis is placed on how radiation, CO_2 and temperature modulate leaf photosynthesis. Other factors affecting photosynthesis, such as plant water status and nitrogen nutrition are discussed in other chapters.

In the second part of this chapter we discuss the relation between biomass production and the amount of radiation absorbed by photosynthetically active tissues, i.e. the efficiency in the use of radiation for biomass production. Absorbed radiation is closely related to intercepted radiation, i.e. the difference between incoming radiation and that reaching the soil surface (Chap. 3). Radiation use efficiency varies between crop types in relation to both photosynthetic metabolism (C4-C3) and seed composition (cereals, legumes and oilseed crops); there is also moderate variation between cultivars that can be exploited in plant breeding. Plant age, source-sink ratio, dry matter and nitrogen allocation also affect crop radiation use efficiency. Nitrogen, water and temperature are major environmental factors with effects on both radiation interception and radiation use efficiency.

13.2 Leaf Level Photosynthesis

Most (85–90 %) of the dry matter accumulated in a crop derives from photosynthesis, which can be decomposed into the following three processes:

(a) Diffusion of CO_2 from the atmosphere to the chloroplasts, following the concentration gradient:

$$P_n = g_{sc}(C_a - C_i) \tag{13.1}$$

where P_n (μmol m^{-2} s^{-1}) is the net flux of CO_2 entering the leaf, g_{sc} is stomatal conductance for CO_2 (mol$m^{-2}s^{-1}$) and C_a and C_i are the concentrations (μmolmol^{-1}) of CO_2 in the air surrounding the leaf and in the substomatal cavity, respectively.

(b) Absorption of light by the photosynthetic pigments and photolysis of water. The amount of radiation absorbed depends on the concentration of pigments, mostly chlorophylls, present in the chloroplasts. In this stage, O_2 is released and energy compounds (ATP and NADPH) are generated. This process does not depend on the temperature or the concentration of CO_2.

(c) Reduction of CO_2 using the compounds generated in the photolysis of water. Between 8 and 12 light quanta are required for each molecule of CO_2 reduced. The reduction can occur in the dark and is very sensitive to temperature.

In summary, the photosynthesis of a leaf of a healthy, well watered and well fertilized plant depends on irradiance, CO_2 concentration and temperature.

The energy efficiency of photosynthesis, i.e. the ratio of energy stored in chemical form and incoming solar radiation, has a maximum value around 6 %, but actual efficiency in agricultural crops usually does not exceed 2–3 %. We can calculate the relative importance of photosynthesis in the energy balance equation (Chap. 7) as follows. Net radiation (R_n) above a crop is equivalent to 60–80 % of solar radiation (R_s) depending mostly on cloud cover. On a clear day we can assume $R_n = 0.6\ R_s$ so that the energy stored with 6 % of efficiency represents 10 % of net radiation. However, the energy spent in photosynthesis also includes a fraction that is lost by respiration. If that fraction is one third, then 15 % of net radiation may be spent in photosynthesis. Therefore the common assumption of neglecting energy use in photosynthesis may be wrong in particular when productivity is high (e.g. greenhouse crops) and irradiance is low.

13.3 Plant Types According to Photosynthesis Mechanisms

Higher plants have developed three different photosynthetic systems (C3, C4 and CAM) that have distinct chemical and anatomical features. Terrestrial plants evolved from algae and initially were all C3. Subsequently there has been a shift towards C4 and CAM systems. Agricultural species and natural flora present mostly the C3 system. Few but important cultivated species have the C4 system (maize, sorghum, millet, sugar cane, and some tropical grasses such as *Paspalum spp*), whereas the CAM system is rarer and less important in crops (agave, pineapple). C3 plants originate mostly in high to intermediate latitudes and high altitude, whereas C4 are more typical of subtropical to tropical regions. C4 photosynthesis is a complex evolutionary trait that resulted from a major reorganization of leaf anatomy and metabolism leading to a CO_2-concentrating mechanism that counteracts the inhibitory effects of low atmospheric CO_2 on photosynthesis. The C4 pathway evolved independently at least 66 times within the past 35 million years. The main features of the three systems are as follows:

(a) C3 plants. The first compound formed in the process is phosphoglyceric acid (three carbon atoms) by combination of ribulose diphosphate (5C) with CO_2. The enzyme responsible is the ribulose-bisphosphate carboxylase (Rubisco). Although primarily serving for carboxylation, Rubisco can also act as oxygenase. Thus, in the presence of light, O_2competes with CO_2 at the enzyme active sites which leads to a loss of CO_2 (photorespiration). In addition to its enzymatic role, the large amount of Rubisco in plants means it plays a major role as reserve of reduced nitrogen. This is most evident during the grain filling and senescence of annual crops, where a significant part of the nitrogen, stored as Rubisco, is transported and contributes to the protein content in grain.

(b) C4 plants. The first compound formed in the process is oxaloacetic acid (four carbons) by combining phosphoenol pyruvate (PEP) with CO_2. The enzyme responsible is the phosphoenol-pyruvate carboxylase. C4 plants have higher photosynthesis per unit energy and per unit water than their C3 counterparts, and this contributes to their adaptation to dry environments.

(c) CAM plants (Crassulacean Acid Metabolism). This system is predominant in the *Crassulaceae* family that includes numerous cactuses. CO_2 fixation occurs during the night by formation of PEP which is converted to organic acids that are stored in the vacuoles. During the day malate enters the chloroplasts where PEP is regenerated. CAM plants behave as C3 if the water supply is adequate. In drought situations CAM plants have reduced rates of water use as compared to C3 and C4 plants.

13.4 Effects of Environmental Factors on Photosynthesis

The main environmental factors affecting photosynthesis rate are solar radiation, temperature and CO2 concentration. Diseases, water and nutrient deficit may limit strongly photosynthesis which is discussed in Chaps. 14 and 15.

13.4.1 Radiation

The net photosynthesis of a leaf (P_n) responds to irradiance (I) as shown in Fig. 13.1. For $I = 0$, the leaf loses CO_2 at a rate R_d (dark respiration). Assimilation is zero at the so called light compensation point where gross photosynthesis is equal to respiration rate. With higher I, P_n grows rapidly to a maximum in which the system reaches light saturation. For many species, P_n is saturated well below the typical radiation of clear days, this is particularly true of most C3 plants. The

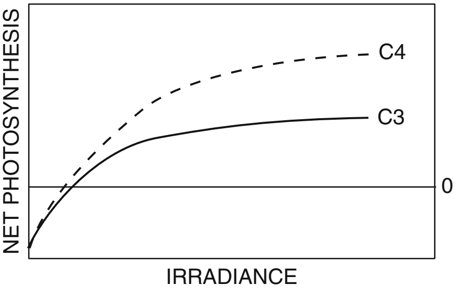


Fig. 13.1 Relations between leaf net photosynthesis and irradiance for C3 and C4 plants

maximum value of P_n varies greatly between the C3 and the C4 groups and also within each group. However, the initial slope of the relationship $P_n = f(I)$ is relatively constant for all species.

If R_d is constant as I increases, gross assimilation is defined as $P_g = P_n + R_d$. The gross assimilation rate increases with irradiance along a curve which can be fitted to a hyperbola of the type:

$$P_g = \frac{\varepsilon I P_{gx}}{\varepsilon I + P_{gx}} \tag{13.2}$$

where P_g is the rate of gross photosynthesis (μmol m^{-2} s^{-1}), I is irradiance (W m-2), ε is the initial slope of the curve $P_g = f(I)$ and P_{gx} is the asymptotic value of P_g when I tends to infinity. C3 plants have values of P_{gx} in the range 10–40 μmol m^{-2} s^{-1} while C4 show a range 18–55 μmol m^{-2} s^{-1}. The initial slope of the curve is similar for C3 and C4 species with a value around 0.076 μmol J^{-1}. When I is expressed as absorbed PAR (mol photons m^{-2} s^{-1}) the initial slope is called quantum efficiency of photosynthesis, which is a measure of the intrinsic efficiency of the photosynthetic system. In the range 20–25 °C both C3 and C4 plants have quantum efficiencies around 0.06 mol CO_2 E^{-1}. For lower temperatures C3 plants perform better and for higher temperatures the opposite occurs.

C3 plants reach their P_{gx} with much lower irradiance than C4 plants. Under optimal conditions C4 plants show higher P_{gx} than C3 plants, although the differences are attenuated as we scale up from leaf to plant community. Thus, the maximum biomass produced by C3 and C4 crops differs much less than the maximum rates of photosynthesis at leaf level.

The irradiance under which leaf growth occurred also affects its response to radiation. When a leaf has grown in the shade, P_{gx} is lower than when it has grown under high radiation. This process of acclimation is due to increased accumulation of proteins (photosynthetic enzymes) in the leaves under high irradiance.

13.4.2 Temperature

The maximum photosynthesis responds to temperature following a bell shaped curve with a maximum between 15 and 25 ºC for C3 plants and between 25 and 35 ºC for C4 plants (Fig. 13.2). Very few C4 species perform well under low temperature, whereas most of these species suffer irreversible damage with temperatures between 10 and 12 ºC (chilling injury). Many C3 plants such as cotton and sunflower perform well with high temperature (30–40 ºC) although some C3 are sensitive to low temperatures (e.g. banana). However leaves of most of C3 plants can withstand temperatures down to 0 ºC.

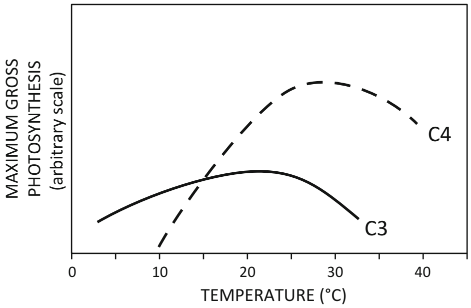


Fig. 13.2 Response of maximum gross photosynthesis to temperature for C3 and C4 crops

13.4.3 Concentration of CO_2 and Endogenous Factors

Photosynthesis increases as CO_2 concentration increases because of the larger concentration gradient between the atmosphere and the leaf mesophyll (Eq. 13.1). Net photosynthesis responds linearly to the [CO_2] for C3 plants. Leaves of C3 species lose CO_2 (P_n is negative) for CO_2 concentrations below 50–100 ppm. The concentration of CO_2 for which $P_n = 0$ is called CO_2 compensation point. C4 plants show little response to CO_2 concentration in the range 200–400 ppm.

In addition to the environmental effects, photosynthesis rate can be affected by the existence of sinks capable of accumulating carbohydrates. For example, suppression of the tubers of potato plants leads to a decrease in the rate of leaf photosynthesis.

13.5 Respiration

Respiration (oxidation of carbohydrates and other compounds to produce energy) in plants can be decomposed into two main categories: growth respiration (R_g) which is proportional to the gross photosynthesis and maintenance respiration (R_m), proportional to crop biomass (B):

$$R_d = R_g + R_m = a\ P_g + b\ B \qquad (13.3)$$

The growth respiration is the energy cost involved in the synthesis of plant tissues from glucose, which is considered the building block of plant tissues. For example, 1 g of glucose allows building approximately 0.65 g of leaves (or vegetative tissues in general). The energy cost depends mainly on tissue composition: synthesis of fats and proteins involve a higher R_g than carbohydrates (see 13.11).

Maintenance respiration is the energy cost associated with maintaining the organization and functioning of the crop tissues. The fundamental processes in which R_m is inverted are protein turnover and keeping active ion transport

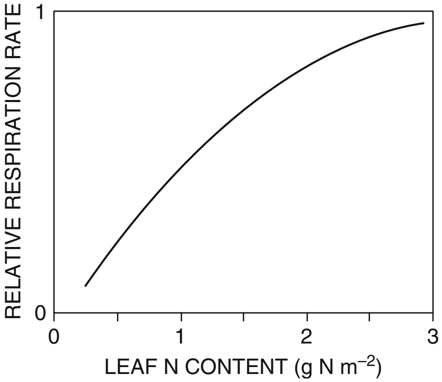


Fig. 13.3 Leaf respiration at 30 °C as a function of leaf N concentration per unit leaf area

mechanisms. For this reason, N-deficient plants or older plants with lower nitrogen concentration have lower maintenance respiration per unit of dry matter as illustrated in Fig. 13.3. The R_m per unit biomass increases exponentially with temperature up to 40–50 ºC, depending on the species. For higher temperatures irreversible damage occurs. Indicative values of R_m at 20 ºC range 0.01 and 0.035 g glucose/g of dry matter/day.

13.6 Crop Photosynthesis

The response of photosynthesis of a crop to environmental conditions is in principle more complex than that of its individual leaves. A crop is a set of leaves of different age and nitrogen concentration, subjected to different radiation intensities that change throughout the day. As will be seen later, in many cases crop photosynthesis is linearly related to irradiance (or better, to intercepted radiation).

Considering the extinction of radiation within the canopy (Chap. 3) and the response of leaf assimilation to irradiance (Eq. 13.2) we can integrate assimilation for all the leaves and arrive to an equation for the rate of net photosynthesis of the crop:

$$P_{nc} = \frac{P_{gx}}{k} ln\left(\frac{\varepsilon\, k\, I_0 + 1.2\ P_{gx}}{\varepsilon\ \ k\, I_0\ e^{-kL} + 1.2\ P_{gx}}\right) - L\, R_d \qquad (13.4)$$

where I_0 is incident radiation, k is the extinction coefficient (see Chap. 3), L is the Leaf Area Index and R_d is dark respiration per unit leaf area. The main determinants of canopy photosynthesis are discussed using Eq. 13.4 in the examples below.

Example 13.1 Figure 13.4 shows the net photosynthesis of C3 crops with extinction coefficients 0.5 (vertical leaves) and 0.9 (horizontal leaves) as a function of LAI. The maximum crop photosynthesis occurs for LAI around 3 for horizontal leaves and LAI close to 5 for vertical leaves. When LAI is low, horizontal leaves are more efficient for crop photosynthesis. Vertical leaves show a clear advantage for large LAI.

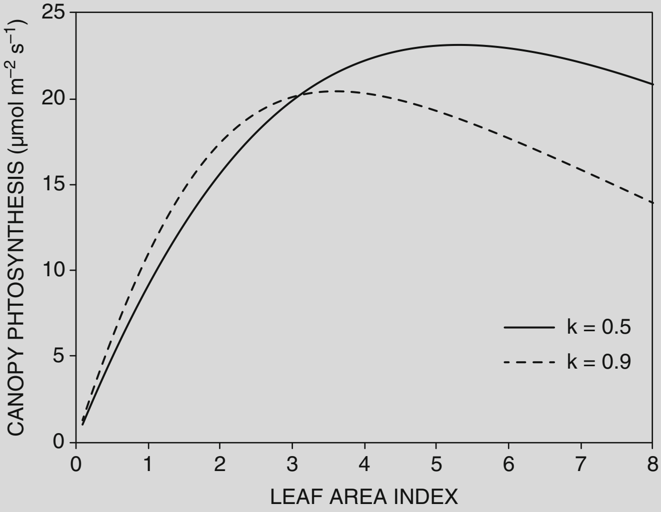


Fig. 13.4 Net photosynthesis of C3 crops with extinction coefficients 0.5 (*vertical leaves*) and 0.9 (*horizontal leaves*) as a function of LAI

Example 13.2 Figure 13.5 shows the net photosynthesis of C3 crops with LAI=1 and LAI=4 as a function of incoming radiation. The response is closer to linear than that shown by leaf assimilation to irradiance (Fig. 13.1). When irradiance is low, the crop with LAI=1 assimilates more CO_2 which is explained by the smaller respiration loss.

(continued)

Example 13.2 (continued)

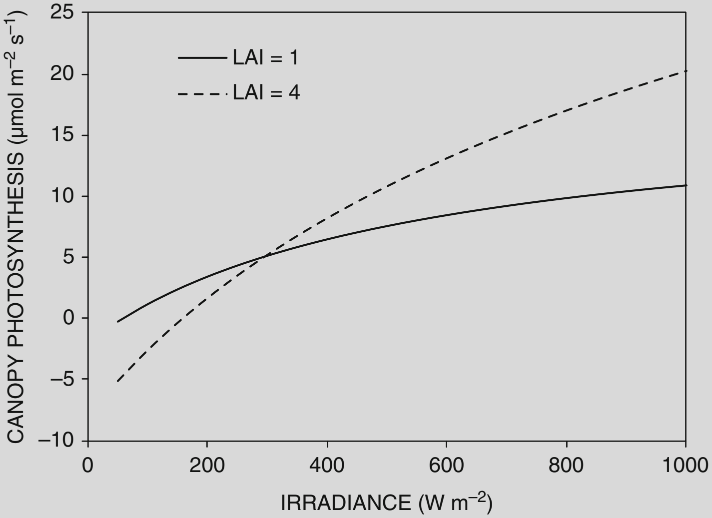


Fig. 13.5 Net photosynthesis of C3 crops with LAI=1 and LAI=4 as a function of incoming radiation

Example 13.3 The effect of leaf photosynthetic capacity on canopy photosynthesis is shown in Fig. 13.6 for crops of different LAI. The range in maximum leaf gross photosynthesis goes from the low range in C3 species to the high range of C4. We have assumed that respiration is 10 % of P_{gx} and solar radiation of 500 W m^{-2}. It is clear that the importance of leaf photosynthetic capacity is reduced as the canopy grows. For very high LAI, crop photosynthesis is almost independent of P_{gx}. This may explain why breeding for high leaf P_{gx} has not been successful in enhancing biomass production.

(continued)

Example 13.3 (continued)

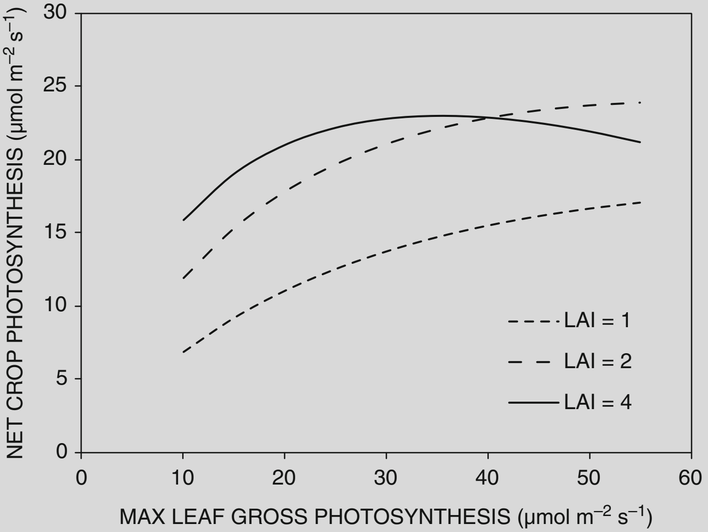


Fig. 13.6 Effect of leaf photosynthetic capacity on net canopy photosynthesis. The range in maximum leaf gross photosynthesis goes from the low range in C3 species to the high range of C4. We have assumed that respiration is 10 % of P_{gx} and solar radiation is 500 W m^{-2}

13.7 Intercepted Radiation

We analyzed radiation interception by crops in Chap. 3. Actual interception depends on LAI, leaf angles and the geometrical distribution of incoming radiation (sun angle, fraction of diffuse radiation). Models of radiation interception may be quite complex and allow considering also the actual 3D distribution of foliage elements in the canopy which is required for tree orchards or forests.

A more simple approach uses the relationship between crop coefficients and radiation interception seen in Chap. 10. The FAO method for calculating K_c divides the crop cycle into four stages (initial, rapid growth, maximum, declining). Rapid growth starts when ground cover is around 0.2 and ends at ground cover 0.8–0.9. Full radiation interception corresponds to K_c around 1.2 which leads to the simple model:

$$f_i = K_c - 0.3 \tag{13.5}$$

where f_i is the fraction of intercepted PAR. This should be valid for the third and fourth stages. In the initial stage, when we move from zero to 20 % interception we

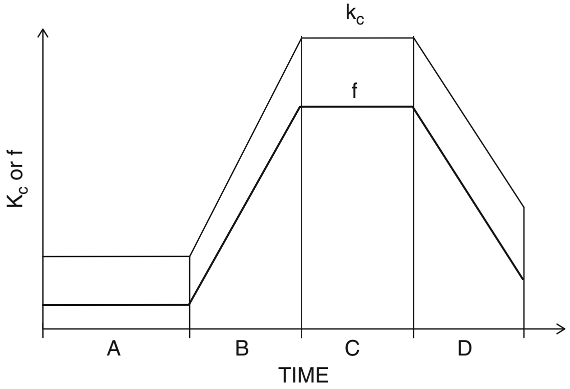


Fig. 13.7 Time course of crop coefficient and the fraction of intercepted PAR for an annual crop. A: sowing to 20 % ground cover, B: 20 % to 80 % ground cover, C: 80 % ground cover to start of leaf senescence, D: start of senescence to harvest

may assume an average value of $f_i = 0.1$. Values of interception for the rapid growth stage may be calculated by linear interpolation (Fig. 13.7). Note that in this simple model intercepted radiation in the fourth stage, when leaves are old and the canopy is senescing, is a surrogate for absorbed radiation by pigments. In other words, dead leaves do not contribute to photosynthesis or transpiration, so the estimated value of intercepted radiation refers to functional leaves.

13.8 Radiation Use Efficiency

The relationship between crop growth rate (CGR: increase in above ground biomass per unit time) and intercepted radiation is approximately linear. Therefore the relationship between biomass production (B) and the sum of intercepted radiation should be linear:

$$B = RUE \sum_{emergence}^{harvest} f_i R_{sp} \qquad (13.6)$$

where the proportionality coefficient is the RUE (Radiation-Use Efficiency, units of g/(MJ PAR)) and R_{sp} is incoming PAR. The first to propose such a relation was Monteith in 1977, who plotted biomass versus accumulated solar radiation intercepted by different C3 crops (sugar beets, potatoes, barley, apples) and found similar linear relationships with slope around 1.4 g dry matter/MJ solar radiation despite the obvious differences among these crops. The RUE of C3 plants inside greenhouses is higher than outdoors, with values in the range (2.2–2.5 g/(MJ PAR), which is explained by the higher proportion of diffuse radiation, the favorable thermal environment and lack of wind that promotes higher shoot:root ratio (Fig. 13.8).

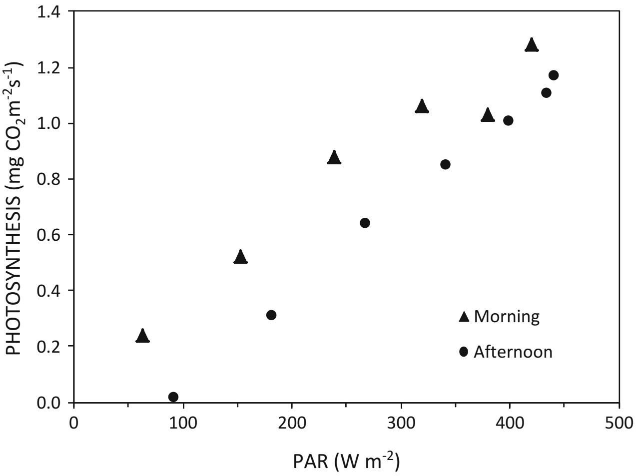


Fig. 13.8 Relationship between hourly crop photosynthesis and intercepted PAR in a cotton crop. Cordoba, Spain. June 23, 2003. For the same radiation photosynthesis is higher during the morning than during the afternoon

13.9 Crop Potential Productivity

We can calculate crop yield (Y) as the product of biomass and harvest index (see below), and further expressing biomass as the product of RUE and total intercepted PAR (Eq. 13.6):

$$Y = HI\ \ RUE \sum_{emergence}^{harvest} f_i\ \ R_{sp} \tag{13.7}$$

Assuming crops grown under ideal conditions that maximize capture and efficiency in the use of radiation and harvest index, we can calculate the potential dry matter yield of a crop in a given environment. Abiotic and biotic stress factors can reduce harvest index (see below), and the components of crop biomass (Sects. 13.10 and 13.11). It is important to keep in mind that a fraction of mass harvested by farmers is water. Therefore the commercial or fresh yield can be calculated using Eq. 13.7 as:

$$Y_{fresh} = \frac{1}{1-w} HI\ \ RUE \sum_{emergence}^{harvest} f_i\ \ R_{sp} \tag{13.8}$$

where w is the fraction of water over fresh mass. Values of w for different species are shown in Table 24.1. The difference between Y and Y_{fresh} is small for crops that are harvested dry (cereals, grain legumes) but it is very large for some species (e.g. potato, tomato).

The fraction of biomass that is harvested is called Harvest Index (HI = Y/B). Biomass usually refers only to the above ground fraction, unless the harvested organ is underground, in which case it is included in the biomass. The HI of fodder crops is very high (up to 0.9), as we may harvest and use almost all the aerial biomass (see Table 13.1). Small grain cereals like wheat can reach HI near 0.50, and many legume and oilseed crops show HI in the range 0.30–0.40. Crops with subterranean harvestable organs show high HI like sugar beet (up to 0.7) and potato (up to 0.8). It should be remembered, however, that the values shown in Table 13.1 correspond to "normal" cropping conditions, and that in extreme situations the HI may go down to zero, for example if a crop fails to set grain due to untimely frost or heat.

13.10 Dry Matter Partitioning and Harvest Index

The dry matter accumulated during the crop cycle is partitioned among the different plant organs. In determinate annual crops there is a distinct vegetative growth phase where assimilates are partitioned to leaves, stems and roots. This phase is followed by a reproductive phase when inflorescences, flowers, seeds and supporting structures grow while vegetative growth stops. In plants with an indeterminate growth habit, vegetative and reproductive growth overlap for much of the cycle. The difference between determinate and indeterminate growth is relative in the sense that there will always be some overlap between vegetative and reproductive growth. The shorter the overlap is, the more determinate the growth habit. Interestingly genetic variability exists for growth habit which has been exploited to develop determinate cultivars that allow mechanical harvesting (e.g. processing tomato).

The fraction of dry matter that goes to each plant organ is called the partition coefficient. Part of the dry matter may be remobilized later and be transported from one organ to another. This typically occurs with reserve carbohydrates in the stem, which support partially seed growth during the seed filling period. In crops like sunflower and wheat, stem reserves can contribute significantly to grain yield, in particular under conditions that constraint photosynthesis during grain filling such as drought and foliar diseases.

The general trend over the twentieth century was the increase in Harvest Index of the different crops, which has enabled significant increases in yield without major improvements in biomass production. One example is that of the wheat cultivars obtained by the International Center for Improvement of Maize and Wheat (CIMMYT) in which improved HI was associated to short stature plants which enabled increasing N fertilization without increased risk of lodging. Maize is an exception to this trend, as improvement in yield has been primarily achieved by increasing crop biomass mediated by tolerance to crowding in turn allowing higher sowing densities. For the last 50 years, plant breeders have focused their improvement programs on increasing HI to the point that the major crops are now approaching their biophysical limits in terms of HI.

Table 13.1 Harvest index (%) of different crop species

	HI_{min}	HI_{max}
Alfalfa	90	90
Apple	60	70
Barley	40	50
Cassava	30	65
Chickpea	30	36
Citrus	50	60
Cotton	25	40
Cowpea (determinate)	44	60
Cowpea (indeterminate)	15	30
Bean (dry seed)	25	45
Faba bean	25	40
Garlic	50	55
Grain sorghum	40	50
Grapevine	40	60
Lentil	35	50
Lupin	30	50
Maize	40	55
Oats	40	50
Oil palm	40	45
Olive	50	70
Onion	60	85
Opium	30	40
Pea	35	45
Peanut	35	42
Pepper	40	60
Potato	50	80
Rapeseed	30	35
Rice	40	55
Safflower	25	35
Soybean	35	50
Sugarbeet	50	70
Sugarcane	70	80
Sunflower	25	40
Tobaco	60	80
Tomato (industry)	45	60
Triticale	45	47
Vetch	40	50
Wheat	40	50

The typical intervals for commercial crops are shown. These values may be taken as representative of crops not suffering from extreme biotic or abiotic stress.

Table 13.2 Effect of nitrogen supply on harvest index (relative to a maximum value of 0.47) of wheat at three locations in Australia

N rate (kg N/ha)	Ginninderra	Pucawan	Wagga
0	0.94	0.89	0.72
200	1.00	0.85	0.55

Adapted from van Herwaarden et al. (1998) Austr J Agri Res 49, 1067–1082

Harvest index depends mainly on the developmental pattern of the crop, on the distribution of assimilates among plant organs and on the ability to translocate assimilates to the harvestable organ. In particular in determinate crops (e.g. sunflower) the reproductive phase is clearly separated in time from the vegetative phase. Failure in setting seeds (or harvestable organs in general) may be a primary cause for reduced HI. Later, low post-anthesis assimilation or poor translocation of assimilates may reduce further the HI. Therefore several critical periods for determining the HI may exist (flower initiation, flowering, pollination). A greater flexibility of the HI may be expected for indeterminate crops (e.g. cotton) as both vegetative and reproductive growth overlap during most of the crop cycle.

Nutrient and water deficit have variable effects on harvest index. This relates to the definition of harvest index as a ratio, yield to biomass. Stress may reduce both biomass and yield in equal proportion with no consequence for harvest index, or reduce biomass proportionally more than yield hence increasing harvest index, or reduce yield proportionally more than biomass, thus reducing harvest index. The actual response of harvest index to stress is thus contingent to the nature of the stress, and its timing, intensity and duration. Table 13.2 illustrates all three possibilities. In comparison to unfertilized crops, well-fertilized crops had similar, lower or higher harvest index depending on location-specific growing conditions. The seasonality of rainfall in dryland systems often has an impact on yield mediated by harvest index. In Mediterranean environments with winter rainfall that favors biomass growth and scarce rainfall during reproductive stages, harvest index is often much lower than its potential. In irrigated systems, strategies of deficit irrigation may be used to improve HI by reducing water use during specific periods that favor reproductive over vegetative growth (see Chap. 21).

13.11 Crop Factors Affecting Interception and Efficiency in the Use of Radiation

Chapter 3 discussed crop traits affecting radiation interception, including optical and geometrical properties of leaves and canopies. The RUE, which is the amount of dry matter produced per unit of intercepted PAR, depends on the crop species. Under optimal temperature and water supply C3 plants produce between 2 and 2.5 g/MJ PAR and C4 plants produce 2.5–3.0 g/MJ PAR.

Differences in seed composition explain the higher RUE of cereals in comparison to both oilseed crops and grain legumes. Following the analyses of Penning de Vries, the conversion factor for formation of dry matter (CVF: g dry matter/g glucose) can be calculated as:

$$1/\mathrm{CVF} = (1.24\ \mathrm{FC} + 1.70\ \mathrm{FP} + 3.11\ \mathrm{FF} + 2.17\ \mathrm{FL} + 0.93\ \mathrm{FO} + 0.05\ \mathrm{FM}) \tag{13.9}$$

where FC, FP, FF, FL, FO and FM represent the fractions of carbohydrates, protein, fat, lignin, organic acids and minerals in the dry matter being formed. With these values we derive an approximate method to calculate RUE of a crop based on biomass composition, assuming that the harvested product consists of carbohydrates, proteins and fats, and the crop residues contain only carbohydrates:

$$RUE = \frac{RUE_c}{(1 - HI) + HI(FC + 1.4\ FP + 2.5\ FF)} \tag{13.10}$$

where $\mathrm{RUE_c}$ is the RUE for production of carbohydrates. Appendix 32.1 (Chap. 32) presents data of composition of harvested parts of many crops species.

Example 13.4 Winter cereals have a seasonal RUE around 2 g/(MJ PAR) which may be taken as the reference $\mathrm{RUE_c}$. Then for oilseed sunflower with HI = 0.35 and seeds containing 45 % fat and 20 % protein, RUE will be:

$$RUE = \frac{2}{(1\ -\ 0.35) + 0.35(0.35 + 1.4 \times 0.2 + 2.5 \times 0.45)} = 1.58\ g/(MJ\ PAR)$$

Example 13.5 We will calculate the potential yield (without limitation of water and nutrients) of castor bean (Ricinus communis) in Cordoba, (Spain). The crop is sown on April 1 and harvested on September 30. The average fraction of intercepted radiation is 0.2 in April, 0.4 in May, 0.9 in June, July and August and 0.2 in September. Harvest index is 0.25. Seed water content is 5 %. The castor seed contains 50 % fat and 15 % protein (dry mass basis). We also assume that temperature does not affect crop productivity. Solar radiation data and PAR interception calculation are presented in Table 13.3. Seasonal intercepted PAR is 1106 MJ m^{-2}.

First we calculate RUE using Eq. 13.10 and assuming $\mathrm{RUE_c} = 2$ g/(MJ PAR), which yields

$$\mathrm{RUE} = 1.66\,\mathrm{g/(MJ\ PAR)}$$

(continued)

Example 13.5 (continued)

Table 13.3 Calculation of intercepted radiation for a castor bean crop in Cordoba (Spain)

Month	Rs	PAR	Days/month	f	Intercepted PAR per month
	MJ/m^2/day				MJ/m^2
1	8.8	4.0	31		
2	9.9	4.4	28		
3	11.7	5.2	31		
4	16.9	7.6	30	0.2	45.7
5	20.1	9.1	31	0.4	112.3
6	23.8	10.7	30	0.9	289.7
7	25.1	11.3	31	0.9	315.4
8	23.5	10.6	31	0.9	295.4
9	17.8	8.0	30	0.2	48.0
10	10.9	4.9	31		
11	8.0	3.6	30		
12	6.3	2.8	31		
Season					1106.4

And now we calculate yield applying Eq. 13.8:

$$Y_{fresh} = \frac{1}{1-w} HI\ RUE \sum_{emergence}^{harvest} f_i R_{sp} = \frac{1}{1-0.05} 0.25 \cdot 1.66 \cdot 1106 = 483\,g\,m^{-2}$$
$$= 4830\,kg/ha$$

Variations in RUE due to the composition of the harvested product and loss of photosynthetic capacity that occurs in many crops during the final phase of the cycle reduce seasonal RUE below the maximum values. Thus, for seasonal calculation we propose intervals of RUE of 1.6–2.0 g/(MJ PAR) for non-leguminous C3 plants, 1.5–1.8 for C3 leguminous plants and 2.2–3.0 g/(MJ PAR) for C4 plants. These RUE values represent "well adapted" crops under normal cropping conditions, so RUE values include the effect of temperature and assume good supply of water and nutrients. However, RUE is expected to change under cooler or hotter environments, and when water and nutrients are in short supply, as explained in the next section.

Some species show low RUE due to their low leaf photosynthesis; for example in olive RUE is 1.3 g/(MJ PAR) for non bearing trees and 0.9 g/(MJ PAR) for bearing trees. This difference is basically due to the higher cost of biomass production of olive bearing trees as fruits accumulate oil. In citrus RUE of adult trees is 1.3 g/(MJ PAR).

The intra-specific variation in RUE is smaller than the differences between crop types associated with photosynthetic metabolism and seed composition.

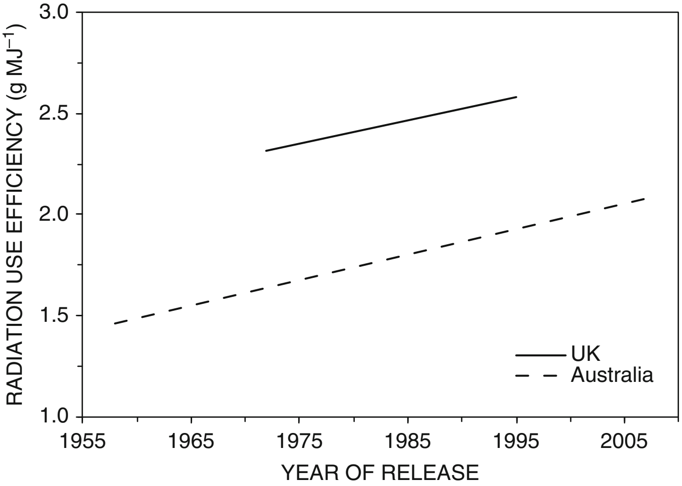


Fig. 13.9 Selection for yield indirectly improved the pre-flowering radiation use efficiency of wheat varieties in UK and Australia (Adapted from Evans JR (2013) Plant Physiol 162:1780–1793)

Nonetheless, selective pressure for yield has improved the radiation use efficiency of wheat in both favourable (UK) and stressful (Australia) environments (Fig. 13.9). The improvement in pre-flowering RUE of Australian wheats was associated with higher nitrogen uptake (i.e. greener leaves), and changes in canopy architecture that favoured greater PAR penetration in the profile; effectively, modern varieties have a greater proportion of leaves contributing to total crop photosynthesis, whereas the photosynthesis per unit leaf area remained unchanged. The role of nitrogen on crop photosynthesis is discussed in the next section.

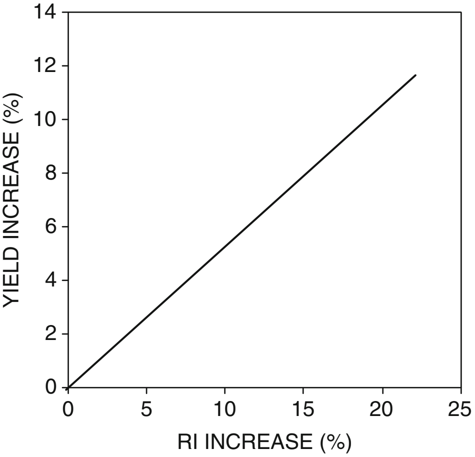
A single RUE value is useful for comparisons between contrasting crops types (C3 v C4, cereal v oilseed) and also captures large environmental effects, such as shortage of water or nitrogen (next section). However, RUE changes with crop age, developmental stage and the pattern of nitrogen and dry matter allocation. For example, studies of RUE in sunflower distinguished three phases: establishment (sowing to 47 days after sowing), rapid growth (47 days after sowing to anthesis) and grain filling (anthesis to maturity). Radiation use efficiency was highest during rapid growth (2.4 g/MJ) and lower during establishment (1.0 g/MJ) and grain filling (1.3 g/MJ). The low RUE during establishment was associated with a large proportion of leaves exposed to high radiation, and the intrinsically lower efficiency of leaves at saturated light regimes. The low RUE during grain filling was related to high respiration and high synthesis cost of oil and protein in the seed (see Eq. 13.10) and to leaf senescence.

The concept of source and sink is useful to understand the physiology of the crop, despite some problems in definitions. A mature leaf is a net source of carbon, whereas the growing seed is a sink. A leaf however transitions from sink at early stages of development to source at later stages. Likewise, wheat and sunflower stems are sinks of carbohydrates during early growth stages but became sources for grain filling. The source:sink ratio can be manipulated experimentally by increasing source activity (e.g. increasing ambient CO_2 concentration or radiation), reducing source activity (e.g. defoliation, shading), reducing sink activity (e.g. removal of maize ear, cooling of potato tubers), or increasing sink activity (e.g. applying gibberellic acid). Experiments where the source:sink ratio is diminished often show increase in photosynthesis, whereas increasing source:sink ratio may reduce photosynthesis. With high source:sink ratio, the plant has a relative excess of photosynthates, and the accumulation of starch in leaves can trigger the feedback-inhibition of photosynthesis usually mediated by reduction in stomatal conductance. Conversely, leaf photosynthesis may be stimulated if the capacity of the source to meet the carbohydrate requirements of the sink is restricted. These source: sink interactions are agronomically important. For example in pasture species such as alfalfa or grasses, animal browsing reduces the size of the canopy relative to root biomass, hence the reduced source:sink ratio. After browsing, the rate of photosynthesis of remanent leaves may increase in response to low source:sink ratio, hence contributing to re-growth. This “compensatory photosynthesis” has also been recorded in plants after damage by insects that reduce source:sink ratio (e.g. defoliators). In wheat varieties developed in CIMMYT (International Centre for Improvement of Maize and Wheat), increased seed number in modern varieties, compared with older ones, has increased RUE during grain filling; this increase in crop photosynthesis has been interpreted in terms of reduced source:sink size, as grain number increased without a proportional increase in canopy size. Effectively, more grains are “pulling” photosynthesis up.

13.12 Environmental and Management Factors Affecting Interception and Efficiency in the Use of Radiation

Effects of temperature on biomass production and its components, radiation interception and RUE are twofold. First, and most important, temperature changes the duration of the period from sowing to harvest, setting the limits of integration in Eq. 13.7. At high latitudes in Europe, Asia and North America, warming over recent decades has extended this period, with positive implications for crop growth and yield (Chap. 11). In contrast, increasing temperature in subtropical and temperate environments may shorten season length, with potentially negative effects for crop yield. The early observation by Westlake thus remains relevant in this context: “. . .adaptation of agricultural techniques to increase the proportion of the year with the ground completely covered by leaves is probably the most rewarding change that could be made to increase the world’s food supplies. . .” Second, RUE is non-linearly related to temperature, an effect that is mediated by the effects of temperature on lower-level processes such as leaf gross photosynthesis, respiration

Fig. 13.10 Relationship between percentage yield increase in response to increase in radiation interception due to reduction in row spacing for maize, soybean and sunflower (Adapted from Andrade et al. (2002) Agron J 94:975–980)



and dry matter partitioning. For example, field pea RUE is reduced with average ambient temperatures below 12 °C or above 22 °C.

Row spacing is manipulated to improve capture and efficiency in the use of resources, and to accommodate practices such as weed control and tillage (Chap. 17). The best row spacing for a combination of crop, soil, climate and cropping system is usually determined empirically. Alternatively, we can apply the physiological concepts developed in this chapter to predict the responses of crop yield to row spacing as illustrated in Fig. 13.10. For the well-watered crops in this study, no yield gains are expected from narrowing the space between rows when wide-row crops intercept 90 % of incident radiation in the critical period of yield determination but gains up to 12 % can arise if wide-row crops intercept 60–90 % of radiation. The gain in yield with narrowing row distance is proportional to the gain in intercepted radiation (Fig. 13.10). In recent decades, even though row spacing has been diminishing to increase radiation interception, in practice sowing machinery and tillage/traffic practices are the major determinants of row spacing.

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Chapter 14
Effects of Water Stress on Crop Production

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Abstract Water stress is due to a low water potential in the plant as a result of low soil water potential, high evaporative demand and/or a substantial resistance to water flow through the plant. The water deficit affects many processes in the crop, although most of the effects are related to the reduction in growth, the most sensitive process, and to stomatal closure. Mild to moderate deficits do not affect harvest index, and in some species they may increase it. Instead severe water deficits reduce the HI. The effect of water stress on crop yield can be quantified by Stewart's equation which establishes that the relative reduction in yield is directly proportional to the relative reduction in ET, with an empirical coefficient (K_y) which ranges between 0.8 and 1.5. More mechanistic type models may be used to characterize the yield responses to variable water supply, but they need to be locally calibrated for accuracy.

14.1 Introduction

Cultivated plants require a continuous supply of water to replace that lost by evaporation from the aerial organs, particularly from the leaves. This requirement is due simply to the fact that the leaves are exposed to a high evaporative demand (solar and thermal radiation and warm, dry air) while the substomatal cavities are saturated with water vapor. The gradient in water potential between the substomatal

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cavity and the leaf surface thus drives the evaporation process. Leaf cuticle however is a significant barrier for evaporation, leading to a mainstream transpiration flow through the stomata. For carbon dioxide to enter into the leaves, the stomata must be open, allowing water vapor to escape in response to the vapor pressure gradient. To maintain water flow without tissue desiccation, terrestrial plants have developed elaborate systems for the uptake and transport of water. Water flows from the soil into the root system and then is carried by xylem vessels to the leaves, where they replace the water evaporated into the atmosphere. Thus, from a purely physical point of view, the plants transport water from a source, the soil, to a sink, the atmosphere. These systems are capable of transporting large quantities of water, equivalent, in a typical summer day to a water depth of 6–8 mm in the field, which involves several times the total weight of the plant. However, a small, hardly detectable imbalance in the transport process in response to changes in the supply of water from the soil or in atmospheric demand, causes a water deficit in the plant. These mild deficits that are often harmful to crop growth and yield may occur in spite of the large amounts of water used by the plants. In this chapter, we outline the concepts of energy status of water in the plant, and its role in driving water flows. Then we look at the responses of crop processes to water deficits and the mechanisms of crop regulation of transpiration. After establishing these principles, we conclude with an analysis of the important links between water and crop production from an agronomic viewpoint.

14.2 Energy Status of Water in the Plant

As we have seen for the soil (Chap. 8), the energy status of water in the plant may be characterized in terms of water potential. To do this we must go down to the cellular level, since water status varies between subcellular compartments.

Schematically a plant cell is a protoplast (nucleus, cytoplasm and vacuoles) surrounded by a membrane (plasmalemma) which presses on a semi-rigid cell wall. This pressure, called turgor, reflects turgor potential (Ψ_p). The osmotic potential (Ψ_o) due to the presence of solutes is the other main component of total water potential (Ψ) in the protoplast. In the cell wall, a porous structure composed of microfibers and polysaccharides, the solute concentration is much lower, so Ψ_o is very small and Ψ_p is zero. Thus, the major component of potential outside the protoplast is the matrix potential (Ψ_m) due to adsorption forces that the porous cell wall matrix exerts on water. Another component of the potential, the gravitational is negligible in plants with the exception of very tall trees.

Example 14.1 In an equilibrium situation the water potential in the vacuole is -0.5 MPa with components $\Psi_p = 0.2$ MPa and $\Psi_o = -0.7$ MPa. The total potential in the cell wall is also -0.5 MPa. Its components are $\Psi_m = -0.48$ MPa and $\Psi_o = -0.02$ MPa.

Outside the cell, in the xylem, for the same water potential, its components will be different than in the cell. The Ψ_o is much lower and Ψ_p is negative since water in the xylem is under tension. In fact, turgor in the protoplast and tension outside creates a very large pressure gradient that would tear the plasmalemma if not for the rigidity of the cell wall containing it.

The pressure potential is the main driver of expansive growth of plant shoots and leaves and is largely responsible for the proper functioning of some basic processes for growth and crop production.

14.3 Causes of Water Deficits

From soil to substomatal cavity, water moves in liquid phase whereas the flow from substomatal cavity to atmosphere is in vapour phase. Transpiration (E_p) is the water vapor flux from the substomatal cavities into the atmosphere following a vapor pressure gradient. This loss of water from the plant is compensated by the inflow of water absorption from the soil by the root system. The water flow can be expressed in terms of the water potential gradient between the soil and the leaves:

$$E_p = (\Psi_s - \Psi_l)/R_{sl} \tag{14.1}$$

where Ψ_s is soil water potential, Ψ_l is leaf water potential and R_{sl} is the resistance to flow between the soil and the leaves. Rearranging Eq. 14.1:

$$\Psi_l = \Psi_s - E_p R_{sl} \tag{14.2}$$

That is, the leaf water potential, which is always lower than Ψ_s, is a function of soil water potential, the flow resistance and transpiration rate. A low leaf water potential is required for water to move from the soil, so leaves are under a water deficit as long as transpiration occurs. However, it is considered that a plant is water stressed when the water potential in its tissues decreases enough to affect physiological processes. Thus, the causes that can lead to low leaf water potential and therefore to water deficit are:

(a) Low soil water potential (low water content and/or high salt concentration in the soil solution).
(b) High evaporative demand (high E_p)
(c) High resistance to water flow (high R_{sl}) in the soil (low hydraulic conductivity, dry soil) or in the plant (low root length density, vascular diseases, etc.)

These processes can act simultaneously and in the same or in opposite direction. For instance, low soil water potential causes an increase in the soil-root resistance, while increases of transpiration may be accompanied by a reduction in resistance.

Water deficits may occur in the short term in plants with good water supply during the middle of the day, in response to increased evaporative demand. By

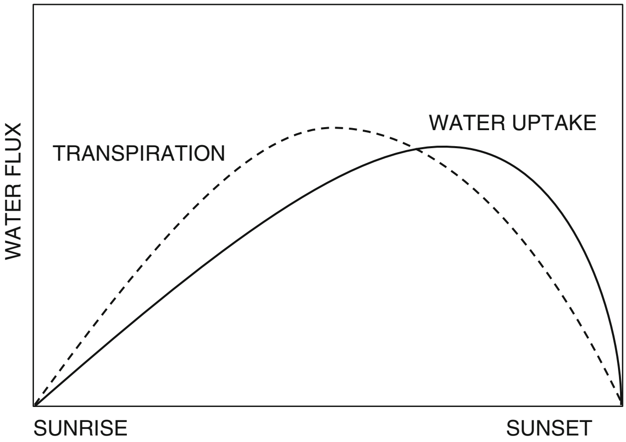


Fig. 14.1 Diurnal variation of transpiration and water uptake

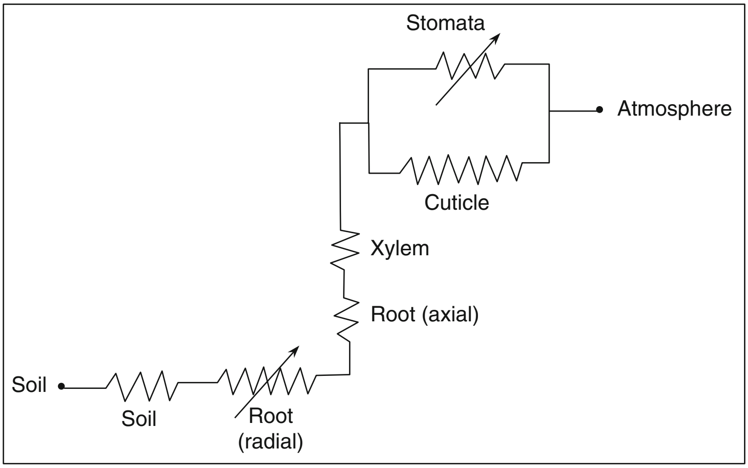


Fig. 14.2 Diagram of the soil-plant-atmosphere water flux

contrast, long term water deficits are commonly associated with progressive depletion of soil water.

We have seen then that the water status of the plant is the result of interactions between atmospheric demand (E_p) and the ability of the plant to meet this demand, which depends on the water content in the soil and the flow resistance. Transpiration rates and soil water uptake follow similar diurnal patterns with a maximum in the middle of the day, due to the high evaporative demand, but are offset in time (Fig. 14.1).

The role of R_{sl} is critical in regulating the water flow between the soil and the atmosphere. Between the soil and the leaves the resistance can be separated into several, as indicated schematically in Fig. 14.2. The resistance between the soil and

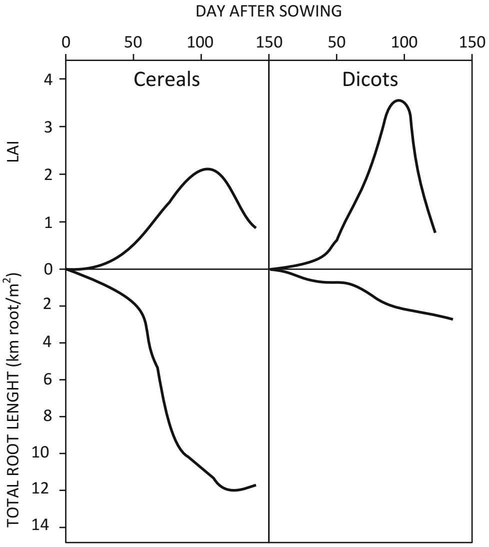


Fig. 14.3 Cereals (e.g. wheat) have a much larger root length density than dicots (e.g. lupin) in crops of similar leaf area index (Adapted from Hamblin and Tennant (1987). Australian Journal of Agricultural Research, 38, 513–527)

the root depends on the soil hydraulic conductivity (K_h), root length density (L_v), and root resistances. As the soil dries, K_h decreases exponentially and R_{sl} increases. The root length density (root length per unit volume of soil) usually decreases exponentially with depth. A higher L_v implies a shorter average distance between the soil and the root surface and thus lower R_{sl} values.

Cereals have higher root length density than dicots for crops of similar size (Fig. 14.3), reaching L_v between $3{\cdot}10^4$ and $10{\cdot}10^4$ m m^{-3} in the surface layers (0–30 cm). The low root length density of dicots, which can support similarly large canopies, is compensated by larger and more abundant metaxylem vessels and smaller axial resistance to water flow. Numerous studies have shown that L_v around $1{\cdot}10^4$ m m^{-3} is enough for full soil water extraction down to the Permanent Wilting Point. In fact, some crops such as sunflower are capable of full extraction of subsoil water with L_v of about $0.5{\cdot}10^4$ m m^{-3}. It is likely that the adaptive value of higher L_v is related to the extraction of immobile nutrients as P, rather than to the absorption of water.

Once water penetrates the surface of a root, it must overcome a significant radial resistance before reaching the xylem. This resistance is due to the suberization of a layer, the endodermis, which prevents water from flowing through the apoplast hence forcing water flow through cell membranes. The lipid bilayer of cell membranes is a significant resistance to water flow in roots. However, membranes contain a particular type of proteins, called aquaporins. Effectively, aquaporins can control water flow across membranes by changes in their abundance, by opening and closing the channel (gating), or both; for these properties an analogy can be drawn between aquaporins and stomata. In some cases, there is a good correlation between expression of aquaporins and physiological traits, e.g. aquaporin expression follows a day/night cycle consistent with the daily changes in root hydraulic conductivity coupled with transpiration. After reaching the xylem, the axial resistances from the root to the base of the stem and from the stem to the leaves are smaller (Fig. 14.2).

Water in the leaves finds two resistances in parallel: the stomatal resistance of variable magnitude depending on stomatal opening and the cuticular resistance, much greater than the stomatal resistance, but highly variable among crops, with rice having half the value of corn or sorghum.

Although the crop is a simple intermediary for water transport between the soil and the atmosphere, the modulation of the resistances described above allow the matching, within certain limits, of soil water supply to the evaporative demand of the atmosphere.

14.4 Effects of Water Deficits

Water stress can affect virtually all morphological and physiological processes of the crop if the duration and severity of stress are intense enough. The general response is reflected in a reduction in plant size, leaf area and harvestable yield.

The main effects of water stress on crops can be explained largely through the effect on two processes: expansive growth and stomatal functioning.

14.4.1 Expansive Growth

Turgor is responsible for the plant form and is a prerequisite for cell expansion, since the increase in size requires both new cell wall synthesis and turgor pressure against the wall. Relative growth rate of the cell may be related to Ψ_p by the following equation:

$$\frac{dV}{dt}\frac{1}{V} = \varepsilon\left(\Psi_p - \Psi_{pu}\right) \tag{14.3}$$

where V is the volume of the cell, ε is the cell wall extensibility and Ψ_{pu} is the threshold turgor potential, below which the expansion is stopped. The value of Ψ_{pu} is high which means that with a small reduction in Ψ_p, expansion may cease, and this would occur much sooner than wilting ($\Psi_p = 0$).

In general if the crop is subjected to a progressive water deficit, acclimation occurs by increasing ε and/or reducing Ψ_{pu} that conditions the future plant responses to water deficit. These acclimations occur differentially in the expansion of roots and aerial parts, so that the growth of the shoot is much more sensitive to water stress than root growth. In roots Ψ_{pu} is reduced rapidly and solutes accumulate so that Ψ_o is reduced (osmotic adjustment), allowing root growth to continue under low soil water potential.

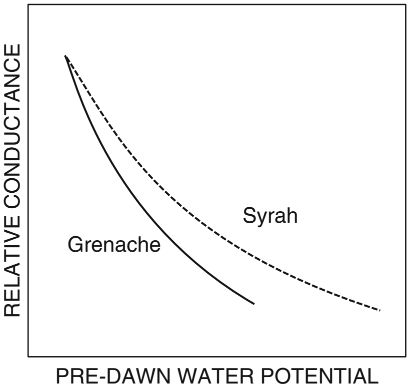
The great sensitivity of expansive growth to water deficits leads to expansion reductions for all organs that are within their growth phase when the water deficit occurs, which causes varying effects at the crop level depending on the timing of water deficit.

14.4.2 Stomata Functioning

In terms of evolution, stomatal closure prevents desiccation and death of the plant in the aerial environment, in special when water is scarce. The tradeoffs of stomatal closure are the reduction in the flux of CO_2 into the leaves and thus in assimilation, and the increase in canopy temperature. Stomatal closure under high vapor pressure deficit or drying soil favors a higher photosynthesis/transpiration ratio which is related to water use efficiency as discussed below (Sect. 14.5).

The stomata are formed by two guard cells of kidney shape which are welded at their ends. The stoma opening occurs when the guard cells are turgid. If their turgor is reduced the guard cells approach and the stoma closes. Therefore stomatal resistance is a function of pressure potential of the guard cells which is regulated by leaf water potential and other factors in a rather complex way. The complexity in stomatal behavior arises from several causes. First, stomata are responsive to many environmental (CO_2 concentration, temperature, vapor pressure deficit, radiation, light quality) and plant factors (e.g. leaf age, source-sink ratio, see Chap. 10). Second, the process of stomata regulation is highly dynamic; for example stomatal resistance increases when evaporative demand increases, but the increased resistance improves hydration and thus leaf water potential, which in turn stimulates stomata opening. In short-time scales (minutes) the size of the stomata pore changes continuously, and there is also variation among stomata in the same leaf. Third, there are genotype-dependent differences in stomata response to soil and atmospheric dryness. In some species such as maize and soybean, stomata tend to close when leaf water potential drops; this allows for maintenance of leaf water potential and for this reason this strategy has been called "isohydric". In other crops such as sunflower, stomata is more likely to remain open at low water potential; this response is called "anysohydric". There is, however, intra-specific variation in these strategies and a wide range in responses between the extreme isohydric and anysohydric behaviors (Fig. 14.4). Fourth, there are adaptive trade-offs. To understand these trade-offs, we need to recognize three functions of stomata: regulate the ratio between photosynthesis and transpiration, prevent cavitation, and regulate canopy temperature. Stomata closure in drying soil or under high evaporative demand favors the photosynthesis/transpiration ratio, and prevents cavitation. However, stomata closure increases canopy temperature. This trade-off means that stomata physiology cannot always be optimized. In wheat, cotton and Shiraz grapevines, heat stress favors stomata opening and evaporative cooling at the expense of photosynthesis/transpiration, suggesting that keeping the canopy cool is, under some conditions, more important than saving water (Fig. 14.5). The role of stomata in regulating canopy temperature is particularly important in warm regions where heat waves, compounded with dry soil, can cause severe damage.

Fig. 14.4 Stomatal conductance declines with increasing water deficit, but stomata are more responsive in Grenache (*continuous line*) than in Shiraz (*dotted line*) (Adapted from Schultz (2003). Plant, Cell and Environment, 26, 1393–1405)



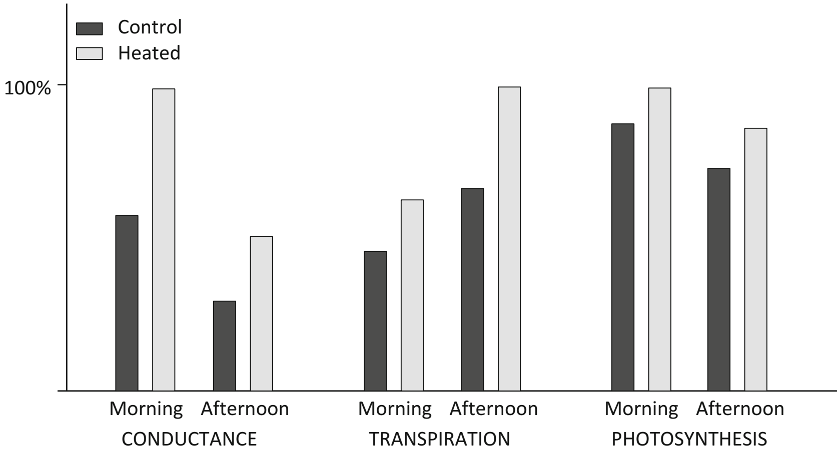


Fig. 14.5 Comparison of stomatal conductance, transpiration and net photosynthesis in well-watered Shiraz vines grown under ambient (control) and elevated (heated) temperature. Elevated temperature increased stomatal conductance and transpiration, and to a lesser extent photosynthesis. Evaporative cooling maintained difference in canopy temperature below 1°C between heated and control vines, at the expense of lower photosynthesis/transpiration ratio. *M* morning, *A* afternoon (Adapted from Soar et al. 2009. Functional Plant Biol 36, 801–814)

14.4.3 Crop Regulation of Transpiration

Crop transpiration (E_p) can be analyzed as the product of three factors: total transpiring area, approximated by the leaf area index (LAI), intercepted radiation (IR) per unit leaf area index, and transpiration per unit intercepted radiation:

$$E_p = LAI \cdot IR/LAI \cdot E_p/IR \tag{14.4}$$

Table 14.1 Relative importance rated from greatest (+++) to negligible (–) of mechanisms regulating transpiration of sunflower in pre- and post-anthesis

Process	Mechanism	Effect	Pre-anthesis	Post-anthesis
↓ intercepted radiation	↓ leaf growth rate	↓ LAI	+++	–
↓ intercepted radiation	↑ leaf senescence		+	++
↓ intercepted radiation	↓ extinction coefficient (wilting)	↓ IR/LAI	+	++
↓ transpiration per unit IR	↓ stomatal conductance	↓ E_p/IR	–	++

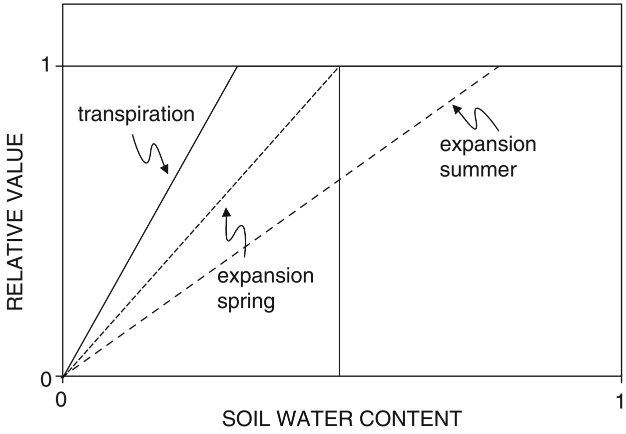


Fig. 14.6 Relations between expansive growth or transpiration and soil water content for sunflower in spring and summer. Soil water content is relative to the values in Permament Wilting Point (0) and Field Capacity (1) (Adapted from Sadras et al. 1993. Agron J 85, 564–570)

A small canopy is the most effective means of transpiration control. Indeed, LAI components including tillering or branching, and area of individual leaves are very responsive to water deficit. For a given LAI, the amount of radiation intercepted, which provides the energy for water evaporation, depends on canopy architecture. Figure 13.6 (Chap. 13) shows how wilting can transiently reduce IR/LAI and therefore reduce transpiration. Transpiration per unit intercepted radiation is related to the conductance of crop canopies, which is related to both its aerodynamic properties and stomatal conductance (Box 14.1).

The relative importance of the factors in Eq. 14.4 changes with crop development (Table 14.1). In general tissue expansion is much more sensitive to water deficit than stomatal conductance, and regulation of LAI is the main control of transpiration. Figure 14.6 illustrates this idea with experimental data of sunflower in Cordoba in 1991. In summer the expansion rate decreases when relative soil water content is 0.8, while stomatal conductance is affected when relative soil water is

0.2–0.3. In spring expansion is reduced after half of soil water is depleted, which is explained by the better water status of plants under lower evaporative demand. Thus, during the period of canopy expansion, reduction in LAI is the main control of transpiration. However, in annual crops LAI peaks around flowering, when the number and individual size of leaves is fixed; canopy expansion is therefore no longer relevant during grain filling. In this stage, leaf senescence is the only possible regulation of LAI, and often water deficit accelerates this process (Table 14.1).

Box 14.1 Canopy-Atmosphere Coupling

Figure 14.2 emphasizes the flow of water from soil to atmosphere at the level of the plant. At the level of the crop, however, there is a further resistance between the canopy and the atmosphere. This is often called aerodynamic resistance. With increasing aerodynamic resistance, the canopy and the atmosphere became increasingly decoupled. In these cases, the impact of stomatal resistance in modulating crop transpiration is less than in cases where the aerodynamic component represents a smaller resistance. In tall, aerodynamically rough vegetation such as conifer forests, the aerodynamic resistance is small, canopies and atmosphere are closely coupled, and stomata regulation has significant impact on transpiration. In contrast, in short and aerodynamically smoother vegetation, such as grassland, the aerodynamic resistance is higher, canopy and atmosphere are less coupled, and stomata regulation has less impact in regulating transpiration.

14.4.4 Effects on Other Processes and Interactions

The effects of water stress depend on its timing, duration and severity. A very severe stress affects almost all processes of the crop, and may lead to total crop loss. Crops do not usually suffer such severe deficits as to affect their survival, so we will only consider the effects of mild to moderate water deficits. Effects can be defined and investigated at different levels of organization. For example, water deficit can reduce the rates of cell division and expansion, lead to abnormal cell differentiation processes, which can result in abortion of flowers and/or a reduction in the number of flower primordia. Water stress can cause hydrolysis of proteins and accumulation of amino acids which, at the leaf level, reduces CO_2 fixation by a direct effect of stress on photosystems. Water deficit changes increases levels of abscisic acid and ethylene and reduces levels of indole acetic acid, cytokinins and gibberellins. These hormonal changes can lead to accelerated senescence. Water stress has little effect on the respiratory processes, the transport of assimilates and the rate of development.

Water stress in real field situations, however, does not occur in isolation. In arid and semi-arid environments, low soil fertility interacts with low rainfall in leading to water-nutrient co-limitation. Water and nitrogen co-limitation is particularly

Table 14.2 Ear damage (%) caused by heat stress in rainfed wheat crops grown under two sowing densities and several nitrogen rates. No ear damage was observed when the same treatments were applied under irrigation

N rate	Half density	Normal density
None	10	22
Low	23	32
High	33	60

Adapted from Rodriguez et al. 2005. Aust J Agric Res 56, 983–993

important for the yield of cereals in Mediterranean environments. In these environments, water stress is also combined with heat stress. In wheat crops in south-eastern Australia, ear damage caused by a heat episode close to flowering was significant in rainfed crops but not in irrigated crops (Table 14.2). Conditions that favored more vigorous growth and faster depletion of soil water, including excessive nitrogen supply and higher sowing density, compounded the effects of heat in the rainfed crops (Table 14.2). The sensitivity of crops to insects and diseases can increase, diminish or remain unchanged in water-stressed plants. Water-stressed cotton, for example, was found to be less susceptible to spider mites than their well-watered counterparts. This was because water deficit increased leaf thickness and hardness, making them less palatable to mites. In choice-tests, mites showed a marked preference for leaves from well-watered plants. Root diseases can compound the effect of water deficit.

14.5 Coupling of Photosynthesis and Transpiration

The flow of CO_2 into the leaf follows the same path as the flow of water vapor out of the leaf (transpiration). Any opening or closing of stomata affects the two processes.

The flux of transpiration (E_p, mol m^{-2} s^{-1}) may be expressed as:

$$E_p = 1.6 g_{sc} \frac{e_i - e_a}{P_{at}} \tag{14.5}$$

Where g_{sc} (mol m^{-2} s^{-1}) is the stomatal conductance for CO_2, e_i and e_a (both in kPa) are the vapor pressure in the substomatal cavities and the air outside the leaf, respectively, and $P_{\acute{a}t}$ (kPa) is atmospheric pressure. The factor 1.6 is the ratio of diffusion coefficients for water vapor and CO_2 in air at 25 °C. A similar equation (Eq. 14.1) is used for photosynthesis.

Air within the substomatal cavities is usually close to saturation ($e_i = e_s$ at leaf temperature), so adding and subtracting e_s at air temperature we may write:

$$e_i - e_a = e_s(T_c) - e_a + e_s(T_a) - e_s(T_a) = VPD + \Delta(T_c - T_a)$$

where VPD is the Vapor Pressure Deficit (Chap. 5), T_c and T_a are the leaf (crop) and air temperature, respectively, while Δ (kPa K^{-1}) is the slope of the saturation vapor pressure function versus temperature.

Therefore the ratio of net photosynthesis and transpiration will be:

$$\frac{P_n}{E_p} = \frac{(C_a - C_i)P_{at}}{1.6[VPD + \Delta(T_c - T_a)]} \tag{14.6}$$

Several authors have shown that the ratio C_i/C_a tends to fairly constant values of 0.7–0.8 (C3 plants) and 0.3–0.4 (C4 plants). Assuming that leaf and air temperature are equal:

$$\frac{P_n}{E_p} = \frac{C_a(1 - C_i/C_a)P_{at}}{1.6VPD} = \frac{\alpha_w}{VPD} \tag{14.7}$$

This equation implies that the photosynthesis/transpiration ratio (also called Water-Use Efficiency, WUE) depends mainly on the vapor pressure deficit: the amount of carbon fixed per unit of water lost will decrease as the atmosphere is drier or warmer. This is illustrated in Fig. 14.7 that shows hourly values of cotton WUE as a function of VPD during summer days in Cordoba, Spain. Here WUE was calculated as the ratio of canopy photosynthesis and ET. Equation 14.7 also indicates that WUE increases as C_a increases.

For a current value of $C_a = 397$ μmol mol^{-1}, the coefficient α_w would be 5,111–7,667 μmol mol^{-1}kPa for C3 plants and 15,334–17,890 μmol mol^{-1}kPa for C4 plants. If we convert these values to biomass production of carbohydrates and taking into account the relation between daytime VPD and mean VPD, the

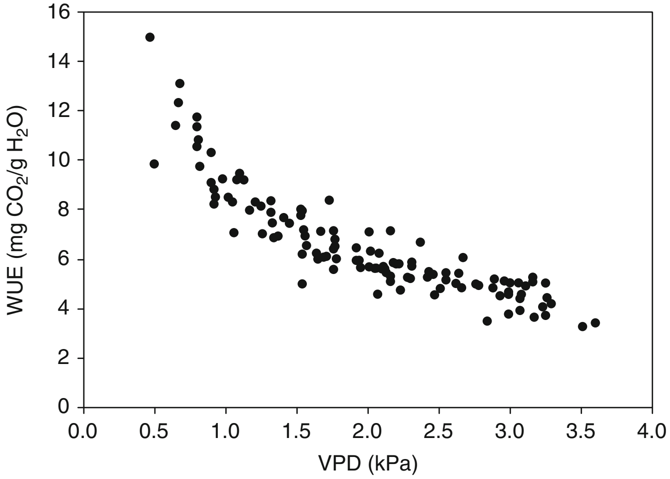


Fig. 14.7 Relationship between WUE and VPD for cotton in Cordoba (Spain) during summer days of 2003. WUE was calculated as the ratio of canopy photosynthesis and ET

coefficients would be 5.2–7.7 g dry matter L^{-1}kPa for C3 and 15.5–18.09 g dry matter L^{-1}kPa for C4. If we consider also night respiration, the coefficients would be reduced to around 60 % of the previous values for seasonal estimates.

Therefore, biomass accumulation (g m^{-2} day^{-1}) can be calculated as:

$$\Delta B = E_p \frac{\alpha_w}{VPD} \tag{14.8}$$

The same equation applies to isolated trees or plants, but then transpiration is expressed in L/tree/day and the increase of biomass in g/tree/day.

Example 14.2 Typical seasonal values of WUE (g dry matter/kg water transpired) for various C3 species in Southern Spain are: olive (3.4), sunflower (3.5) and wheat (5.3).

The higher value of wheat is due in principle to lower VPD during its cycle from December to May (average 0.7 kPa) compared with sunflower (February to July, 1.3 kPa) and olive (January to December, 1.2 kPa). The theoretical estimates, taking $C_i/C_a = 0.75$, would be:

Wheat: 6.5 g dry matter L^{-1}kPa/0.7 · 0.6 = 5.6 g dry matter/kg water
Olive: 6.5 g dry matter L^{-1}kPa/1.2 · 0.6 = 3.25 g dry matter/kg water
Sunflower: 6.5 g dry matter L^{-1}kPa/1.3 · 0.6 = 3.0 g dry matter/kg water

Example 14.3 In Example 9.5 we calculated transpiration of an olive tree with radius 0.5 m in Cordoba, Spain on 21 March with ET_0 3 mm day^{-1}. Calculated E_p is 2.07 L/day.

If average VPD is 1.5 kPa the increase of biomass would be:

$$\Delta B = E_{ptree} \frac{\alpha_w}{VPD} = 2.07 \frac{L}{tree\ day} \frac{6.5 \frac{g\ kPa}{L}}{1.5\ kPa} = 9 \frac{g}{tree\ day}$$

14.6 Quantifying the Impact of Water Deficit on Crop Production

The impact of water deficit on crop production can be quantified using models of different complexity. Here we illustrate the simple model of Stewart, and the more complex AquaCrop model.

14.6.1 Stewart Model

The model is based on the empirical relations found between crop evapotranspiration and yield which derives from the association between transpiration and photosynthesis. These two processes are linked for two reasons. First and most importantly, both processes are driven by radiation that provides the energy for water evaporation and CO_2 reduction. Smaller canopies capture less radiation, fix less carbon and transpire less. Second, the flows of both water and CO_2 between crop and atmosphere are partially regulated by stomata. These two mechanisms account for the correlations between biomass and transpiration. Therefore, if the harvest index (HI) is known, yield could be calculated as a function of seasonal transpiration:

$$Y = HI \sum_{t=emergence}^{t=harvest} WUE\, E_p \tag{14.9}$$

where WUE is the biomass produced per unit transpiration (g dry matter/kg water), which depends mainly on VPD and the crop species (see Eq. 14.10). For simplicity we will assume that WUE is constant throughout the season and that HI is not affected by water deficit, but see Eq. 13.10 for a more realistic discussion. As evapotranspiration is the sum of soil evaporation and transpiration:

$$Y = HI\, WUE \left(\sum_{t=emergence}^{t=harvest} ET - \sum_{t=emergence}^{t=harvest} E_s \right) \tag{14.10}$$

We arrive to a linear relationship between yield and total evapotranspiration (ET^{sea}). The intercept is negative, and the x-intercept is an approximation to soil evaporation while the slope is the product of HI and WUE.

We are interested in computing yield as a function of water used (ET^{sea}). A simple approach that requires a priori estimates of ET and yield in unstressed crops (ET_x^{sea} and Y_x) is the model of Stewart which calculates the relative reduction in yield as a linear function of the relative reduction in ET:

$$1 - \frac{Y}{Y_x} = K_y \left(1 - \frac{ET}{ET_x} \right) \tag{14.11}$$

where K_y is a coefficient of sensitivity to water stress. If HI is not affected by water stress and we change ET^{sea} while keeping soil evaporation constant, K_y will depend only on the ratio soil evaporation: transpiration:

$$K_y = 1 + \frac{E_s^{sea}}{E_p^{sea}} \tag{14.12}$$

On the other hand, if soil evaporation if proportional to ET, K_y should tend to 1. These relations are not valid for severe water stress that reduces HI (see Eq. 13.10). In general, the empirical values reported for K_y are in the range of 0.8–1.5.

The Stewart model which was adopted by the FAO Manual 33 of Doorenbos and Kassam, has been used as a first approximation for calculating yield as a function of ET but has a number of limitations:

- Variation in WUE: For a given environment the actual mean WUE will depend on when actual transpiration occurs due to the inverse dependence of WUE on Vapor Pressure Deficit. Under water stress the pattern of water use will change as compared to the unstressed situation which may lead to important changes in WUE.
- Calculation of unstressed yield: In the absence of local, reliable data a good alternative would be to use a crop simulation model, calibrated and verified for local conditions.
- Irrigation method: the irrigation method affects evaporation from the soil surface. Obviously different E_s leads to different ET for the same transpiration (the variable which is directly related to biomass and yield). The K_y coefficient of Eq. 14.6 can be considered independent only if E_s and E_p are affected equally by a reduction in the supply of irrigation, which is very unlikely.
- Acclimation: crops responses to water stress are conditional to the previous history of stress. In addition, the effect of water deficit in perennials can be carried over from one season to the next.

These limitations are common to any empirical model used to generate universal production functions. However, their use can be advantageous in those cases where a high accuracy is not required, and in many cases these empirical models are the only available alternative for practical purposes.

14.6.2 The AquaCrop Simulation Model

AquaCrop (www.fao.org/nr/water/aquacrop.html) is a simulation model that predicts yield as a function of water supply. It is based on the relation between B and T and on the constancy of WUE (for a given species) if normalized by the evaporative demand (reference ET). After seedling emergence, the model calculates the rate of canopy expansion, and the T and E components of ET by computing soil water extraction on a daily basis. Based on the amount of T, the model then calculates the increment of B which is accumulated until harvest. As the canopy develops and the crop grows driven by thermal time, different developmental stages occur and, depending on the crop, the harvest index is built up during the pertinent period and yield is computed at harvest date.

Water stress affects the computations via reductions in canopy expansion first, followed by reductions in stomatal conductance and acceleration of canopy senescence. Different crop-specific thresholds in root zone water content are defined for each process, and the HI is also modulated by water deficits, generally decreasing under severe stress. The model gives an estimate of water-limited potential yield without any other limiting or yield-reducing factors. It has a soil fertility module to make adjustments to non-optimal fertility conditions which are common in many agricultural systems.

To obtain accurate predictions, AquaCrop should be calibrated and validated with experimental data in the environment where it will be utilized. Its description, together with its numerous applications may be found in FAO 66.

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Chapter 15
Limitations to Crop Productivity

Victor O. Sadras, Francisco J. Villalobos, and Elias Fereres

Abstract Environmental factors including water stress, nutrient deficiency, high or low temperatures, chemical (Al-toxicity, salinity) and physical soil constraints (e.g. compaction), and biotic factors reduce crop yield. Deficit of water and nitrogen, and soil constraints generally have a larger impact on canopy size and duration, hence growth reductions are closely linked with reduced intercepted radiation; radiation use efficiency is generally less responsive to stress. Extreme temperatures at critical stages usually reduce harvest index and yield. Other stresses can be neutral, positive or negative for harvest index; this depends in particular on the nature, timing, intensity and duration of stress and its relative impact on total and harvestable biomass. Yields are also reduced by the action of biotic agents such as pests, diseases and weeds. Potential yield losses to biotic stresses may be quite high but are decreased by crop protection practices.

15.1 Introduction

In Chap. 13 we have analyzed crop yield as a function of temperature and radiation interception. This "potential" yield will be higher than actual yields as other biotic and abiotic factors come into play. The main abiotic factors that reduce crop yields are water stress (already reviewed in Chap. 14), nutrient deficits, adverse chemical conditions (salinity, acidity), water excess and meteorological events (extreme high or low temperatures, hail, wind). Biotic factors are weeds, animal pests and diseases.

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In this chapter we'll revise the main impact of these factors on crop productivity. Some of them will be treated in more detail in specific chapters of this book (salinity, nutrient deficits, frost).

15.2 Nutrient Deficiency and Soil Related Limitations of Productivity

Deficit of water and nutrients reduce biomass by primarily reducing leaf area index and radiation interception; under severe stress radiation use efficiency is also reduced. This is because tissue expansion is more sensitive to both water and nutrient deficit than leaf photosynthetic rate. Indeed, a common short-term response of water and nitrogen stressed plants is to accumulate carbohydrates as the restriction in expansion is more severe than the restriction in photosynthesis, leading to transient excess of reduced carbon.

The effects of nitrogen supply on crop growth and yield can thus be explained in terms of its effects on interception and efficiency in the use of radiation. Nitrogen deficit reduces crop LAI by reducing tillering or branching, and leaf expansion (Fig. 15.1). Reduced leaf size of nitrogen-deficient crops is associated with reduced rates of cell division and expansion (Table 15.1). Nitrogen deficit can accelerate leaf senescence (Fig. 15.2), further contributing to reduced radiation interception and photosynthesis. Rubisco and light-harvesting proteins involved in photosynthesis represent 60 % of the leaf N content, hence the link: shortage of nitrogen → less Rubisco → less photosynthesis.

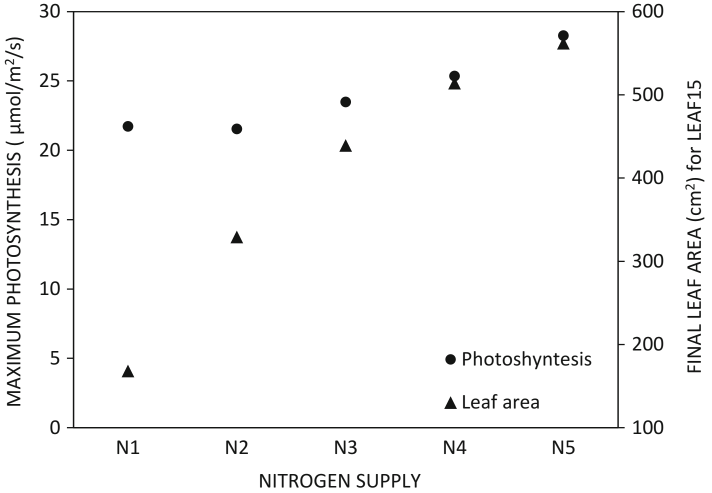


Fig. 15.1 Nitrogen deficit reduces photosynthesis and leaf size. Sunflower plants where grown under five nitrogen regimes, with extreme treatments receiving 0.25 (N1) and 7.5 g N per plant (N5) (Adapted from Connor et al. (1993) Aust J Plant Physiol 20: 251–263)

Table 15.1 Nitrogen deficit reduces cell number and size, hence leaf area of sunflower

	Number of cells	Area per cell	Leaf area
	$\times 10^6$	μm^2	cm^2
High N	56	554	302
Low N	33	443	147

Data for leaf number 10 at full expansion under high or low N supply are shown

Adapted from Trapani et al. (1999) Ann. Bot. 84:599–606

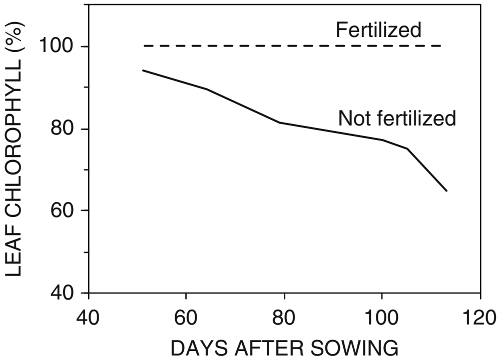


Fig. 15.2 Nitrogen deficiency accelerates leaf senescence of wheat. Leaf chlorophyll, measured in the youngest expanded leaf, is expressed as percentage of that of fertilized crops (Adapted from Caviglia and Sadras (2001) Field Crops Res 69:259–266)

The effects of water supply on crop growth and yield (Chap. 14) can also be explained in terms of interception and efficiency in the use of radiation. In response to water deficit, plants have largely irreversible responses such as reduced tillering or branching, and reduced leaf expansion. Reduced stomatal conductance and wilting are transient crop responses to water deficit that reduce both crop water use and photosynthesis. Figure 15.3 illustrates the saw tooth pattern of radiation interception in alternating dry-wet periods with transient wilting and recovery after irrigation. In addition to the individual effects of nitrogen and water, these resources often interact in complex ways. In wheat crops growing under a combination of irrigation and fertilizer regimes, RUE was 1.8 g/MJ in rainfed, unfertilized crops and increased to 2.1 g/MJ with nitrogen fertilization. Weekly irrigation did not improve RUE in unfertilized crops, but irrigation combined with nitrogen fertilization increased efficiency to 2.5 g/MJ.

In common with water and nitrogen supply, the reduction in crop growth in response to physical and chemical soil constraints is mostly mediated by reduced canopy size and interception of radiation, whereas radiation use efficiency is less responsive to stress. This is illustrated in two examples. Soil compaction is a common problem, often caused by tillage, machinery traffic, and loss of organic matter, which is reflected in increased soil bulk density. Its effects on the crop are twofold: it hinders the emergence and establishment of seedlings and slows down growth of the root system and depresses shoot growth. The effect of compaction on root growth is quantified by the penetration resistance, which can be measured with a penetrometer. For a particular soil, penetration resistance is directly proportional to the apparent density and inversely proportional to the water content of the soil.

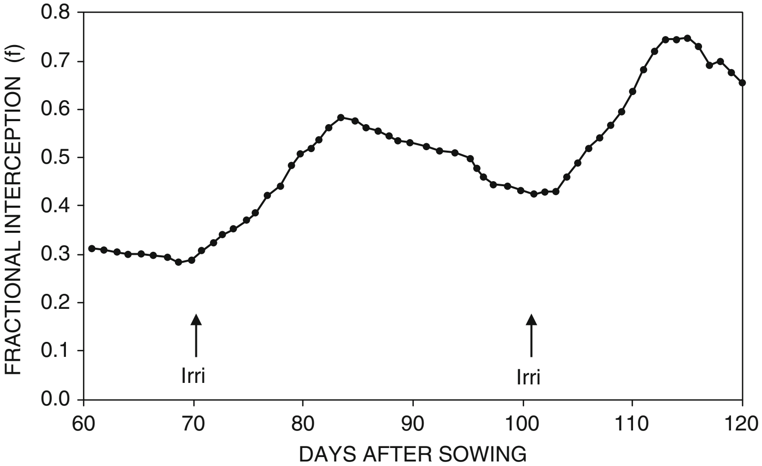


Fig. 15.3 Dynamics of fractional radiation interception of peanut crops. The saw-tooth pattern of radiation interception results from transient wilting and recovery after irrigation. During this period LAI increased from 0.5 to 2. *Arrows* show time of irrigation (Adapted from Matthews et al. (1988) Exp Agric 24:203–213)

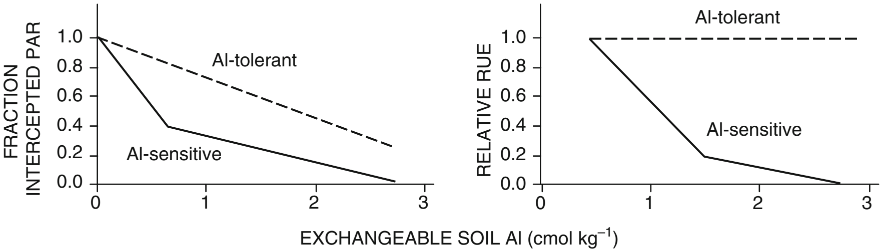


Fig. 15.4 Effects of soil aluminium toxicity on (**a**) intercepted radiation and (**b**) radiation use efficiency of wheat crops (Adapted from Valle et al. (2009) Field Crops Res 114:343–350)

Therefore the effects of compaction are more severe when the soil is dry (Chap. 17). In the Mallee region of south-eastern Australia, sandy soils often develop a compacted layer at 0.2–0.3 m depth, thus restricting root proliferation, and water and nitrogen uptake below this depth. Crops in compacted soil were compared with crops in soils were deep ripping was used to remove the constraint. Wheat yield in compacted soil ranged from 1.2 to 2.9 t/ha, and ripping improved yield up to 40 %. The reduction in yield associated with compaction was fully accounted for by the reduction in leaf area index and intercepted radiation, whereas radiation use efficiency was unaffected by soil condition. Aluminum toxicity reduces yield in acid soils ($pH<5.8$), which represent about 30 % of agricultural soils worldwide. Growth analysis of Al-tolerant and Al-sensitive wheats in southern Chile showed a marked reduction in intercepted radiation with increased concentration of Al in soils, a largely unresponsive RUE in the tolerant wheat, and reductions in RUE in sensitive wheat only at high Al concentrations (Fig. 15.4).

15.3 Climatic Accidents

We will consider the effect of extreme low temperatures in Chap. 29 and the effects of wind in Chap. 27.

15.3.1 High Temperature

In general the main effect of extreme high temperature is a reduction in HI due to reduced pollination or seed abortion. For instance, the number of grains in winter cereals decreases with canopy temperature above 31 °C. On the other hand, high temperatures will promote leaf senescence and shorten the grain filling period.

In Mediterranean climates low water availability is coincident with high temperature so low transpiration due to water stress amplifies heat stress as canopy temperature increases above air temperature.

15.3.2 Hail

Hail is a form of solid precipitation consisting of ice balls or lumps of ice which originate in strong thunderstorm clouds (cumulonimbi). The hailstones show diameters typically between 5 and 12 mm. Hail occurrence is localized, with areas affected from a few hectares to hundredths of has.

Occurrence of hail is more frequent in mid-latitudes (inland areas, elevated regions) than in the tropics despite the higher frequency of thunderstorms. Some areas where hailstorms are common are Northern India and some regions of China and Central Europe. During the year hail will occur mostly during spring and summer.

Damage to the crop is due to the impact of hailstones which velocity will be proportional to size. For a 1 cm diameter hailstone, terminal velocity could reach 9 m/s while an 8-cm hailstone would fall at 48 m/s. Apart from the direct physical damage that destroys leaves or reproductive structures, wounds facilitate the infection by pathogens. The effect of defoliation due to hail on crop yield depends on the development stage when hail occurs and the level of defoliation. Partial early defoliation may be compensated by increased dry matter allocation to leaves resulting in a small reduction in yield. Full defoliation before anthesis may be catastrophic for yield. Damage to reproductive structures leads to reduced Harvest Index in proportion to the number of structures affected. Partial damage of fruits reduces their commercial value.

High value crops may be protected by covering with anti-hail nets. In field crops or extensive fruit production the main protection alternatives are:

- anti-hail rockets that use silver iodide
- ground generators that produce smoke with silver iodide
- anti-hail guns: they use shockwaves directed at the hail storm
- crop insurance

15.4 Waterlogging

High soil water content implies a limited supply of oxygen for root respiration, so root functioning (absorption, growth) is impaired. If the soil is saturated the roots decompose starting from the tips, plant stops growing and eventually it will die. Most often crops will suffer from temporal waterlogging events and will recover partially afterwards, but the poor root system will have a low capacity for water and nutrient absorption. The overall effect will be reduced yield.

Waterlogging also contributes to N losses by denitrification (see Chap. 24), the conversion of nitrate to volatile N compounds. Low N uptake will cause symptoms of N deficiency.

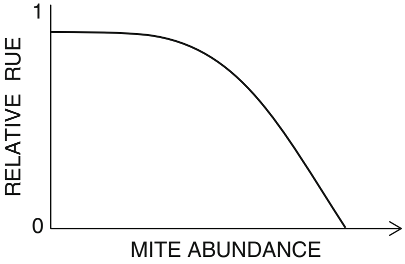
Waterlogging may be prevented by improving the drainage system of the field or using raised bed planting.

15.5 Biotic Factors

Biotic agents causing crop damage (generically known as pests) are weeds, animal pests (arthropods, nematodes, gastropods, rodents, birds), pathogens (fungi, bacteria) and viruses.

The effect of pests and diseases on crop growth can also be analyzed in terms of capture and efficiency in the use of radiation, and harvest index (Eq. 13.3). Insects that feed on reproductive structures, such as cotton bollworms, have a primary effect on harvest index. In extreme cases of uncontrolled infestation for example, cotton crops can accumulate large amounts of biomass with little fruit set, hence reduced harvest index and yield. Defoliators reduce leaf area and intercepted radiation, whereas some diseases can also reduce photosynthetic rate of individual leaves and RUE. Spider mites for example, pierce the leaf epidermis with needle-like mouthparts and feed on mesophyll and palisade cells, thus reducing leaf photosynthesis and RUE (Fig. 15.5). Comparisons of wheat crops protected with fungicides, and unprotected crops exposed to damage by foliar pathogens showed that growth reduction was mostly associated with reduced healthy leaf area, with a secondary contribution of reduced radiation use efficiency.

Fig. 15.5 Spider mites feed on mesophyll and palisade cotton leaves, reducing leaf photosynthesis and radiation use efficiency (Adapted from Sadras and Wilson (1997) Crop Sci 37:481–491)



15.5.1 Arthropods

Many species of insects and other arthropods are present in the agro-ecosystem but only a few are important pests, and may cause complete yield loss. Insects are six-legged invertebrates that usually undergo metamorphosis during development. Adult insects have three body regions (head, thorax and abdomen), three pairs of legs, one pair of antennae, complex mouthparts, and frequently two pairs of wings. The skin of an insect is the exoskeleton, which covers the whole body.

All insects have an egg and an adult stage. Complete metamorphosis includes four stages (egg, larva, pupa and adult). The most common, foliage-eating insect pests are larvae of *Lepidoptera* (butterflies and moths) and larvae and adults of *Coleoptera* (beetles). Aphids, leafhoppers and thrips not only feed on the crop but are also the main vector for transmission of plant virus diseases.

Many insect species are predators or parasites of other insects and are, thus, beneficial.

15.5.2 Plant Pathogens

Plant pathogens (fungi, bacteria, virus, nematodes, etc.) affect crop plants by altering the following processes:

- photosynthesis: destruction of photosynthetic tissue, degradation of chloroplasts, leaf senescence, yellowing, etc.
- water and nutrient transport: destruction of roots, formation of root galls and root knots, impaired root absorption, destruction or blocking of xylem tissue, damage to leaf cuticles or stomatal function (higher transpiration), altered phloem transport.
- plant respiration increases after infection which contributes to depleting the plant reserves.

- membrane permeability also increases causing leaf damage by loss of nutrients and entry of toxins
- changes in transcription and translation of nucleic acids alter plant function and structure and the synthesis of enzymes or substances involved in plant resistance.

The disease starts with a primary infection (first in the season) due to primary inoculum (spores or fungal mycelium) that overwinters. Overwintering is the ability of a pathogen to survive from one growing season to the next.

The probability of a disease epidemic is proportional to the amount of inoculum and to the proximity to its host. Primary infection occurs when the pathogen is in contact with a susceptible host under suitable conditions. The pathogens enter directly through the surface of the plant or through wounds or natural openings. Bacterial and fungal pathogens usually require free water for spore germination, so infection is favored by wet periods with high air humidity and by wet canopies.

Dissemination of the pathogen from an inoculum source to a host can occur by wind, splashing rain, runoff, insects, infected seeds or seedlings, etc. Fungi grow and spread within their host by means of mycelium, and eventually produce spores on or within the infected tissue. These spores lead to secondary infections during the season. Bacteria spread in the plant by rapidly increasing the population. Then, when fissures develop on infected tissue, the cells (secondary inoculum) are exposed to the environment and thus, dissemination may proceed.

The secondary infection cycle can be repeated many times during the growing season, depending on the biology of the pathogen and its host and environmental conditions.

15.5.3 Yield Losses Due to Pests

Two crop yield loss rates may be differentiated. The loss potential characterizes the risk that the agent exerts on crop yield in a no-control scenario. The actual losses are those occurring despite the crop protection practices. The efficacy of the crop protection practices may be evaluated as a percentage of potential losses prevented. The potential and actual loss are quite variable depending on the crop species and the region considered. Among crops the loss potential of all biotic factors worldwide varies between 50 % (wheat) and more than 80 % (cotton). Actual losses are estimated at 26–31 % for soybean, wheat, maize and cotton, and 37–40 % for potatoes and rice, respectively (Table 15.2). Overall, weeds have the highest loss potential (23–40 %) with animal pests and pathogens being less important (9–37 % and 9–29 %, respectively). Although viruses cause serious problems in potatoes and sugar beets in some areas, worldwide losses due to viruses average 6–7 % on these crops and <1–3 % in other crops. The efficacy of crop protection lies between 43 and 65 % for the different crops. Global efficacy in weed control (67–80 %) is

Table 15.2 Yield losses (%) due to pests at a global scale. Potential and actual yield losses are those occurring in a no-control and a current control scenario, respectively. The efficacy of control is the percentage of losses prevented by current control measures

		Wheat	Rice	Maize	Potato	Soybean	Cotton
Weeds	Potential	23	37.1	40.3	30.2	37	35.9
	Actual	7.7	10.2	10.5	8.3	7.5	8.6
	Efficacy	67	73	74	73	80	76
Animal pests	Potential	8.7	24.7	15.9	15.3	10.7	36.8
	Actual	7.9	15.1	9.6	10.9	8.8	12.3
	Efficacy	9	39	40	29	18	67
Pathogens and viruses	Potential	18.1	15.2	12.3	29.3	12.4	9.3
	Actual	12.6	12.2	11.2	21.1	10.1	7.9
	Efficacy	30	20	9	28	19	15
Total	Potential	49.8	77	68.5	74.9	60	82
	Actual	28.2	37.4	31.2	40.3	26.3	28.8
	Efficacy	43	51	54	46	56	65

Adapted from Oerke (2006)

much higher than that of animal pests (9–67 %) or diseases (9–30 %). These values have to be taken only as indicative as they are based on estimates of reference yields (not affected by pests).

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Part III
Crop Management

Chapter 16
Sowing and Planting

Francisco J. Villalobos, Francisco Orgaz, and Elias Fereres

Abstract Successful crop establishment depends on several factors at the time of sowing (soil water content, soil structure and soil temperature, seed viability, presence of pests). Therefore decisions regarding the date and depth of sowing, the planting density, the spatial arrangement of plants and other cultural techniques (irrigation, fertilization, application of pesticides) will be critical. Sowing date should match the growing cycle to the best possible environmental conditions for the crop. Early spring sowings improve water use efficiency in Mediterranean areas but increase the risk of attacks by biotic factors. Seeding rate is a function of single seed mass, desired planting density, seed viability and expected fraction of emerged plants. Trees and some annuals species are sown in nurseries where they grow for some time until they are transplanted to the field. The best time for planting trees is autumn when they are dormant and the risk of desiccation is minimal.

16.1 Introduction

By sowing or planting the farmer intends to ensure good crop establishment and get the right conditions for growth, development and yield. For many crops the establishment phase (germination, emergence and early seedling growth) is the most critical phase of the cycle. To succeed, the farmer must make a series of

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decisions related to the amount of seed to be used, the method of planting and the spatial distribution of seeds, the planting date, the application of pesticides or performing additional tasks like irrigation.

16.2 Crop Emergence

Some time after sowing the seeds, the seedlings will emerge from the soil. The duration of this period and the success, i.e. the fraction of seeds leading to emerged seedlings, depend on several factors:

- Seed viability: A viable seed is one able to germinate under suitable conditions. Viability decreases with time from the harvest of the seeds, and occurs in parallel to the loss of reserve substances (e.g. lipid oxidation in sunflower seeds). In some species there are mechanisms that delay seed germination, such as the presence of germination inhibitors or waterproof coats. For these cases germination may be improved by scarification (mechanical abrasion or chemical treatment with acids to improve the permeability of seed coats) or stratification (placing the seeds between layers of cold (1–5 °C) moist soil).
- Soil water content: Germination is a process that begins with water uptake by the dry seed (imbibition). If the soil is dry or the contact seed-soil is loose the transport of water from the soil to the seed is prevented and germination does not proceed. After germination, the radicle expands, which contributes to guarantee the supply of water to the seedling. The increase in depth of the radicle occurs in advance to hypocotyl growth, so that, at the time of emergence, root depth normally exceeds 10 cm.
- Temperature: Along with depth, temperature will determine the duration of the sowing-emergence period. If this period is too long, the likelihood of attacks by pathogens or soil insects increases. Table 16.1 shows the average values of thermal time from sowing to emergence and its base temperature for a series of annual crops.
- Soil structure: the presence of a surface crust or excessive soil compaction above the seed makes emergence difficult as they prevent the expansion of the hypocotyl, especially if the soil is dry (see Chap. 17). A greater amount of seed or wetting the soil can contribute to mitigating the effects of the surface crust.
- Presence of pests or pathogens: during emergence and initial seedling growth, attacks by insects or soil fungi can often lead to a failure of crop establishment. To avoid this problem fungicides (seed treatment) and/or insecticides (seed and/or soil treatments) are applied.
- Oxygen concentration in the soil: the processes of germination and emergence use energy derived from the seed reserves through respiration, which is an aerobic process. This is why the fraction of emerged plants can be greatly reduced in waterlogged soils.

Table 16.1 Base temperature (T_b, °C) and thermal time (TT, °Cd) required to complete the phase sowing-emergence for a series of crop species

	Thermal time	T_b
	°C d	°C
Amaranthus	32	11.7
Barley	120	0
Bean	52	10.6
Buckwheat	37	11.1
Castor bean	95	12.5
Chickpea	94	4.5
Cotton	60	15.5
Cucumber	40	15.5
Faba bean	200	1.2
Lentil	90	1.4
Linseed	89	1.9
Maize	75	8
Melon	52	15.5
Millet (finger)	40	13.5
Millet (foxtail)	42	10.9
Millet (pearl)	40	11.8
Millet (proso)	45	10.4
Oats	132	1.6
Pea	110	1.4
Peanut	76	13.3
Pepper	135	13
Rapeseed	79	2.6
Rye	91	2.2
Ryegrass	130	2
Safflower	70	7.4
Sesame	21	16
Sorghum	74	8
Soybean	70	9.9
Sunflower	67	7.9
Tomato	57.5	9.3
Trifolium spp	150	0
Watermelon	55	15.5
Wheat	110	0

The values shown in this table have been obtained experimentally under field conditions with high water content in the soil and planting depth of about 3 cm

Adapted from Angus et al. (1980) Field Crops Res 3:365–378 and Moot et al. (2000) New Zealand J Agric Res 43:15–25

16.3 Decisions Related to Sowing

The farmer has to make a series of operational decisions before sowing the crop, such as the date of sowing, the amount of seed (seeding rate), the sowing depth, the planting pattern (row distance, plant spacing within the row). Additional operations may be required such as fertilization, irrigation, application of pesticides or tillage.

The method of sowing which may imply the selection of the planting machinery (e.g. seed drill) is a key strategic decision for the farmer.

16.4 Sowing Date

The choice of sowing date has to ensure that the crop cycle matches the most suitable period for growth and yield. A first limitation on the growth of a crop is its ability to survive when exposed to low temperatures. In mid latitudes, this limitation allows classifying crops into two categories:

(a) Autumn sown crops: species able to withstand frost and grow at low temperatures (winter cereals like wheat or rye, rapeseed, flax, faba beans, beets, etc.). They have a low base temperature.
(b) Spring planting: species with high base temperature (corn, cotton, soybeans). They are damaged even by low temperatures above freezing.

Regardless of the type of crop, early plantings have several advantages:

(a) The Water Use Efficiency is inversely proportional to Vapor Pressure Deficit (Chap. 14). If crops are grown in a period of low evaporative demand (early planting date) they produce more biomass and will require less water in irrigated conditions. This is especially important in Mediterranean climates as rainfall decreases and evaporative demand increases from spring to summer.
(b) The grain filling process is more efficient and longer if the temperature is not too high. If we avoid this process to occur under very warm conditions the harvest index will increase and so yield will do.
(c) In some spring-summer crops the cycle may be terminated by cold temperatures in autumn (e.g. cotton). Therefore early sowing favors crop maturing before the low temperatures stop crop development. Additionally, autumn precipitation may adversely affect crop quality.
(d) In some horticultural crops the price is directly proportional to precocity (melon, watermelon, etc.) thus early sowing allows increased revenue.

Early planting may be limited by possible negative effects later in the growing season. For winter cereals it is extremely important to avoid frost during anthesis, and this is achieved by preventing excessively early plantings, and/or using longer season cultivars (winter types with large vernalization requirement). The environmental conditions at the time of sowing may also restrict early sowings:

– If the temperature is too low, the crop takes a long time to emerge and establish, allowing the attack of biotic agents and leading to a significant reduction in the fraction of established plants. Also under low temperature conditions, weed competition will be more severe. In general we must sow when the temperature is such that the sowing-emergence period does not exceed 15–20 days. To calculate the time from sowing to emergence as a function of temperature for different crops, we can use the information presented in Table 16.1.

– Water content in the soil at the time of sowing should ensure seed imbibition and the water supply to the seedlings after they emerge. In Mediterranean areas the autumn sowing is usually delayed until the rains have been sufficient and evaporative demand is low. Sowing over partially dry soil may cause relatively early emergence (with high evaporative demand) but seedlings may die if the rains do not continue.

16.5 Seeding Rate and Planting Density

The amount of seed to be applied per unit area (seeding rate) depends on the cost of the seed and on planting density desired.

(a) Cost of seed: In general the cost of seed is a low fraction of total cultivation costs. However, the consequences of using a small amount of seed or low quality seed may be extremely negative (see the importance of obtaining a suitable planting density in Chap. 12). In general we should use high quality seeds. The indices used to characterize the quality of the seed are viability (germination percentage) and purity (proportion of the seed belonging to the acquired cultivar). The seed should be free of pests, diseases and weed seeds and present a suitable size. The probability of emergence and the growth rate of the seedling afterwards are both proportional to seed size.

(b) Density: The amount of seed used must be sufficient to ensure the emergence and establishment of a sufficient number of seedlings. The excess of seed applied depends on various factors (seed viability, soil structure, pathogens, water content, etc.).

To calculate the seeding rate (g m^{-2}) we can use:

$$QS = \frac{p_u D_p}{f_1 f_2} \tag{16.1}$$

where p_u is the mass of each seed (g/seed), D_p is the desired planting density (plants m^{-2}), f_1 is the viability (fraction) and f_2 is the fraction of viable seeds that become established plants. The values of p_u can be measured directly by weighing a known number of seeds or estimated using Table 16.2, which also shows intervals of D_p for various crops. Viability (f_1) depends largely on the quality of the seed, and is

Table 16.2 Mass per seed, planting density and minimum amount of seed required for different crop species

	Mass (fresh) per seed			Planting density			Seed rate		
	mg/seed			Plants/m^2			kg seed/ha		
Crop	Min	Max	Average	Min	Max	Average	Min	Max	Average
Alfalfa	2.1	2.3	2.2	400	500	450	8	12	10
Cotton	100	120	110	5	10	75	5	12	8
Lupin (white)	200	320	260	30	60	45	60	192	117
Lupin (yellow)	100	130	115	30	60	45	30	78	52
Oat	30	45	37.5	130	250	190	39	113	71
Safflower	30	50	40	25	50	37.5	8	25	15
Barley	30	50	40	150	230	190	45	115	76
Rye	25	35	30	140	250	195	35	88	59
Rape	2.5	4	3.25	50	180	115	1	7	4
Chickpea	50	70	60	25	45	35	13	32	21
Sunflower (oil)	100	140	120	6	12	9	6	17	11
Sunflower (seed)	150	180	165	4	7	5.5	6	13	9
Pea	125	300	212.5	35	100	67.5	44	300	143
Faba bean	350	800	575	15	50	32.5	53	400	187
Bean	130	500	315	25	10	17.5	33	50	55
Lentil	20	80	50	100	150	125	20	120	63
Flax	5	7	6	100	400	250	5	28	15
Maize	350	400	375	7	10	8.5	25	40	32
Sugar beet	20	20	20	6	9	7.5	1	2	2
Soybean	100	200	150	15	60	37.5	15	120	56

Sorghum (grain)	20	30	25	10	13	11.5	2	4	3
Sorghum (forrage)	20	30	25	80	140	110	16	42	28
Clover	0.6	0.8	0.7	500	900	700	3	7	5
Wheat	30	45	37.5	150	250	200	45	113	75
Triticale	30	50	40	180	220	200	54	110	80
Vetch	20	30	25	200	300	250	40	90	63
Potato	23,000	30,000	27,000	7.5	13.3	10	1725	3990	2700
Garlic	1500	6000	3500	20	28	24	300	1680	840
Garlic white type	1000	8000	5000	20	28	24	200	2240	1200
Onion	4	10	7	60	90	80	2.40	9.00	5.60
Pepper	5	10	7	4	6	5	0.20	0.60	0.35
Tomato	2.2	3.3	2.8	2	6	4	0.04	0.20	0.11
Melon	29	47	38	0.4	1	0.7	0.12	0.47	0.27
Watermelon	35	60	47	0.25	1	0.75	0.09	0.60	0.35
Leek	2.5	3.2	2.8	16	38	25	0.40	1.22	0.70

usually above 0.9 for certified seed. The value of f_2 depends greatly on the state of the soil at planting, sowing depth and environmental conditions after planting. Under adverse conditions f_2 will be proportional to seed size.

Example 16.1 We will calculate the seeding rate for wheat to obtain a density of 150 plants m^{-2} if the percentage of viable seeds that emerge is 90 % and the seed has a viability of 0.95.

In Table 16.2 we see that wheat seed mass is between 30 and 45 mg. If we take an intermediate value (37 mg/seed) the seeding rate should be:

$$QS = \frac{37\quad 10^{-3} \times 150}{0.9\quad 0.95} = 6.5\ \ \mathrm{g\ m^{-2}} = 65\ \ \mathrm{kg/ha}$$

16.6 Sowing Depth

The more appropriate sowing depth depends on the conditions of temperature and water content of the soil. In general, soil water content increases with depth while temperature and oxygen availability decrease. The greater the sowing depth the greater expansion of the hypocotyl required to reach the soil surface. If the depth is excessive reserves would be exhausted before emergence. Therefore, larger seeds allow deeper sowings. Very large seeds (faba beans, beans) allow depths up to about 15 cm, while the medium sized seeds (winter cereals, sunflower, cotton) should not exceed around 10 cm sowing depth and small seeds (onion, carrot) allow less than 3 cm. In the latter case it is difficult to ensure adequate soil water content in the surface layer, requiring irrigation for successful emergence.

The rules about sowing depth may show remarkable exceptions. For instance, in the very dry inland area of the Pacific Northwest of the USA winter wheat is sown in late summer at depths as large as 20 cm to ensure water supply to the seed and crop emergence.

16.7 Planting Pattern and Sowing Method

Crop plants are usually sown in rows at spacing between 0.15 and 0.20 m (cereals, rapeseed) and 1 m (e.g. cotton). Wide separations between rows were in many cases required for mechanical control of weeds. The appearance and use of herbicides has allowed reducing the inter-row spacing, which contributes to increase the radiation interception.

In many species yield is relatively independent of the distance between plants (e.g. winter cereals). In some (garlic, beets) excessive crowding can lead to a reduction in yield or quality of the harvested product.

The sowing method to use depends on the type of crop, soil conditions and available machinery. The methods used are:

(a) Broadcasting: the seeds are randomly distributed in the field. The application can be done by hand, using centrifugal fertilizer broadcasters or an airplane, as in the case of rice. Usually a broadcasting sowing requires further operations to bury the seeds, and carries a high cost of seed, poor distribution uniformity and irregularity in the sowing depth.
(b) Sowing in furrows: It is done by opening furrows in the soil and depositing the seeds inside, which is usually performed with a seed drill. This drill has the necessary equipment to open the furrow (shoe type, hoe type or disk), deposit the seeds and close the furrows (plank, disks). In some cases, to allow post-emergence tillage and achieve optimum planting density, crop rows are distributed non-uniformly as in the case of the paired lines, in which the lines are grouped in close pairs, separated from the next pair by enough distance to allow inter-row tillage operations.

Precision seed drills provide a better distribution of seeds which saves seed, and in some cases, avoids the need for plant thinning (e.g. sugar beet).

16.8 Additional Operations

At the time of sowing, other farming operations that contribute to crop establishment may be performed:

(a) Irrigation: The application of irrigation may be needed to ensure germination and emergence. In soils that form surface crust, more than one irrigation application may be needed to prevent hardening of the crust.
(b) Tillage: The pre-planting tillage should contribute to the formation of a suitable seedbed. This entails small aggregates in the surface and sufficient soil water content in the upper layer. In some methods of sowing, the seed once deposited in the soil should then be covered by harrowing. In other cases it may be necessary to slightly compact the soil surface to ensure water supply to the seed (e.g. roller pass in small seed crops). Soil compaction after sowing also contributes to soil warming (Chap. 6) and thus to faster emergence.
(c) Fertilizers and pesticides: It is common to apply fertilizers (P, K and some N) and other products (e.g. pesticides) while preparing the seed bed. Some seed drills allow localized fertilizer application at sowing time which can be of great interest in poor soils, especially for P and K (Chap. 26). Other products (soil insecticides, pre-emergence herbicides) may be also applied along with the seed.

16.9 Transplanting of Annuals

In the case of some horticultural crops, the seedlings are grown at a place (nursery) during some time and then they are transplanted to the field. The need for transplantation may be due to:

(a) High seed cost, poor germination success and/or delicate seedlings: The conditions in the nursery can be manipulated to provide a suitable environment for the seedlings. This can be achieved by soil heating or using plastic or glass covers. The associated cost will be acceptable in the nursery because of its small size.
(b) The need to shorten the cycle: In the nursery we can maintain proper conditions of moisture and temperature, hastening the crop cycle in a time when external conditions are unfavorable.

The structures used as nurseries range from natural shelters to greenhouses. In the nursery the seeds are planted at high density. The seedlings are maintained in the nursery until its final transplanting to the field. During that time some thinning of plants may be required to avoid etiolation.

16.10 Transplanting and Grafting of Trees

Trees of agricultural interest are usually fruit trees with planting densities ranging from 50 to more than 1000 trees/ha. Some species with industrial interest (e.g. rubber tree, cork oak) and ornamental trees and shrubs may be also of commercial value. Plantations of fruit trees are established to last for long, typically more than 15–20 years. Fruit tree species may be evergreen (citrus, olive) or deciduous (pome fruits, stone fruits, walnut).

Plantations are established by transplanting young trees grown in nurseries. In principle trees may be planted at any time of year, provided that temperatures are not too low. However, successful establishment requires an adequate balance between root water uptake and water loss by transpiration to avoid desiccation and death. The best time for planting is autumn when the tree is dormant, the air temperature is low and the soil temperature is still warm, which enhances root growth. Leafless trees of deciduous species may be planted as bare-root trees in autumn or spring. Evergreen species require using trees with active root systems and are then transplanted directly from the pots where they have grown in the nursery.

A typical limiting factor for tree growth is soil compaction so breaking any compacted soil layers by deep vertical tillage is a common practice before transplanting.

Although not specifically planting operations, pruning allows renovating the tree structure while grafting is used to change the cultivar (scion) which constitutes most of the tree shoot while keeping the rootstock.

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Chapter 17
Tillage

José A. Gómez, Francisco Orgaz, Helena Gómez-Macpherson, Francisco J. Villalobos, and Elias Fereres

Abstract Tillage has been developed in farming to improve soil conditions in relation to the water balance and crop growth, to incorporate crop residues, and for weed control and preparation of the seedbed. The effects of tillage depend greatly on the water content and the characteristics of the soil. Clay soils will not be usually found under the more suitable conditions for tilling, which are easier to find on medium or coarse textured soils. The main undesirable effects of tillage are soil compaction, which leads to a reduction in crop yields, and soil degradation, particularly due to water erosion (Chap. 18). Erosion of the surface soil layers reduce the natural fertility and the water retention capacity of soils.

17.1 Introduction

From the point of view of farming, the soil has often been viewed as a mere medium on which the crop grows. Thus, the soil structure should be suitable for the germination of the seeds and the growth of the roots and must have characteristics that enhance the storage and supply of water, nutrients, gases and heat to the crop. From this perspective tillage is inseparable from agriculture. The transformation of a natural ecosystem into an agroecosystem requires necessarily a mechanical intervention on the soil. Since hoe tillage, and later the Roman plow, followed by the appearance of the moldboard plow, and finally the development of mechanical traction, tillage and crop cultivation have been virtually synonymous.

Each soil-crop-climate system presents specific problems that require the use of different tillage operations, which has led to the development of diverse machinery

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whose engineering is well known. Unfortunately, much less is known about the effects of tillage on the physical, chemical and biological properties of the soil, and ultimately on the effects on crop yield. This limited knowledge is often translated into tillage practices whose only rationale is the habit or tradition from the times when tillage was performed using animal power.

In western agriculture traditional or conventional tillage, which is characterized by a large number of operations, using diverse implements and powerful tractors, is increasingly challenged by the high cost of energy expenditure and by soil degradation resulting in different environmental problems in numerous agricultural areas. The rationalization of tillage requires considering the soil as a valuable resource and should be based on a better understanding of the effects of tillage on soil properties and on crop production, which is the objective of this chapter.

17.2 Objectives of Tillage

Traditionally tillage had three main objectives, which were seedbed preparation, improving soil conditions for crop growth and controlling weeds. But the goals have changed with the appearance of new technologies (herbicides, seed drills), new issues or problems (compaction, erosion, offsite contamination) and a better understanding of the relevance of some soil functions (such as carbon sink or natural filter of water). In rain fed agriculture tillage is also an essential tool to modify the water balance so as to improve the availability of water for the crop.

17.2.1 Seedbed Preparation

This is a process that often requires the removal of the residues of previous crops. Removal can be done by burning the residues or burying them with certain operations. The burning of stubble is a fast and cheap method that has been widely used in the past and has some clear advantages, such as the elimination of weed seeds, the destruction of propagules of pathogens and insect eggs and larvae, and the immediate release of some nutrients. But burning causes a loss of organic matter and N (lost as volatile N oxides), contributes to air pollution and to anthropogenic CO_2 emissions, and overall soil degradation and increases the fire risks.

After clearing the residues, we may proceed to preparing the seedbed, which ideally consists of a surface layer of granular structure with a high percentage of aggregates smaller than the seed. In general this objective is achieved only when tillage is performed with a soil water content close to field capacity and is called optimum soil water content for tillage (OPT, e.g. Dexter and Bird 2001) (see 17.3). In some cases it is necessary to compact slightly the seedbed with a roller compactor to enhance seed-soil contact and hydration of the seeds. Furthermore, below the depth of planting, the soil must have a lower bulk density to allow root growth without restrictions, which is often achieved by previous deeper tillage.

17.2.2 Weed Control

Before the advent of herbicides, tillage was the only effective method for controlling weeds. The control may be direct by destroying the plants, cutting the roots or the stem or burying them. The control may be indirect, by changing the position of weed propagules or changing the environmental conditions of the weed seed bank. For example, the moldboard plow buries many seeds below a certain depth making them unable to emerge. In other cases, such as weeds that propagate through underground organs (tubers, rhizomes), tillage contributes to cutting such organs and therefore enhances the dispersion of the weed when the soil is wet but it may have the opposite effect when the soil is dry as the weed propagules would desiccate.

In this tillage strategy for controlling weeds it is essential to till immediately before planting to minimize weed-crop competition. This operation can reduce the water content of the seedbed and therefore cause poor seedling emergence in dry areas. This occurs, for example, in spring sown rain fed sunflower. This negative effect can be solved by replacing the tillage operation by a pre-plant herbicide application.

In those crops for which there are no selective herbicides or when they are not very effective against the weed community, inter-row tillage operations will be required after crop emergence. Although it is possible to control weeds only with tillage, herbicide use, at least partially, is often a much more effective alternative in terms of cost and time.

17.2.3 Modification of Water Balance

In rain fed crops the main objective of tillage is to improve the water balance to maximize the availability of water for the crop. In a natural ecosystem, with the soil covered by vegetation, the macropores formed by the roots and mesofauna allow high and stable infiltration rates even at relatively high bulk density. The situation is very different in an agroecosystem as seedbed preparation involves traffic of machinery and the surface of the soil is kept bare. This kind of tillage results in a low bulk density but in a pore system in which many of the pores are less stable than the macropores formed by vegetation or soil fauna or are even occluded with no connection to the soil surface (Fig. 17.1). In this situation the impact of raindrops breaks soil aggregates and causes the sealing of pores, thus reducing the infiltration rate. This is reversed after tilling, by breaking the surface crust and increasing the

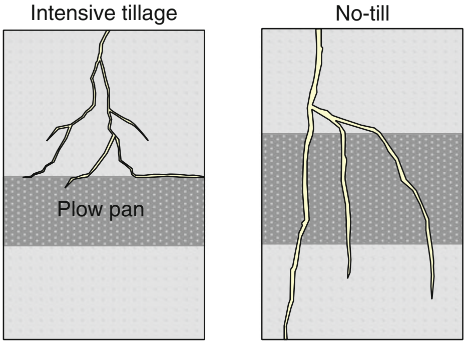

Fig. 17.1 Conceptual model of soil porosity in tilled and long-term no till systems (Adapted from Ontario Ministry of Agriculture and Food)

soil porosity and surface roughness, but the effect is temporary and the infiltration rate is reduced after new rain events occur. The velocity of the surface sealing process depends not only on the amount of precipitation but also on soil characteristics, especially its structure (closely related to soil texture and organic matter content), being at its best state in undisturbed natural soils under grassland or forest plant cover.

Tillage thus serve to break the surface crust, but also increases porosity, which improves water retention capacity and aeration, which in turn favor root growth.

In many rain fed areas farmers consider tillage an effective method for reducing evaporation from the soil surface (E_s). Indeed, in soils prone to cracking, sealing of the surface cracks by tillage helps reducing E_s. Large cracks increase evaporation in relatively deep sections of the subsurface soil in desert areas providing that transport of the pore water from the sediment matrix to the crack walls is not a limiting factor. This would explain the adoption of inter row cultivator passes in summer crops (e.g. cotton) in expansive soils. In many cases, however, tillage may increase soil evaporation. Evaporation from a dry soil surface is very small (second stage evaporation). If the soil is tilled the dry surface layer mixes with moist soil from below thus increasing evaporation. In Fig. 10.3 (Chap. 10) an increase in evaporation on day 157 was due to a pass of cultivator for weed control. In the long run, the impact of tillage on Es is of very limited magnitude as most the Es takes place before the tractor with its tillage implements can enter the field. Thus, with the exception of expansive soils, the effect of any tillage system on soil evaporation has much less impact on the water balance than on infiltration.

17.2.4 Other Goals

Tillage can serve other purposes such as the modification of the energy balance, or incorporation of fertilizers or soil amendments. For instance, the reduction of bulk density and the soil water content after tilling, increases thermal diffusivity which favors a faster warming of the soil surface.

Sometimes we find some tillage practices whose objectives are unclear and may be due more to tradition or aesthetic reasons. Traditionally good farmers kept their fields "clean" of weeds at all times and this has led to excessive tillage and the adoption of unsustainable practices.

17.3 Influence of Soil Water Content on the Effects of Tillage

The energy required for tilling the soil and the effects of tillage depend on the soil water content. In medium or fine textured soils the cohesive strength of soil aggregates decrease with increasing water content. The adhesion forces between the soil and the tools increase with water content up to a maximum, in which the soil passes from the plastic, i.e. moldable, to the liquid state. In the liquid state, tillage causes the dispersion of the soil particles, and the soil loses its structure. The coherent state of the soil occurs with low water content and does not allow deformations without breaking of the aggregates. In this state tillage generates large blocks of aggregates (lumps) with large gaps between them. Between the coherent and the plastic state there is a point in which the sum of both of adhesion and cohesion forces is minimal, which occurs with a medium content of water below the upper limit. At this state, which is called optimum soil water content for tillage (OPT, e.g. Dexter and Bird 2001) the soil crumbles after tillage (Fig. 17.2).

The water content of the soil not only determines the effects of tillage on soil conditions but also the degree of soil compaction due to traffic of machinery. Soil compaction occurs mainly in the plastic state but it is not likely to be important in drier soil, since in this case the force causes breakage of aggregates. Within the plastic state two zones may be distinguished above and below the Adhesion Point: above that point the soil will adhere to a smooth surface cutting it, as is the case with

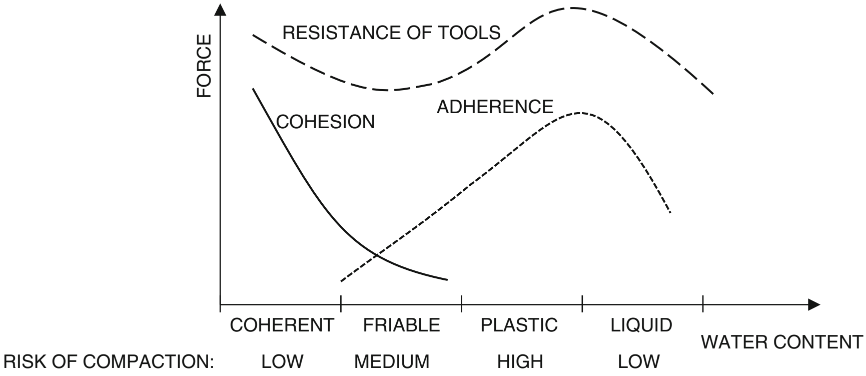

Fig. 17.2 Coherence and adhesion forces between soil and tillage tools as a function of soil water content

implements. This implies a high energy expenditure for tilling and the danger of cementation once the soil dries.

The best condition for tilling occurs in a range of water contents below field capacity. This occurs approximately 2–3 days after rain or irrigation for medium texture soils. In this zone the energy required for tillage is minimal and a granular structure is achieved, which is desirable for the seedbed while the risk of compaction is moderate. Medium and sandy textured soils drain well, and have a narrow range of plastic state, so they move quickly to the plastic state and reach the OPT quickly after a rain or irrigation, staying that way for a long time. That state, however, is not easy to achieve in clay soils where drainage is slow and the plastic state interval is wide. If we till in that state the soil is cut into slices, which get extremely hard when dry and the tillage operation barely increases soil porosity. Besides, the risk of compaction is maximum when a soil is tilled in the plastic state. To promote drainage in clay soils it is necessary to till before the rainy season. Only so it will be possible to get a proper moisture condition before planting. The drawback is that tilling in the dry season, when the soil is in coherent state, requires much energy and generates large clods which then must be disaggregated by additional secondary tillage operations. That subsequent disaggregation can be very difficult when rainfall is low. The disadvantages of tilling when the soil is dry do not occur in sandy soils as they do not show a coherent state.

17.4 Conventional Tillage

Maintenance of the infiltration rate, weed control and seedbed preparation require performing several tillage operations that vary widely across geographic areas, soil types and crops. This set of operations, which we call conventional tillage, can be classified according to different criteria. In conventional agriculture it is common to distinguish between primary and secondary operations. The primary operations are performed with a moldboard plow or a disc plow sometime after harvest and serve to incorporate crop residues and to improve soil conditions. The moldboard plow cuts, lifts and turns the soil down to 40 cm deep at most. This process improves infiltration, incorporates crop residues, and buries the weed seed bank. For the rupture of compacted deep layers subsoilers are used which can achieve greater depths (60–70 cm), performing a vertical cut so that residues are not incorporated. Subsoilers have replaced the moldboard plows in many areas, leaving 50–80 % of the residues on the soil. The chisel plow performs a similar but shallower (less than 30 cm) vertical tillage than the subsoilers.

Secondary tasks are performed with harrows, cultivators and other implements, affecting only the surface 10–20 cm. They serve to refine the soil before sowing (reducing the size of the aggregates on the surface) and to control weeds. The primary operations often result in large aggregates which are then broken down by harrowing. The finer structure is achieved with cultivators, which are also used for weed control before and after sowing (passes between rows). To finish the shredding of the aggregates and/or for compacting the soil surface layers, various tools can be used (e.g. compactor, harrow tines).

Example 17.1 Sunflower conventional tillage in a wheat-sunflower rotation in a Mediterranean area. After burning the wheat stubble in summer a moldboard pass results in large aggregates and many gaps. After the first rains we may use a cultivator or a disk harrow to reduce the size of the aggregates. Then two additional passes of cultivator are needed in autumn-winter to remove weeds, and another before planting. Additionally one can have one to two passes of cultivator between rows to control weeds during the campaign. Tillage costs in this case may account for over 60 % of the total production costs of the sunflower crop.

17.5 Compaction and Plow Pan

The existence of compacted layers may be due to natural causes (e.g. petrocalcic horizons) but it is a widespread phenomenon due to tillage. Compaction can occur in the uppermost layer (of a few mms width) of the soil due to the impact of rain. This surface crust hinders seedling emergence, especially if the soil is dry, and reduces infiltration (Fig. 17.3). Secondary tillage favors the formation of surface crusts when it leaves very fine aggregates on the surface.

Another kind of compacted horizons are those within the soil profile, which not only delay or prevent the growth of the root system, but also lead to reduced growth of the aerial part of the plant and finally, to yield losses (Fig. 17.4), even when the supply of water and nutrients is not limited. Figure 17.5 shows the relationship between penetration resistance and soil water content for a loamy soil with or without compaction. Taking into account that with a penetration resistance of 3.2 MPa root growth is considerably reduced, one can deduce that the growth conditions for the root in the compacted soil were greatly restricted. Compaction has other side effects such as the development of waterlogging conditions, which promotes denitrification (see Chap. 24), root anoxia and a higher incidence of soil diseases (e.g. Phytophthora).

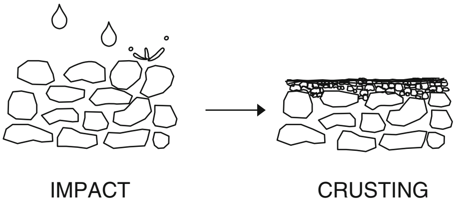

Fig. 17.3 Schematic representation of the formation of a depositional crust on a soil with sand, silt and clay-sized particles (Adapted from Cattle et al. 2002 In: SuperSoil 2004: 3rd Australian-New Zealand Soils Conference, Dec 2004, Univ of Sydney, Australia (published on CDROM))

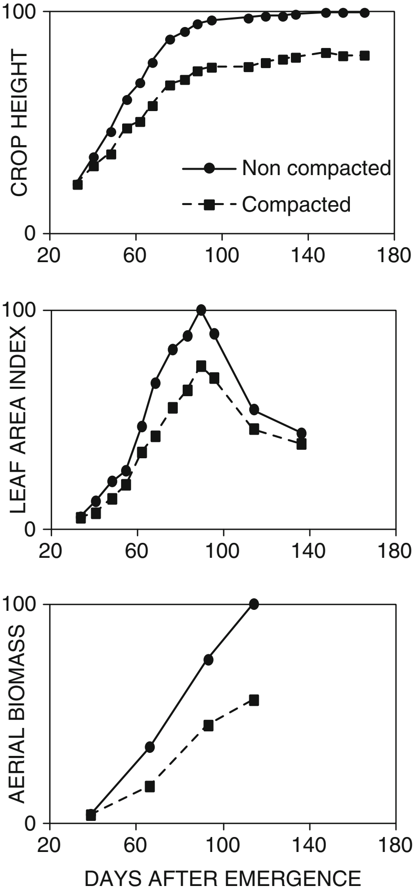

Fig. 17.4 Time course of LAI and biomass of cotton on non-compacted (*solid line*) and compacted (*dotted line*) soil (Adapted from Coelho et al. 2000)

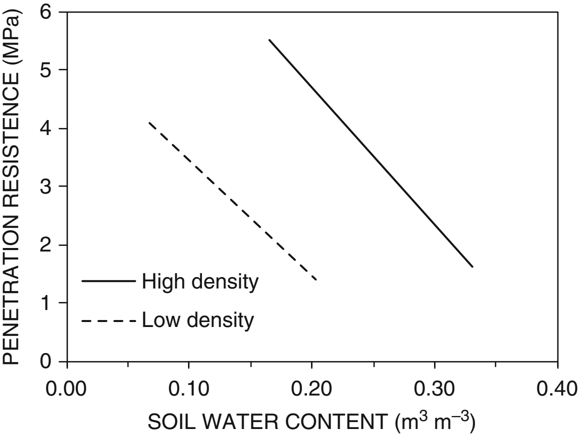

Fig. 17.5 Relationship between soil bulk density, soil water content and soil resistance to penetrometer. Sandy loam soil (Adapted from Coelho et al. 2000)

Compaction is caused by the weight of the implements (plow, disk) at the depth on which they act resulting in a plow pan, and/or by the wheels of the tractor or other machines that compact the entire surface horizon. In either case the magnitude of the compaction is dependent on the pressure applied (regulated by axel load and tire type and pressure) and water content of the soil at the time of the operation, thus traffic should be avoided if the soil is in the plastic state. This is why compaction risk is very high in clay soils. Also in this case the plastic state which promotes compaction is transmitted in depth. By contrast in medium textured soils the risk of compaction is usually lower and generates a compacted layer below the tilled depth (Fig. 17.1). This is why subsoiling to relieve compaction problems is more effective in medium textured soils than in clay soils.

17.6 Energy Requirements of Tillage

Primitive tillage was based only on human power with hand tools. It first evolved to the ard with draft animals and then to the plow until now, when tillage is carried out with powerful tractors that require external energy sources (fossil fuel).

Apart from the risk of compaction, tillage has been questioned because it increases soil erosion risk and for its large energy expenditure. These negative effects have fostered the adoption of reduced tillage systems (see Chap. 18). In Sect. 7.4 we discussed the classification of energy inputs in agricultural operations. In the case of tillage only two components are relevant to calculate energy requirements per unit land area:

$$E_{req} = E_{dir} + E_{ind} = E_{fuel} + E_{ind\ (tractor)} + E_{ind\ (implement)} \tag{17.1}$$

The direct component is the energy in fuel consumed and the indirect component is that corresponding to manufacturing, maintenance and repair of the machinery (tractor and implement or machine). The calculation of indirect energy requirements (MJ ha^{-1}) may be performed with the following equation:

$$E_{ind\ (tractor)} + E_{ind\ (implement)} = \frac{M_{tractor}\ EM_{tractor}}{L_{tractor}\ MFC} + \frac{M_{machine}\ EM_{machine}}{L_{machine}\ MFC} \tag{17.2}$$

where M is mass (kg), EM is the ratio of energy required and mass (MJ kg^{-1}), L is the useful life (hour) and MFC is the machine field capacity (ha hour^{-1}). Using average values of these parameters we have calculated the indirect energy requirements of different operations shown in Table 17.1. Typical values of direct requirements are also presented for comparison. These data should be taken as an example. Actual direct requirements will be higher when tillage is performed under conditions

Table 17.1 Energy requirements of different agricultural operations calculated with Eqs. 17.2 and 17.3

	Indirect			Direct	Total	Labor	Total
	Tractor	Machine	Total				Inc. labor
Operation	MJ ha^{-1}						
Plow	80	133	213	1000	1213	80	1293
Sprayer	13	5	18	68	86	13	98
Spreader	11	2	13	73	86	11	97
Sow rows	28	103	131	200	331	28	360
Roller	29	48	77	200	277	29	306
Disc harrow	69	20	90	264	354	69	423
Cultivator	20	27	47	220	267	20	287
No till drill	42	135	177	200	377	42	419
Combine	0	646	646	500	1146	51	1197

The value of EL, the daily energy required per human has been taken as 1000 MJ day^{-1} which corresponds to farmers of developed countries. *WD* the work duration has been assumed 10 h day^{-1}

departing from optimal (OPT). Actual indirect requirements may differ if the parameters M, EM, L or MFC change. The consumption of energy increases with the use of high power tractor for small operations and with deeper tillage, and depends on the shape of teeth or disks of implements.

Many studies on energy requirements of agricultural practices ignore the energy associated to human labor. Table 17.1 also shows the energy required for labor calculated as:

$$E_{labor} = \frac{EL}{WD\ MFC} \tag{17.3}$$

where EL is the daily energy required per human (MJ day^{-1}) and WD is the work duration (hours day^{-1}). The value of EL depends strongly on the standards of living of the farmer (Chap. 7). Even using a very high value (EL = 1000 MJ day^{-1}) the fraction of energy due to labor is small (5–15 %).

The relative importance of tillage in the energy requirements of farming is limited. In Example 7.2 (Chap. 7) we saw a case of rain fed wheat farm producing 2500 kg d.m. grain ha^{-1} with total energy requirement of 14,779 MJ ha^{-1} (1500 for tillage, 1900 for sowing, harvest and other operations, 9613 for fertilizer, 1050 for seed and 716 for pesticides). In this case tillage is limited to one plowing and one pass of cultivator and the fraction of energy used in tillage is only 10 % of the total thanks to the use of herbicide. Even with more intensive tillage, its share of energy is small as compared to the energy inputs in fertilizers. Therefore the adoption of reduced or no tillage should be primarily promoted for improving soil conditions rather than for saving energy.

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Chapter 18
Soil Conservation

Helena Gómez-Macpherson, José A. Gómez, Francisco Orgaz, Francisco J. Villalobos, and Elias Fereres

Abstract Tillage serves to improve soil conditions in relation to the water balance and crop growth, to incorporate crop residues, to control weeds and to prepare the seedbed. However, tillage significantly increases the risk of soil erosion. These problems have led to the development of conservation tillage techniques which typically rely on the maintenance of plant residues on the ground and in a substantial reduction in tillage operations. When conservation tillage is combined with the use of crop rotations is termed conservation agriculture. Conservation tillage requires the use of herbicides and specific direct drills for crop sowing. The transition from conventional to conservation tillage should be gradual as additional problems may arise (e.g. compaction) in some soil types. Sporadic tillage or controlled traffic could then be adopted. In tree orchards many options for soil management are available, from conventional tillage to the no-tillage with bare soil and herbicide applications. A particular case is that of rain fed tree orchards in Mediterranean areas, whereas the problems of no-till (gully erosion, reduced infiltration) can be partially alleviated by temporal cover crops that protect the soil during the rainy season and are killed in early spring to avoid competition for water with trees.

18.1 Introduction

Soil erosion is the main threat to the sustainability of agricultural systems in many parts of the world. The development of powerful tractors in the last century allowed rapid mechanization of tillage operations but also resulted in a reduction of ground cover by vegetation and stubble, a decrease in soil organic matter, and a

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deterioration of soil structure, and therefore, in an increased risk of water and wind soil erosion. The "Dust Ball" period in USA in the 1930s exemplifies the relevance of this problem.

Conserving the soil in agricultural lands is not a straightforward task. Success requires adapting various soil management practices to local conditions as well as considering costs and profitability. The recommended approach is to develop a set of practices based on adapting and adopting a package of agronomic technologies known as Conservation Tillage guidelines that allow for minimum disturbance of the soil, maintenance of soil cover with vegetation and/or residues, and spatiotemporal diversification of cropping systems.

18.2 Soil Erosion

Erosion is the process of soil loss. Firstly it requires energy for removing the particles, and then some transport medium. The energy is obtained from the impact of raindrops and the transfer of momentum from water (surface runoff) or wind. The transport medium will be the fluid (water or air). The water erosion is proportional to runoff which depends on the relationship between precipitation and infiltration (Chap. 8) and a parameter (Erodibility) that reflects the ease with which the soil is eroded. The erodibility depends mostly on the structural stability of the soil which is related to the organic matter content, as well as soil texture. In bare soils with fine aggregates erodibility is highest.

Erosion has two major effects on the agricultural system: soil loss results in a decrease of soil depth which in turn involves a reduction of the water storage capacity, and therefore a reduction in long-term yield. Moreover the surface soil lost is often richest in nutrients, so that erosion involves a loss of fertility (and yield potential), and causes an environmental problem (sediment and pollutants accumulate in surface waters). Unfortunately it is not easy to control erosion due to its ephemeral nature, and often, most of the erosion occurs in a few episodes of torrential rain. In any case, excessive tillage destroys the soil structure and maintains the soil surface exposed to the wind and rain for prolonged periods, making it the leading cause of erosion in many agricultural systems. Although it initially increases water infiltration, its effect is temporary and, in some lime-fine texture soils, it can favor the rapid formation of surface crust after the subsequent rainfall.

On a larger scale, erosion is a process with positive feedback: soil loss implies a reduction of vegetation which favors intensified erosion, which ultimately leads to desertification (the process by which a dryland region becomes increasingly arid, typically losing its bodies of water as well as vegetation) that is advancing in some areas of the planet, being soil erosion one of its major drivers.

Several methods have been proposed to quantify soil erosion among which the most popular is USLE (Universal Soil Loss Equation) and its revised version, RUSLE (Renard et al. 1997). Both were designed to predict the effect of different soil management on average annual erosion rates at hillslope scale. According to the RUSLE, the average loss of soil by erosion (SLE, t/ha/year) is calculated as the product of six factors:

$$\mathrm{SLE} = \mathrm{R}_1\ \mathrm{K}_1\ \mathrm{L}_1\ \mathrm{S}_1\ \mathrm{C}_1\ \mathrm{P}_1 \tag{18.1}$$

where R_1 is the average annual rainfall erosivity, which is a measurement of the rainfall energy available for water erosion. It depends on amount and intensity of the rainfall and its calculation is explained in detail by Renard et al. (1997). There are several equations that can be used as a regional approximation, such as Eq. 18.2 for the USA, based on the monthly rainfall distribution ():

$$\mathrm{R}_1 = 4.17 \sum \left(\mathrm{P_i}^2/\mathrm{P}\right) - 152 \tag{18.2}$$

where $\mathrm{P_i}$ is the precipitation (mm) of month i, and P is the annual precipitation.

K_1 is the soil erodibility factor, and is equivalent to soil loss (t/ha/year) that would occur in standard conditions, that is, if the land is kept as clean fallow, and has a slope of 9 % and a length of 22 m. It depends on soil texture and soil organic matter. The values can be approximated from values in Table 18.1.

L_1 and S_1 are two factors that include the effect of the slope length (L) and steepness (S). In its most basic form (USLE) L_1 and S_1 are combined to represent the ratio of erosion in the specific situation and that happening in standard conditions (22 m long 9 % steepness), and their product is calculated as:

$$\mathrm{L}_1\mathrm{S}_1 = \left[0.065 + 0.0456\,\mathrm{p_t} + 0.006541\,\mathrm{p_t}^2\right]\left(\mathrm{l_t}/22.1\right)^{\mathrm{NT}} \tag{18.3}$$

where $\mathrm{p_t}$ is the slope (%) of the land, $\mathrm{l_t}$ is the length (m) and NT is a factor that depends on the slope steepness (see Table 18.1).

C_1 is the factor that reflects the effect of cover and management and their interaction with the rainfall erosivity distribution during the year. It can be approximated from tables developed for local conditions as presented in Table 18.1.

Finally, the factor P_1 indicates the effect of several agronomic measures for erosion control (Table 18.1) such as contour plow.

The value calculated using Eq. 18.1 is compared with the tolerable soil loss rate (Table 18.2), i.e. the maximum value before the long-term natural soil productivity is severely affected. The tolerance level varies depending on the type and rooting depth of soil. Generally, deep soils not previously eroded are assumed to have a higher tolerable soil loss rate than shallow and/or previously eroded soils.

Table 18.1 Parameters for calculating soil loss using the USLE

	K_1		
Soil texture	Low OM	Medium OM	High OM
Clay	0.2	0.17	0.13
Fine sand	0.16	0.14	0.1
Fine sandy loam	0.35	0.3	0.24
Loam	0.38	0.34	0.29
Loamy fine sand	0.24	0.2	0.16
Loamy sand	0.12	0.1	0.16
Loamy very fine sand	0.44	0.38	0.3
Sand	0.05	0.03	0.02
Sandy clay loam	0.27	0.25	0.21
Sandy loam	0.27	0.24	0.19
Silt loam	0.48	0.42	0.33
Silty clay	0.25	0.23	0.19
Silty clay loam	0.37	0.32	0.26
Very fine sand	0.42	0.36	0.28
Very fine sandy loam	0.47	0.41	0.35

Tillage and cropping practice	Crop sequence	C_1
Forest	Permanent	0.0005
Pasture	Permanent	0.005
Rotation 1/6	C-G-M-M-M-M	0.011
Rotation 2/5	C-S-G-M-M	0.027
No till cover crop after soybean	C-S	0.0027
Chisel, 50 % residue on contour	C-S	0.16
Chisel, little residue	C-S	0.35
Moldboard plow, spring	C-S	0.35
Moldboard plow, fall	C-S	0.39
Bare soil	None	1

Slope %	NT
<1	0.2
1–3	0.3
3–5	0.4
>5	0.5

Direction of tillage	P_1
Same as slope	1
Contour lines	0.5

Sources: For K_1 and NT: Stewart et al. (1975) US EPA Report No. 600/2-75-026 or USDA Rep No. ARS-H-5-1

For C_1 and P_1: Franzmeier et al. (2009) Indiana Soils. Evaluation and Conservation. Purdue University

C corn, *M* meadow (forage crop), *G* small grains, *S* soybean

Table 18.2 Soil loss tolerance rates for comparison with values derived from USLE or RUSLE

Soil erosion class	Potential soil loss (t/ha/year)
Very low (tolerable)	<6.7
Low	6.7–11.2
Moderate	11.2–22.4
High	22.4–33.6
Severe	>33.6

Example 18.1 Let us calculate the average erosion on a farm in Flint, Michigan with 5 % average slope and slope length 50 m. The soil is loam with average OM (2 %) and the crop is a rotation of corn and soybean with moldboard plow in the fall, which is made on contour.

Monthly rainfall values are:

Month	1	2	3	4	5	6	7	8	9	10	11	12	12
Precipitation mm	35	32	55	75	67	81	69	89	90	55	66	53	53

Therefore, rainfall erosivity is:

$$R_1 = 4.17 \sum \left(P_i{}^2/P\right) - 152 = 136$$

Now, in Table 18.1 we see that for a loam soil with medium OM content $K_1 = 0.34$ and with slope 5 % $NT = 0.4$. As $p_t = 5$ and $l_t = 50$ we can calculate the product of L_1 and S_1 as:

$$\begin{aligned} L_1S_1 &= \left[0.065 + 0.0456\, p_t + 0.006541\, p_t{}^2\right] (l_t/22.1)^{NT} \\ &= \left[0.065 + 0.0456 \times 5 + 0.006541 \times 5^2\right] (50/22.1)^{0.4} \\ &= 0.63 \end{aligned}$$

According to Table 18.1 with contour tillage we have $P_1 = 0.5$ and the maize-soybean rotation with fall plow has $C_1 = 0.39$. Therefore the estimated soil loss due to erosion is:

$$\begin{aligned} SLE &= R_1K_1L_1S_1C_1P_1 = 136 \times 0.34 \times 0.63 \times 0.39 \times 0.5 \\ &= 5.7\ \text{t/ha/year} \end{aligned}$$

According to Table 18.2 this value is considered to be very low soil erosion. Note that for this specific field if tillage direction was that of the slope, the estimated soil loss would double as P_1 would be 1 instead of 0.5. Then the estimated soil loss (11.4 t/ha/year) would be classified as moderate.

18.3 Conservation Tillage

As discussed above, conventional tillage has a number of disadvantages:

(a) The increased infiltration due to tillage is only temporary and for some soil types it enhances the formation of a superficial crust.
(b) Soil compaction is increased by the formation of a plow layer and by the frequent traffic of machinery.
(c) Tillage prevents the accumulation of organic matter in the soil surface which is necessary to protect the soil and improve and stabilize its aggregate structure. Organic matter generates aggregating agents (especially polysaccharides) that promote cohesion of the aggregates.
(d) Tillage has high economic and energetic costs and promotes the emission of greenhouse gases from soils. The use of fossil fuels also contributes to anthropogenic CO_2 emissions.
(e) In general tillage favors erosion, although some operations may reduce it temporarily.

All of these problems and the emergence of new technologies have allowed for alternative systems for managing agricultural soils. These systems range from reducing the number of operations (reduced tillage) to the complete elimination of tillage (no tillage) but not all of them contribute to soil conservation. In order to avoid confusions with the terminology, Conservation Tillage has been defined by ASAE as tillage operations (or no tillage) that leave enough residues to cover 30 % of the surface after sowing, and at least 110 g/m^2 of organic material during the critical periods of erosion risk. Conservation Agriculture (CA) adds a third component to minimum soil disturbance and maintenance of residues: the use of more than one crop in the rotation (FAO 2016).

Compared to conventional tillage, adopting no-tillage may have more negative than positive effects on crop productivity (Fig. 18.1). A major concern is the impossibility to decompact the plough layer, particularly when heavy direct-drill seeders enter in a field with wet soil. Compacted soil will reduce root and plant growth, whereas compacted superficial soil will result in lower water infiltration and soil water content; waterlogging and even seedlings death may then occur. Another major concern when adopting no-tillage is the potential increase of weeds, diseases and pests. Adopting no-tillage requires attentive weed control and increased herbicide use. On the other hand, the major advantage of no tillage is the possibility to enter earlier in the field for sowing the crop. This is particularly relevant to adjust the crop to a narrow cropping season window and for crop sequence intensification.

Most negative effects may be counteracted by maintaining crop residues on the soil surface after harvest (Fig. 18.1). Crop residues protect the soil from the direct impact of rain and wind and improve soil structural stability. The presence of decomposing roots from the previous crop also favors the structural stability of the soil surface layers and thus reduces erosion. Another positive effect of the

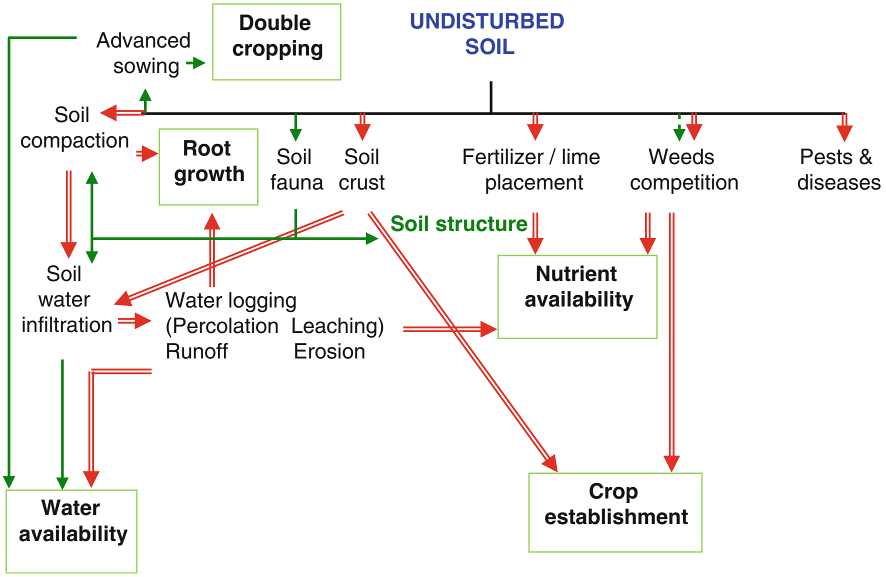

Fig. 18.1 Main pathways through which a change in management from conventional to conservation agriculture (zero-tillage with mulching and crop rotation) may impact key drivers (highlighted in *green boxes*) of crop yields. From the cropping system performance perspective, a *single dark green arrow* and a *double red arrow* indicate positive (beneficial) and negative (constraining) effects, respectively, of a conservation tillage management on yield drivers and component attributes. A *dotted line* indicates a beneficial effect expected to only accrue over the long term (Adapted from Brouder and Gómez-Macpherson (2014))

presence of residues is the increased surface roughness, which implies an increase in the water held in the surface that is retained until it infiltrates. Leaving crop residues has other positive effects in the longer term (2–5 years) such as an increase in organic matter content, and in the activity of the soil mesofauna (generating macropores) and the soil flora which are enhanced as surface temperature fluctuations are reduced. All these processes contribute to the improvement of the infiltration capacity. Furthermore the favorable microclimate near the soil surface promotes root proliferation which competes favorably with direct evaporation from the soil surface.

The effect of the presence of residues on evaporation from the soil surface depends on the frequency of rainfall. If they are frequent, the soil is kept in evaporation stage 1, so the residues will reduce evaporation in proportion to the radiation they intercept. However, if rainfall is infrequent, the soil remains in phase 2 (limited by hydraulic conductivity) so the presence of residues has little effect on evaporation. In short, if the amount of residues is sufficient to cover the ground, the water balance is expected to improve due to enhanced rainfall infiltration and, to a lesser extent, to less evaporation. In fact, CA has had more positive results by increasing yields (relative to conventional tillage systems) in rainfed systems in the semiarid zones than in other environments where water is not limiting.

Maintaining residues may also have negative short term effects on plant growth (Fig. 18.1). In the initial phase of adopting no-tillage and mulching, high amounts of residues may result in N immobilization. Greater N fertilizer amounts will then be required to compensate for the immobilization until soil fertility is increased and the system is balanced. Additionally, non-mobile soil nutrients, like phosphorus, cannot be incorporated into the soil unless the fertilizer is placed next to seeds during sowing. Residues also reduce radiation absorption by the soil which delays soil warming during early establishment of spring crops when temperatures are low; on the other hand, in the tropics, lower temperatures may benefit nutrient cycling and plant growth. Leaving residues on the ground also require specific drills to sow through them, and makes difficult flood or furrow irrigation or herbicide application.

In conservation agriculture, crop rotation has the role to facilitate weed control and to reduce the risk of pests and diseases incidence (Fig. 18.1), particularly in the soil. For example, higher incidence of diseases caused by soil fungi in no-tilled wheat monoculture systems were observed in Australia but were controlled when rapeseed was included in the rotation following wheat. The rotation would also help to maintain the optimum amount of residues in the system by combining high and low-residue producing crops. The value of adopting a rotation under conservation agriculture may be evident in the long term only.

There are differential responses to tillage systems in the different agricultural systems. In a meta-analysis it was found that no-tillage reduces crop yield compared to conventionally tilled systems but that these negative effects decrease if residues are maintained. While CA has been widely adopted in North and South America, so far it has been little adopted in Europe (except cover crops in orchards). Reasons limiting CA adoption in Central and Northern Europe include technical problems with crop establishment in cold and wet soils, high natural organic matter content of many soils, flat topography and low erosion risk, and management problems with crop residues and weed control.

Example 18.2 Intermediate system of conservation tillage (*reduced tillage*, also called *minimum tillage*) for wheat-sunflower rotation includes vertical tillage often with chisel and causes severe erosion also (Fig. 18.2):

- Sunflower is sown directly on wheat stubble using a special drill for direct planting. Weeds are controlled with two applications of herbicide (glyphosate) and a residual herbicide applied before planting.
- The residues of sunflower are cut with disc harrow (2 passes crossed) or burned. Then herbicide is applied or cultivator is passed before planting wheat.

In this system it would be difficult to completely avoid tillage, unless a no-till drill for cereals and sunflower is used, but in any case it improves soil

(continued)

Example 18.2 (continued)

Fig. 18.2 Severe rill erosion after chisel tillage (Photo by Juan Jose Perez)

protection and reduces costs compared to traditional tillage. However it may require some deep tillage to break deep compacted layers, which can be done by subsoiling every 4–8 years. At harvest, it will be convenient to cut the cereal as high as possible and have a residue chopping and distributing system located in the harvester, to avoid problems at planting. These systems in which the residues are distributed simultaneously may favor the dispersal of weeds in the field, as weed seeds are spread along with the crop residues (Chap. 30).

In humid environments some forage crops with very small seeds such as alfalfa may be sown without burying the seed, which is distributed at random on previous crop residues or over the previous crop and is thus protected. If environmental conditions are suitable (frequent rain, low evaporative demand) an acceptable plant stand is achieved.

The transition from conventional tillage to conservation tillage should be a gradual process and adjustments will be needed to cope with the specific problems of the soil and crops and techniques to be adopted. For instance, no-till has fewer problems adapting to medium or light textured soils because of their lower risk of compaction. In heavy clay soils no-till may aggravate soil compaction and cause yield reductions. Furthermore the performance of no-till seeders is usually worse in heavy soils, which when cut with the hoe of the drill remain slightly open, so that

Fig. 18.3 Ridge tillage: direct sowing of maize over cotton stalks

the seed-soil contact is not good. These problems can be solved in part by changes in the implements of the seeder. For example you can add several blades which cut and remove the soil in a section of 10 × 10 cm in front of the sowing boot, which favors the seed-soil contact. This localized tillage can be applied ahead of planting, using a cultivator with blades spaced as boots on the planter. This procedure has been called *strip tillage*, and allows the localized application of P and K fertilizers and promotes soil warming of plant rows.

In *ridge tillage* or *permanent bed planting* (Fig. 18.3), the soil is left undisturbed from harvest to planting except for nutrient injection. Ridges are rebuilt annually. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residues are left on the surface between ridges. Weed control is accomplished with herbicides and/or light cultivation. The beds or ridges, on which the rows of plants are sown, have the advantage of drying sooner and warming faster in spring.

18.4 Soil Conservation Systems in Orchards and Vineyards

In permanent woody crops the objectives of soil management are different than those in arable crops because sowing is not required. Traditionally, tillage in orchards targeted the elimination of weeds and the improvement of the water balance. The wide availability of herbicides or mowers to control weeds allows restricting tillage while ensuring an adequate water balance and erosion control.

The soil management options used in orchards are numerous but we can mention the following:

- Conventional tillage maintains the soil bare by periodic surface tillage (cultivator, disc harrow) to increase infiltration and control weeds. It is the system used traditionally and is still widespread in rain fed orchards (olive, almond, vineyards). This system generates compaction problems, keeps soil organic matter low and increases erosion risks.
- Minimum Tillage: The weeds are controlled by herbicides and tillage operations are limited to a cultivator pass in summer-autumn to improve infiltration.
- No tillage with bare soil. The soil is kept bare with herbicides but the long-term effect is a reduction in infiltration due to unavoidable traffic (application of herbicides and fertilizers, harvesting). For rain fed systems the lower infiltration usually involves a worsening of the water balance and a reduction in yield. In sloping areas no tillage favors gully erosion due to higher runoff coefficients.
- Permanent cover crops: A cover crop is sown and managed by periodic mowing when needed. It is not advisable under water-limiting conditions due to the competition for water with the trees..
- Temporary cover crops: erosion problems in orchards have forced the search for viable floor management alternatives in rain fed or irrigated areas where water availability is limited. In these cases permanent herbaceous covers are not feasible as they increase the ET and reduce the water availability to trees. In those cases, temporary cover crops may be used. Depending on the farm conditions the cover crop may be seeded or generated by the community of weeds. In Mediterranean conditions the cover is established in the fall, before the rainy season but is removed early in the spring to prevent competition for water during spring and summer. This can be done with herbicides or by mowing, with the residues providing mulch until the next fall. Mowing usually needs to be repeated more than once during the season depending on the rainfall patterns. Cover crops can occupy the whole area or just part of it (cover crops in strips). The main problem to be solved with this method is the decision of when to remove the cover crop, as if late it will mean a reduction of water available to the trees, and therefore a loss in yield, but an early removal will result in less soil protection and increased erosion risk. Although there is a need for annual seeding of the cover crop, several options using perennial species are available. Fig. 18.4 shows the cumulative evaporation from bare soil or from a grass cover under an olive grove established in the autumn (15 October 2010). In this example the cover below the olive trees does not evaporate more water than bare soil, until mid March. By April 1, the water lost due to the cover is 9 mm. By May 1 it is 37 mm. The appropriate date for killing the cover would be around the time when the two curves start to diverge. Unfortunately, this date varies with the conditions of each year for a particular orchard, i.e. in dry years

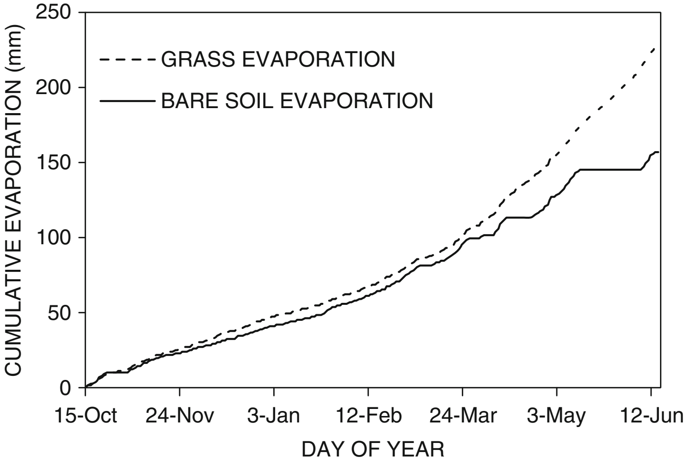

Fig. 18.4 Bare soil evaporation or grass evaporation below an olive orchard of 50 % ground cover in Southern Spain. The grass cover is established in October 15, 2010

the competition between the cover and the trees would start much earlier. The date also varies depending on tree spacing and size, soil type and rooting depth, and cover crop species and extension. A combination of experiments and modelling analyses is being pursued in different countries to reduce this uncertainty.

18.5 Controlled Traffic

Conservation tillage may lead to soil compaction, particularly with the use of heavy drills or harvesters in wet soils. The introduction of controlled traffic may reduce this problem. Controlled traffic implies that traffic is restricted to the same rows all the time so that the tractor wheels stay on the same tracks in the field for all operations while the crop is cultivated in the zone within these tracks. This approach has been facilitated with the availability of Global Positioning System (GPS) guidance for field equipment. Track widths of commonly available equipment dictate the width of the area without traffic. The adoption of controlled traffic combined with conservation tillage can increase soil infiltration and reduce soil erosion (Fig. 18.5), increase soil water content, and crop yields and farm profits. Nevertheless, occasional deep ripping or subsoiling of the traffic lanes may be needed.

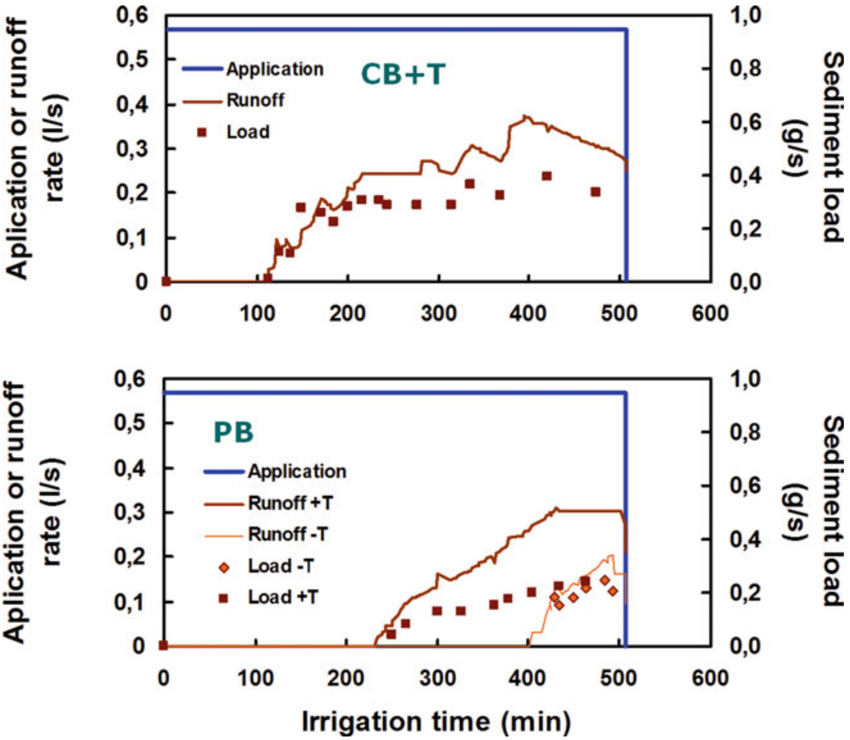

Fig. 18.5 Time course of runoff rate and sediment load in runoff water during rainfall simulations in conventional ridge system (CB) and in furrows of permanent ridge system (PB), with (+T) and without (−T) traffic

Example 18.3 In Southern Spain, a ridge planting system combined with controlled traffic has been developed successfully to deal with soil compaction and excessive residues produced by an irrigated maize-cotton rotation. Irrigation was applied from a central pivot but ridges were formed to facilitate controlled traffic and to have residues in the furrows rather than on the beds where crops are sown. Applied irrigation was reduced by 17 % since the introduction of the system, without yield loss, but most important to the farmer, the costs were also reduced.

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Chapter 19
Irrigation Systems

Luciano Mateos

Abstract Irrigation methods are classified into surface irrigation, sprinkler irrigation, and localized irrigation (drip/micro irrigation). Surface irrigation uses gravity: the water is distributed over the field as it infiltrates. With sprinkler irrigation, water is distributed across the field using pressurized pipes and sprinkled over the soil through nozzles. Drip/micro irrigation systems are conceived to localize the water to parts of the field and apply it frequently. The factors to be considered when selecting an irrigation method are: project goals (maximize economic return, minimize investment cost, conserving water and water quality), institutional and social site conditions (financial, labour availability, durability and robustness), physical site conditions (soil and topography). Irrigation performance assessment is advisable as part of the processes of operation improvement, and to establish system design criteria. The main irrigation performance indicators are irrigation efficiency, application efficiency, adequacy, and distribution uniformity. They assess different aspects of the irrigation process but have to be used jointly for a comprehensive assessment.

19.1 Introduction

The history of irrigation parallels that of agriculture. Irrigation has been practiced for more than 5000 years and was essential to early civilizations that developed in arid and semiarid environments, where irrigation makes the difference between the viability and non-viability of agriculture. Also in Mediterranean or sub-humid environments, where rainfall is limited or non-uniformly distributed, irrigation is responsible for an important part of the crop production. An estimated of 17 % of global cultivated land is irrigated, and produces about 40 % of the world's food.

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The twentieth century experienced a dramatic expansion of world irrigation. The area equipped for irrigation worldwide is 308 million ha of which 83 % were actually irrigated around year 2005. These figures represent about a sevenfold increase from the beginning of the twentieth century. Sixty-two percent of the area equipped for irrigation uses surface water, while 38 % uses groundwater and only 0.1 % uses non-conventional water sources. About 70 % of the irrigation area is in Asia and 17 % in America. The largest continuous areas of high irrigation concentration are along the rivers Ganges and Indus; in the Hai He, Huang He and Yangtze basins in China; along the Nile river in Egypt and Sudan; and in the Mississippi-Missouri river basin in North America. Zones of high irrigation density in Europe are along the Danube and Po rivers. The 3.8 Mha of land irrigated in Spain concentrate along the main river plains, the Mediterranean coast, and over aquifers in the central plateau.

Agriculture is the largest water-use sector worldwide, accounting for about 70 % of water withdrawals from rivers and aquifers and 90 % of consumptive water uses. The development of irrigated agriculture has boosted agricultural yields and contributed to price stability, making it possible to feed the world's growing population. The future of agriculture in many countries relies on the possibility of maintaining, improving and expanding the irrigated area. However, irrigation is facing increasing competition from the domestic and industrial sectors as the pressure on water resources increases, to the point that in many regions it is becoming a threat to the environment. In order to fully understand some of the irrigation management practices described in Chaps. 20 and 21 it is essential that the reader reviews the main features of the different approaches, methods and equipment used in irrigated agriculture.

19.2 Classification of Irrigation Systems

The earliest irrigation was by gravity diversion (from natural streams) and from water lifters powered by humans, animals, or by the flow of water. The on-farm irrigation systems were supplied either directly from the water source or through channels supplying a number of farms. Water moved by gravity over the soil surface was conducted by the irrigator to the crop plants or spread over level basins limited by small ridges.

Current water distribution systems from the source to the farms use gravity or are pressurized with pumps. They can be collective or serve single farms. Pressurized systems use pipes while gravity systems use mainly open channels. The source of supply may be surface water, groundwater, or both (conjunctive use). A variety of surface irrigation methods, sprinkle, and drip/micro systems are used for the application of water to the fields.

In collective distribution systems, delivery schedules determine when each farmer will receive water and how much, thus affecting on-farm irrigation operations and performance. The delivery schedules may be on-demand, arranged, and fixed rotation. Under on-demand delivery, the user decides when to irrigate, how much water to apply and for how long. It is typical of modern pressurized systems. Under fixed rotation, flow rate, frequency, and duration are fixed by the water authority or agreed within the farmers' community. Under arranged schedules, rate, frequency, and/or duration are arranged between farmer and water supply agency.

Irrigation can be applied to the land in several ways. The choice depends upon many factors, including topography, economics, crop type, soil type, water availability, farming practices and others. The following major categories of on-farm systems cover most of the variation:

- surface irrigation,
- sprinkler irrigation,
- localized irrigation (drip/micro irrigation).

A fourth, less common, category is sub-surface irrigation, that consists in maintaining a saturated water table within reach of the crop roots.

Surface irrigation (also referred to as flood irrigation) consists on the application and distribution of water over the field by gravity, wetting the entire soil surface or most of it. The distinguishing feature of this irrigation method is that water moves over the same medium where it infiltrates to fill the crop root zone. The rate of infiltration and its spatial distribution are therefore controlled by the soil characteristics. This feature makes it difficult to apply small depths of water, thus surface irrigation is typically applied at long (from 1 week to more than 1 month) time intervals. Although the area of surface irrigation is decreasing, it is by far the most common form of irrigation throughout the world, accounting for about 70 % of the total irrigated area.

Sprinkler irrigation consists on the application of water similarly to how rainfall occurs. Water is distributed across the field through a system of pressurized pipes. It is then sprayed into the air to wet the entire soil surface. The spray heads (sprinklers) breakup the water flow into small water drops which fall onto the ground.

Drip/micro irrigation systems apply water directly where the plant is growing, wetting only a small part of the soil surface and sometimes only part of the root zone. This is why localized irrigation is another term to call this method. Water is distributed to the water emission outlets through polyethylene pipes, thus the irrigation system needs to be pressurized. Water application is generally at a low flow rate, in small amounts, and frequently, to keep a high water content in the wetted zones. The water may either be applied above or below the soil surface.

Sprinkler and drip/trickle irrigation are expanding, with current areas of about 20 % and 5 % of the global irrigated area, respectively. The shift from surface to pressurized systems is being faster in countries like Spain, where surface, sprinkler and localized irrigation systems account now for 31 %, 22 %, and 47 % of the total irrigated area, respectively.

19.3 Selecting an Irrigation Method

Irrigation system selection depends on multiple physical and socioeconomic factors. It should be carried out by experienced professionals that interact with the farmer or irrigation manager. The factors to be considered are:

(a) *Project goals*. As in most production activities, the main goal is maximum economic return, although, for example, if capital is limited, the goal could be minimize initial cost. There may be social and environmental (conserving water and water quality) goals that should also be met.

(b) *Institutional and social site conditions*. The former include legal and political aspects like financial incentives, land use regulations or water rights that may be of primary importance. Social site conditions include availability of support for irrigation equipment maintenance, and dependable labour availability. For small-holder irrigation in developing countries, additional site conditions to be considered are: divisibility (suitability of an irrigation method for a wide variety of field sizes and configurations), skills and effort required for operation and maintenance, and ruggedness (durability, robustness).

(c) *Physical site conditions*. These conditions may refer to the water supply and quality, the land features (soil and topography), the cropping system, the climate, and the energy availability.

  - Water. The source, quantity, quality, reliability and delivery schedule for the water supply may make some irrigation methods more preferable or impose constraints to the selection of some of them.
  - Topography and field configuration. Field slope, topographic irregularity, field shape and physical obstructions may preclude the selection of some irrigation methods.
  - Soil characteristics. Soil texture, depth, heterogeneity, infiltration characteristics, erodibility, salinity, drainability, and the presence of a shallow water table must all be considered when selecting an irrigation method.
  - Crops and cultural practices. Crop height, germination, root and foliage diseases, and cultural practices (plant spacing, soil tillage and cultivation, application of fertilizer and pesticides, crop rotation).
  - Climate. Precipitation quantity and distribution will determine whether full or supplemental irrigation is required (Chap. 21), making one or other irrigation method more adequate and economically feasible. Wind is an important factor when considering sprinkler irrigation. Irrigation can be used to modify the crop climatic conditions: regulation of temperature and frost prevention, regulation of humidity, but not all methods offer the same possibilities.
  - Energy availability and reliability. If pumping is required, the energy source must be dependable.

19.4 Performance of Irrigation Systems

Irrigation performance assessment is needed to evaluate the potential for improvement, for meaningful comparison of irrigation systems and to establish system design criteria. Several performance indicators have been defined. Although they are related, they assess different aspects of the irrigation water use process.

The most comprehensive of the irrigation performance indicators is irrigation efficiency, IE, that relates the amount of irrigation water that is beneficially used by the crop to the total amount (beneficial plus non-beneficial uses) of irrigation water that leaves the boundaries (outflow = applied – Δ storage) of the system within a specified time interval:

$$IE = \frac{\text{Irrig. water beneficially used}}{\text{Irrig. water applied} - \Delta \text{ storage of irrig. water}} \times 100 \tag{19.1}$$

If at the end of the time period the water contained in the spatial domain is the same as it was at the start, Δ storage of irrigation water is equal to zero. The system (spatial domain) may be the soil root zone of a given field, an entire farm, an irrigation scheme, or a watershed; while the time domain may be, for example, the interval between two consecutive irrigations, or an entire irrigation season. The water that is beneficially used is mainly crop evapotranspiration, although it also includes salt leaching requirements, water needs for soil preparation, seed germination, seedling establishment and climate control (Chap. 28). Non beneficial uses include deep percolation in excess of leaching requirements, surface runoff, weeds transpiration and evaporation from reservoirs, sprinklers and wetted soil. Note that the term “irrigation water” excludes rainfall.

The determination of IE is complex since it requires detailed quantification of the fates of water that was applied at earlier dates. Usually the determination of IE is done by computing a water balance, which most times requires assumptions to estimate the different components.

Although knowing IE is often necessary to judge the performance of irrigation systems, the difficulty of its determination is overcome by introducing other efficiency terms that focus on parts of the water use processes. Application efficiency, AE, evaluates how efficiently the irrigation water applied during a single irrigation event meets the target irrigation depth:

$$AE = \frac{\text{Avg. depth irrig. water contributing to target}}{\text{Avg. depth of irrig. water applied}} \times 100 \tag{19.2}$$

Therefore, the concept of AE avoids the issues of establishing the beneficial use of the applied water. The target depth may be the root zone soil water deficit, SWD, or some smaller amount. If excess of water is required for salt leaching, then the target depth should be greater than the SWD. Implicit in the definition of AE is that the target depth is uniform over the field. If the target depth is equal to the sum of the expected beneficial uses, then AE provides an estimate for the potential IE. Therefore, AE will typically be higher than IE. Furthermore, high AE may not imply high IE, for instance if the irrigation event takes place at the end of the growing season.

It is easy to attain very high AE in a field by under irrigating. Therefore, AE should be complemented with an indicator of the degree to which the target depth is met. This indicator is irrigation adequacy, AD, that can be defined as the fraction of the field that receives at least the desired amount of water (taking values between 0 and 1). Another expression for adequacy is the so called low-quarter adequacy, $\mathrm{AD_{lq}}$, defined as:

$$\mathrm{AD}_{lq} = \frac{\mathrm{I}_{lq}}{\mathrm{I}_t} \times 100 \tag{19.3}$$

where $\mathrm{I_{lq}}$ is the mean irrigation depth in the quarter of the field area receiving the smallest depths and $\mathrm{I_t}$ is the target depth. If meeting the average low-quarter depth is used as scheduling criterion, then the objective is $\mathrm{AD_{lq}} = 1.0$, meaning that about one-eight of the field will remain under-irrigated. $\mathrm{AD_{lq}} < 1.0$ implies under-irrigation, whereas $\mathrm{AD_{lq}} > 1.0$ implies over-irrigation.

AD and $\mathrm{AD_{lq}}$ can be evaluated by plotting the distribution across the field of the applied depth (Fig. 19.1). The curve is developed by ranking field measurements in descending order, accounting for the field area that each measurement represents. The point where the curve intersects the line for target depth indicates the fraction of the field that is being adequately irrigated.

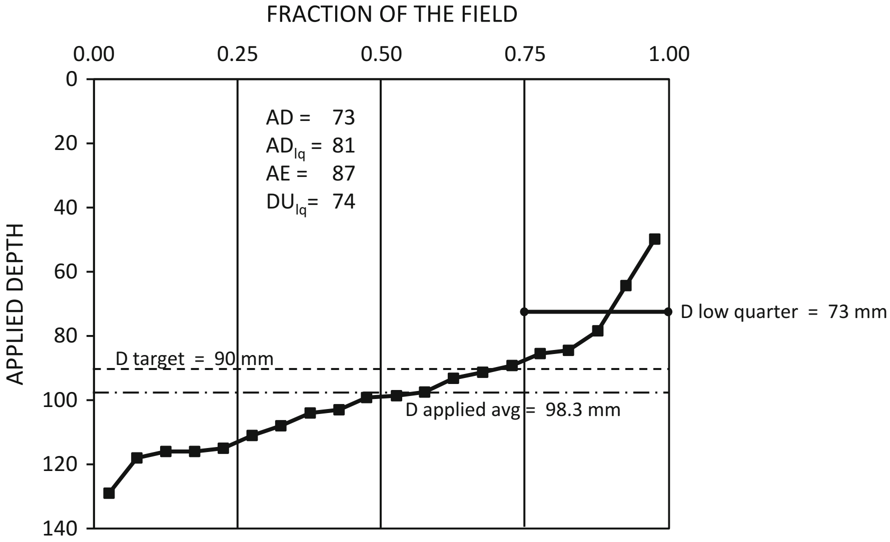

Fig. 19.1 Distribution of applied depth across the field. The distribution is ordered from larger to smaller depth across the field area expressed as fraction of total area. *Horizontal lines* represent the average applied depth, the target depth and the average depth of the low quarter

Figure 19.1 also reveals the importance of how uniformly the water is distributed to the crop. A non-uniform distribution can deprive portions of the crop of needed water and over-irrigate other portions of the field. The low quarter distribution uniformity, DU_{lq}, is an indicator of irrigation uniformity:

$$DU_{lq} = \frac{I_{lq}}{I_{avg}} \times 100 \tag{19.4}$$

where I_{lq} has already been defined and I_{avg} is the average applied depth. DU_{lq} may be calculated using the distribution of applied depth like shown in Fig. 19.1.

The distribution of applied water with localized irrigation is based on measurements of the volume of water applied to the soil by each emitter of a defined sample of emitters. In sprinkler irrigation evaluations, applied water is sampled at the nodes of a defined grid using catch cans usually placed above the crop canopy. In the evaluation of furrow irrigation, the applied water is measured only at the furrow inlet, and the distribution of water is typically derived from measurements of the infiltration time used to estimate infiltrated water by means of an infiltration function.

19.5 Design and Management of Irrigation Systems

19.5.1 Surface Irrigation

The surface irrigation process is described in four phases (Fig. 19.2), although not always all of them take place. The water that is applied to one end of the field (the high edge or point if the field is not levelled) advances over the soil until it spreads across the entire surface or flow paths (furrows). This is the advance phase. Then, if the field is open at its tail end, the water starts to run off; whereas if it is surrounded by a dike or ridge, the water begins to pond. The interval between the end of the advance phase and the inflow cut off time is the wetting phase. After water application is stopped, the water on the surface begins to decline, infiltrating into the soil and draining from the surface if there is an open field end. Two phases are distinguished during the drainage period: the depletion phase (or vertical recession) and the recession phase (horizontal recession). The depletion phase runs from cut off to the appearance of the first bare soil under the water; the recession phase begins then and ends when the surface is completely drained.

The infiltration opportunity time is the difference between the recession and advance times, thus it can be calculated from the advance and recession trajectories easily (Fig. 19.2). The infiltration rate initially decreases rapidly with time to reach later a constant rate. Therefore, the variation of infiltrated water across the field is less than the variation of opportunity time.

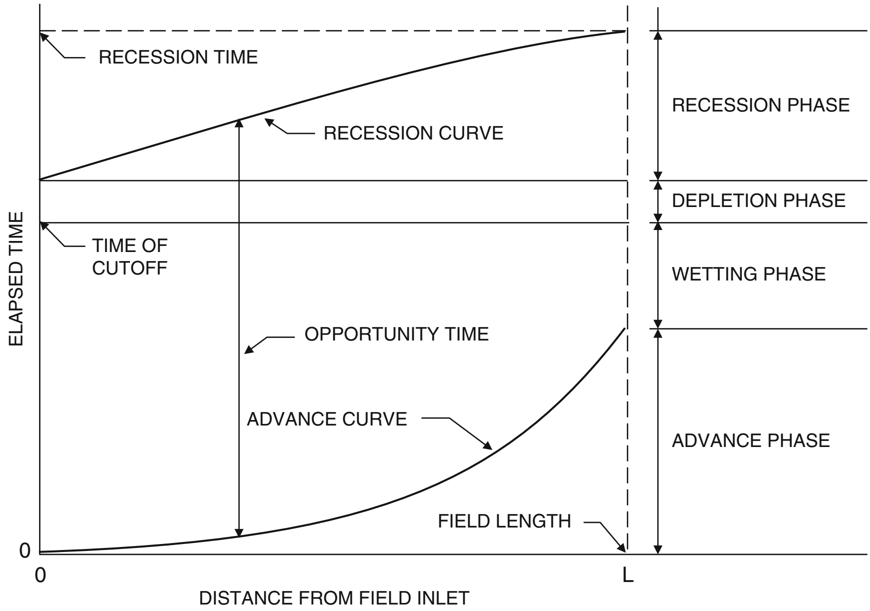

Fig. 19.2 Advance and recession trajectories of the water front in surface irrigation, indicating (on the *right*) the phases of an irrigation event

Furrow irrigation is the most common surface irrigation method. Furrows are small channels formed in the soil by means of a ridger-plough. This method avoids flooding the entire field surface; water infiltrates through the wetted perimeter. Furrows may be level, nearly along a contour line with a small slope, or down the slope of the field. The flow into each furrow is independently controlled, using siphons, gated pipes or perforated pipes. Furrow irrigation can therefore be used with a large range of stream sizes by adjusting the number of furrows irrigated at the same time. The furrow length and inflow rate should be regulated so that water will flow to the end of the furrow rapidly, but without erosion. This will ensure good infiltration uniformity, although the tail flow may be too high and thus runoff excessive. Infiltration uniformity and application efficiency can be improved simultaneously by using a high initial inflow rate, until the advance phase is completed, and cutting back the inflow afterwards. Another way of improving infiltration uniformity is using surge flow: instead of applying a continuous stream of water, the flow is intermittently applied through on-off cycles. By surging the water, some soil surface sealing occurs, thus reducing infiltration and speeding advance during subsequent surges over previously wetted portions.

Border irrigation requires construction of small earthen dikes (borders) separating evenly graded basins or strips typically 5–15 m wide. Water is released onto the border strips through an outlet located near the centre of its top. The slope across the width of the strips is graded to zero slope, thus the water moves along the longitudinal gentle slope of the strip. The entire surface of the strips is flooded. A variation of border systems is level basins, that are perfectly flat and surrounded by check banks, meaning that all the water applied to a level basin infiltrates into the soil and there is no runoff. Borders can then be unnecessary.

19.5.2 Sprinkler Irrigation

All pressurized irrigation systems should apply water at a rate below the infiltration rate of the soil, thus avoiding runoff. Thus, here, the irrigation system controls the rate of water infiltration while in surface irrigation the soil itself controls the infiltration rate during irrigation. With sprinkler irrigation, water is distributed across the field through a pressurized pipe and sprinkled over the soil using nozzles. Sprinkler devices for agricultural use generally fall into two broad categories: rotating head sprinklers and spray sprinklers. Rotating head sprinklers move themselves in a circle driven by different mechanisms. In the case of impact sprinklers, this mechanism is an impact arm. The sprinkler head pivots on a bearing as the impact arm repeatedly hits the water jet pushed by a spring. When the arm hits the jet, water scatters watering the area around the sprinkler. Impact sprinklers can be designed to rotate in a full or partial circle. They can have one or two nozzles and many sizes, allowing flow from 2 to 280 L min^{-1}, radius of throw from 7 to 30 m, with operating pressures between 140 and 690 kPa.

Spray and spinner sprinklers operate typically at pressure less than 200 kPa. The water jet from a nozzle impinges on a plate that deflects the water in all directions. The discharge plate can be smooth or serrated and can be flat, concave or convex, producing different water distribution patterns. Water leaves a smooth plate in small droplets; serrated plates create tiny streamlets with larger droplet sizes. Typical radius of throw of spray sprinklers is in the range of 2.5–5 m.

Rotating spray plate sprinklers, commonly referred to as rotators, have features of both impact and spray sprinklers. The water discharging from the nozzle impinges onto a circular plate that rotates without the need of an impact arm. The shape and configuration of the plate determines the multiple trajectories of the water and its distribution pattern. The radius of throw can be up to 15 m. Rotators typically operate at lower pressure than impact sprinklers (100–345 kPa) and can accommodate lower flow rates without compromising performance.

These sprinkler devices are spaced to give a relatively uniform application of water over the field being irrigated using a series of sets or a continuous move system. There are several types of sprinkler systems. The most common are described below.

Hand-move portable systems consist of one or more pipelines (laterals) with sprinklers mounted on risers connected to the laterals at regular distances. The height of the risers adapts to the crop height. When the desired amount of water has been applied to the area covered by the set of laterals, the pipelines are dissembled and carried to the next position. This operation is repeated until completing the watering of the entire field. Distribution uniformity may be improved by using alternate sets: on every other irrigation cycle the pipelines are placed in intermediate positions. Most hand-move portable systems use rotating impact sprinklers, but rotating spray plate sprinklers are also used. This system adapts to all topographies, soils and crops, although moving the laterals when crops such as corn reach their full size is arduous. Variations of hand-move portable systems are wheel line and side move lateral systems. In the former system, the lateral line is mounted on wheels with the pipe acting as axis driven by an engine that moves the whole lateral from one position to another. In side move systems the lateral is supported by a frame on which the wheels are mounted.

Stationary or solid-set systems are similar to portable systems except that both the main line and the laterals remain in place permanently (if the main and laterals are buried) or during the growing season. Rotating spray plate sprinklers are becoming the most commonly used sprinkler type for stationary systems. Stationary systems adapt well to crops that require frequent applications of water, to facilitate germination and for frost protection. Compared to portable systems, solid-set systems have high initial investment, but require little operation labour.

A center pivot system consists of a single lateral supported by wheeled towers that are self-propelled, typically with electric motors, so that the whole lateral rotates around the pivot point in the centre of the irrigated area. Water is supplied also at the pivot point. For long center pivot laterals (e.g., 400 m) the period of rotation may vary between 12 and 120 h, although 12 h to 3 day cycles are most common, applying between 10 and 25 mm per cycle. Since the outer lateral segments irrigate annulus of greater area than the inner segments, application intensity must increase from the pivot point to the lateral distal end in order to apply uniform water depth. This may generate runoff and erosion in some soils if the system is not designed and managed properly. The sprinklers used in centre pivots may be of any kind, but the trend is towards low pressure sprinklers. Centre pivot systems adapt to most field crops and topographies. They may be unsuitable for small fields or field shapes where circular geometries do not fit well. Moreover, the fields must be free of obstacles. Several solutions have been developed to overcome obstacles, and the installation of end guns (large sprinklers at the end of the lateral) and corner systems (an additional arm that swings out on the corners and tuck back in on the edges) allows irrigating part of the corners of squared fields that would not be irrigated with the conventional centre pivot. Centre pivots can be used for site-specific variable rate irrigation, by using solenoid valves that regulate the application rate of each sprinkler.

Linear move systems are similar to centre pivots except that they do not rotate but translate (move laterally). Water is supplied to the moving lateral using a flexible hose or from an open ditch parallel to the translation direction. Contrary to centre pivots, this system adapts well to rectangular fields and applies the water with uniform intensity across the field. All types of sprinklers can be used in linear move systems. However, the tendency is to use drop tubes, installed at short distances along the lateral, and low elevation spray application (LESA) or low energy precision application (LEPA). LESA systems use sprayers located near the top of the crop canopy, while LEPA systems use low pressure nozzles located very close to the soil surface. The soil is furrowed and the furrows are blocked at regularly spaced intervals to prevent runoff and infiltration non-uniformity.

19.5.3 Drip/Micro Irrigation

Drip/micro irrigation systems are designed to localize the water only to parts of the soil surface and apply it frequently. The water emitters may be micro tubes, orifices, nozzles, or perforated pipes. Applications may be from daily to several times per week, but sometimes (on sandy soils) daily needs are applied in several pulses throughout the day. The systems may be located on or under the soil surface and are permanent (solid set). Subsurface drip irrigation (SDI) is relatively new. The laterals are installed typically at 0.3–0.6 m below the soil surface. This system allows easier traffic and soil cultivation, reduced weed germination and minimal soil evaporation, but may have the problems of root intrusion into the emitters and impaired detection of system failures.

There are many types of emitters that are capable of supplying water directly to the crop root zone. Drip irrigation generally refers to the use of emission devices from which water drips onto the soil: drip tape or on- and in-line emitters (small plastic devices inserted in or embedded in the lateral); while micro irrigation refers to the use of microsprayers or microsprinklers. Microsprayers and microsprinklers are connected to the lateral by means of spaghetti hose. Flow rate of these emitters is very small. Drippers range from 0.5 to 8 L/h and microsprayers or microsprinklers from 20 to 80 L/h.

Drip/micro irrigation is primarily used for wide-spaced or high-value crops such as fruits, fresh vegetables and greenhouse crops. The drip/micro systems differ for permanent crops, non-permanent crops, and greenhouse crops.

Permanent crops include all kinds of fruit tree orchards and vineyards. Drip/micro systems for permanent crops may use drippers, microsprayers or microsprinklers as emission devices. For instance, sandy soils or shallow rooted trees are more effectively irrigated with microsprinklers/sprayers, whereas closely spaced trees (hedgerow) are better suited for drip lines. Sometimes the tree branches interfere with the microsprinklers/sprayers, and sometimes wetting only a small part of the soil prevents diseases. In those two cases drippers are also preferable. However, microsprayers and microsprinklers can provide some frost protection. Drip/micro systems for permanent crops typically have one lateral per plant row if the rows are closely spaced, or two if they are spaced more than, let's say, 5 m. The number of emitters per tree depends on the soil type, plant spacing and type emitter. The idea is to have sufficient root zone wetted volume which depends on annual rainfall, canopy cover, species and soil type. Drip/micro systems are also used for non-permanent crops, particularly for row-crops such as vegetable crops, and also for some field crops (e.g. cotton, tomatoes). After harvest, the irrigation system is removed to allow land preparation. Drip/micro systems for row crops mainly use in-line drippers or drip tape as emission devices. Usually there is one dripline or drip tape per row, but sometimes two are necessary or one every second row is sufficient to provide water to each plant root zone, depending on soil physical properties. Drip tapes last for one or two seasons. Drip lines last longer (7–15 crop seasons) and, if buried (SDI), can remain in the field permanently. Drip/micro systems for greenhouses may use all kind of emitters, depending on the crop and soil substratum.

Drip/micro systems require clean water to avoid emitter clogging. Filters are therefore essential components of drip/micro systems, and water filtration accounts for a great part of the maintenance and operation efforts. Fertigation and chemigation (the application of fertilizers and pesticides through the irrigation systems) are relatively easy and common with drip/micro systems, as well as automation of the operation (initiation and termination of irrigation in the different system irrigation units).

Drip/micro systems allow uniform and efficient application of water. They adapt very well to all kind of topographies, field sizes and shapes and crops, and are very easy to operate. They are more and more used in large scale commercial farming and in smallholder farming both in developed and developing countries.

19.6 Drainage

Drainage is necessary to evacuate the excess of irrigation or rainfall water and to wash the excess of salts. This will ensure adequate aeration of the crop root zone and prevent the harmful effect of salt accumulation. Where natural drainage is insufficient, surface and/or subsurface drainage must be facilitated artificially.

Surface drainage to remove excess water from the soil surface is expedited by excavating shallow open ditches. The dimensions and density of the drainage ditches are calculated based on expected intensity and duration of storms, soil type and crop.

Subsurface drainage is used to control the groundwater table and to remove salts for leaching. Many irrigation projects require subsurface drains, that may be deep ditches or buried perforated pipes. Open ditches have advantages for removing large volumes of water. They may also serve as collectors of subsurface drains. The main disadvantages of open drainage ditches are that they occupy land that might otherwise be cropped, obstruct farming practices, and tend to have high maintenance costs. Clay tile drains have been widely used for subsurface drainage. The tiles are usually of 30–60 cm lengths and of 10–25 cm inside diameter. Corrugated plastic tubing is increasingly being used. Perforated pipe lines are generally available at 8–30 cm diameters. Tile and plastic drains are normally installed with a surrounding envelop (synthetic fabrics, sand and gravel, or other porous filter material) that permits water to pass from the soil into the drain without significant passage of soil particles.

The hydraulic conductivity of a soil is a measure of its drainability; it is therefore a basic criterion for the design of drainage systems. Proper spacing of drains is complex, thus it is best determined from field experience obtained under conditions similar to those of the area to be drained. However several equations have been developed for estimating the appropriate spacing of subsurface drains if available field experience is not applicable. These methods give considerations to factors as hydraulic conductivity, rooting depth, depth of drain, rainfall, irrigation practices, water quality and soil salinity.

Pumped wells may serve to both lower the groundwater table and, where ground water is of good quality for irrigation, to supply water that supplements the main source of irrigation supply. This is called conjunctive use.

19.7 Water Reuse

When applying irrigation water to a field, some water losses (surface drainage and deep percolation) are unavoidable in most situations. These losses return to the hydrological system where the irrigated field is located, so they are called return flows. In many cases, the return flows can be reused downstream, for irrigation or other purposes. Therefore, the reuse of return flows tends to reduce the global benefit of improving on-field efficiency. Reuse can take place within the field (conjunctive use mentioned above), in the farm (e.g., by recycling runoff), at irrigation district or at watershed levels. The reuse of treated urban wastewater is one example of the later, although in this case the origin of the return flow is not from agriculture.

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Chapter 20
Irrigation Scheduling Using the Water Balance

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Abstract The simplest and most robust method for irrigation scheduling, i.e. deciding the dates and amounts of irrigation, is based on the water balance. The soil water deficit (depth of water required to bring the soil to field capacity) is calculated using ET and rainfall data, and rules are defined for calculating the dates and depths of irrigation. The rules are based on the critical SWD, the amount of water that the crop can extract in the rooting depth before water stress occurs. The critical SWD is the product of root depth, soil available water and allowable depletion. The later depends on evaporative demand when we want to prevent reductions in expansive growth. Otherwise most crops can use around 70 % of stored soil water before stomatal closure occurs. In arid areas we can calculate mean irrigation calendars for planning purposes. Irrigation scheduling of high frequency irrigation systems is very simple as it focuses only on irrigating with an amount equal to actual crop ET since the last irrigation, while ignoring water storage in the soil.

20.1 Introduction

Irrigation scheduling is a process by which one determines when to irrigate and how much water to apply by calculating the dates and depths of irrigation.. Measurements of plant (leaf water potential, canopy temperature) or soil water status (water content, water potential) may be used for scheduling irrigations, but here we will

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only deal with the simplest, albeit powerful, method, the water balance approach. It involves the determination of all the inputs and outputs of water from the field, and it is based on maintaining adequate soil water content in terms of crop performance. To use this method it is especially important to know exactly crop ET.

Given the technical difficulties in measuring the water balance components in practice, this method is applied based on estimates of some of the water balance components. It is therefore highly desirable, when possible, to take measurements (neutron probe, gravimetric sampling) that allow us to check the accuracy of estimated values.

This chapter first presents the foundations and applications of the water balance method. Then the information required for applying the method and the rules for determining the dates and amounts of irrigation are presented.

20.2 The Water Balance Equation for Irrigation Scheduling

The water balance equation allows calculating the decrease in soil water content as the difference between outputs and inputs of water to the field. Therefore the Soil Water Deficit (SWD) for day t is calculated as:

$$\mathrm{SWD_t = SWD_{t-1} + ET - I_e - P_e} \tag{20.1}$$

where P_e is effective rainfall and I_e is effective irrigation. In both cases the term effective means after discounting losses due to runoff or deep percolation. The Soil Water Deficit was defined in Chap. 8 as the amount of water required to bring the soil to the upper limit (Field Capacity). Note that instead of considering the amount of water in the soil we use a deficit of water that increases from zero when the soil is at Field Capacity.

Once you have a method to estimate SWD, you must establish rules of decision to determine the date and the depth of irrigation. The decision rule to adopt depends on numerous factors such as the crop, the soil, the climate and the irrigation system.

The critical SWD that should not be exceeded is calculated as:

$$\mathrm{SWD_c = Z_R \ PAW \ AD} \tag{20.2}$$

where Z_R is effective rooting depth (m), PAW is plant available water (mm/m), which is the difference between Field Capacity and Permanent Wilting Point and AD is the Allowable Depletion (fraction). Commonly found PAW values for sandy, loam and clay soils are around 100, 150 and 200 mm/m, respectively. An average PAW value of 120 mm/m has been found for a wide range of light to medium-textured soils and may be used in the absence of local information.

20.3 Effective Rooting Depth

In the context of irrigation scheduling, effective rooting depth (Z_R) is the soil depth where roots can extract most of the soil water, and is equivalent to the soil water reservoir that is being managed by the irrigator. This depth may be considered constant for perennials (alfalfa, fruit trees). In annual crops, Z_R increases from a minimum to a maximum value (Z_{Rmax}) that depends on the crop and the soil. The variation of Z_R for annual crops can be calculated as follows:

$$Z_R = Z_{Rmin} + (Z_{Rmax} - Z_{Rmin})\, R_f \tag{20.3}$$

where Z_{Rmin} is the value of root depth at planting, which is equal to the sowing depth. The maximum value of root depth for annual crops occurs around or after flowering. The factor R_f describes the rate of growth of the rooting depth during the cycle and may be calculated as a function of time (t, Eq. 20.4a) or as a function of thermal time (TT, Eq. 20.4b) from sowing:

$$R_f = \frac{t}{t_{s-m}} \tag{20.4a}$$

$$R_f = \frac{TT}{TT_{s-m}} \tag{20.4b}$$

where $t_{s\text{-}m}$ and $TT_{s\text{-}m}$ are the time and thermal time from sowing to maximum rooting depth, respectively. The primary factor determining maximum rooting depth is the soil, particularly the soil depth and its mechanical resistance to root penetration. Therefore, for any given crop the maximum rooting depth depends on the soil characteristics and that explains the wide variation in maximum effective root depth of each species presented in Table 20.1. For instance, Table 20.1 shows that in the case of sunflower the maximum root depth varies from 1 to 2.5 m. In some extremely open, deep soils it has been found that water extraction by sunflower crops occurs down to 3 m and more. Irrigation management affects the distribution of the root system; frequent irrigation promotes root growth in the surface layers while long irrigation intervals favor more root growth in the deeper layers. Because mechanical resistance increases exponentially as the soil dries, root growth occurs very slowly or does not occur at all in dry soil. This is the reason why it is advisable to start the growing season with a fully charged soil profile (zero water deficit in the anticipated root zone). In that case, if irrigation is delayed, root growth will be occurring at progressively deeper moist layers because water uptake dries progressively the soil layers above and that limits new root growth. The distribution of roots is therefore the result of the dynamics of root water uptake and of the application of water, which determine where the conditions are favorable for new root expansion. This has led to the (wrong) popular belief that roots seek out water. What roots do is to proliferate where soil environmental conditions are good in terms of water and nutrient content and temperature. Thus, irrigation

Table 20.1 Maximum effective root depth (m) under no soil restrictions and factor for calculating Allowable Depletion (F_{AD}) for important agricultural species. The wide interval in root depth shown reflects the sensitivity of root distribution to irrigation management. For information on more species see Appendix 10.3

Crop	Max. root depth	F_{AD}
Alfalfa (hay)	1.0–2.0	0.09
Apple	1.0–2.0	0.10
Barley	1.0–1.5	0.09
Bean (Phaseolus) (dry seed)	0.6–0.9	0.11
Coffee	0.9–1.5	0.12
Cotton	1.0–1.7	0.07
Grapes (wine)	1.0–2.0	0.11
Lettuce	0.3–0.5	0.14
Maize (grain)	1.0–1.7	0.09
Millet	1.0–2.0	0.09
Olives	1.2–1.7	0.07
Orange	1.0–1.5	0.10
Palm trees	0.7–1.1	0.07
Peach	1.0–2.0	0.10
Peas (dry harv.)	0.6–1.0	0.12
Potato	0.4–0.6	0.13
Rapeseed, canola	1.0–1.5	0.08
Rice	0.5–1.0	0.16
Sorghum (grain)	1.0–2.0	0.09
Soybeans	0.6–1.3	0.10
Sugar beet	0.7–1.2	0.09
Sugar cane (virgin)	1.2–2.0	0.07
Sunflower	0.8–1.5	0.11
Tea	0.9–1.5	0.12
Tomato	0.7–1.5	0.12
Winter wheat	1.5–1.8	0.09

management affects the distribution of the root system but not its depth. Frequent irrigation favors high rooting density in the surface layers, while infrequent irrigation or rainfed conditions generate root systems with less density near the surface and much more in the deep layers. If such deep soil layers are dry very little root growth will occur there (Table 20.1).

20.4 Allowable Depletion

Plants can extract soil water down to the Permanent Wilting Point, but crop performance is affected before that. The Allowable Depletion is the fraction of plant available water that can be extracted by the crop without negative effects on yield, but could also be determined as the PAW fraction above which a certain process such as transpiration, assimilation or growth proceeds unaffected. Therefore the AD may depend on the process considered and on evaporative demand, as plant water status is affected by soil water potential and transpiration rate (Chap. 14). Growth rates may by affected after only 10–20 % of available water has been used, while transpiration is usually affected after much higher PAW values (60–70 %). The evapotranspiration of field crops, according to Ritchie, is reduced after two third of available water has been extracted. This is a simple rule valid when expansive growth is not critical for yield (full cover situations, harvest value dependent on dry matter). On the contrary, when growing horticultural crops we are concerned with the size of the harvestable organ (root, bulb, leaves) so water deficits should be avoided and a low AD should be adopted. The same would happen when we deal with field crops during vegetative growth. In those cases, evaporative demand should be taken also into account, with AD decreasing as ET_0 increases:

$$AD = 1 - F_{AD}\, ET_0 \tag{20.5}$$

where F_{AD} is a sensitivity factor shown in Table 20.1 for the main agricultural species (for a more complete list see Appendix 10.3). If Eq. 20.5 yields a value of AD below 0.2, we adopt AD = 0.2.

Example 20.1 The soil in our farm is of sandy loam texture and 1 m depth. We want to irrigate maize (after full canopy cover) and onion and need to know the critical soil water deficit for irrigation management.

The values of maximum ET_0 expected are 5 mm/day (onion) and 8 mm/day (maize). According to the soil type we can adopt a value of potential available water of 120 mm/m.

According to Appendix 10.1 the maximum root depth of onion is between 0.5 and 0.8 m. We take the mean value (0.65 m). The value of F_{AD} is 0.14 (Appendix 10.1) so using Eq. 20.5 we get:

$$AD = 1 - F_{AD}\, ET_0 = 1 - 0.14 \cdot 5 = 0.3$$

Now we calculate the critical soil water deficit as:

$$\mathrm{SWD_c} = \mathrm{Z_R}\, PAW\mathrm{AD} = 0.65\ \mathrm{m} \times 120\ \mathrm{mm/m} \times 0.3 = 23.4\ \mathrm{mm}$$

The maximum root depth of maize is between 1.0 and 2 m, which in any case is greater than the actual soil depth (1 m) so we adopt 1 m as maximum root depth. As we have reached full canopy cover we are not concerned about expansion and adopt AD = 0.7. The critical soil water deficit will be:

$$\mathrm{SWD_c} = \mathrm{Z_R}\, PAW\mathrm{AD} = 1.0\ \mathrm{m} \times 120\ \mathrm{mm/m} \times 0.70 = 84\ \mathrm{mm}$$

20.5 Criteria for Irrigation Scheduling

The basic rule for irrigation scheduling is to irrigate just before the soil water deficit reaches the critical SWD defined in Eq. 20.2, applying a dose equal to SWD. This rule implies no water deficit with a minimum number of irrigations. However, the characteristics of the irrigation system may impose restrictions to the dates and depths of irrigation.

Irrigation scheduling by the water balance is equivalent to operating with a credit card with a maximum credit (PAW) and a critical credit (critical SWD), above which interest rates increase (crop yields decrease). We may deposit money whenever we want (irrigate) and some friends may unexpectedly deposit money as a gift (rain). We spend money every day (ET) thus the deficit in the account increases. If we want to avoid high interest rates and minimize the number of deposits (as they imply a cost, the labor involved in applying irrigation) we should go to the bank just before the deficit reaches the critical value and deposit an amount of money equal to the deficit. This would be the basic rule. If we go sooner to the bank then the number of deposits would increase. If we go later we will exceed the critical credit and the interest rate would increase.

20.5.1 Restrictions to the Dates of Irrigation

Some irrigation schemes, typically those with surface irrigation, are organized according to a rotation and farmers receive water at stated intervals (e.g. weekly) so the possible dates of irrigation are fixed and the farmer decides the irrigation amount. Pressurized irrigation systems may work on demand so the farmer chooses the date and the amount. However, even in this case, dates may be restricted by holidays or other operations in the farm that are incompatible with irrigation (e.g. application of pesticides) or require labor or equipment necessary for irrigation.

20.5.2 Restrictions to the Irrigation Depth

The type of irrigation system and its design may impose restrictions on irrigation depths. Surface irrigation systems are designed for applying a rather large depth (over 50–60 mm) and become highly inefficient when smaller depths are applied, except in smallholder irrigation systems of very small plots. Irrigation machines (center pivot, lateral move, siderolls) move within a given range of speeds that determine the irrigation depths that they can apply. Hand-move sprinkler systems have to be organized taking into account the time required for displacing the lateral, which usually leads to an optimum irrigation depth (or duration).

20.5.3 Decisions on Irrigation Dates and Depths

The basic rule for deciding when to irrigate is to do it just before the soil water deficit reaches the critical SWD which is calculated according to the soil and the crop. If we irrigate sooner than that we will increase the number of irrigations, and thus the cost, but we will be on the safe side in terms of water deficit and would be able to cope with possible failures of the irrigation system. If we irrigate later, and thus SWD exceeds the critical value, water stress will occur and it may have a negative effect. This would be the case of deficit irrigation, when water available is not enough to meet the crop water requirement. In the case of rotation of water supply, for any date when water is available we should irrigate if we expect the critical SWD to be exceeded before the next date with water supply.

Example 20.2 We are irrigating corn during summer with mean daily ET = 8 mm/day. Water is available every 10 days (1 July, 11 July, 21 July, etc.) and the critical SWD is 120 mm. On 1 July the SWD is 20 mm. Should we irrigate? The answer is no. We can wait until 11 July as SWD will be $20 + 10 \times 8 = 100$ mm. We should irrigate on that date (11 July) as SWD would exceed the critical value soon after that, so waiting until 21 July should be discarded.

Once the irrigation date is decided the basic rule is to refill the soil, i.e. bring the soil to zero SWD, therefore the irrigation depth should be equal to SWD at the date of irrigation. However, the irrigation depth could be larger than that (excess irrigation) when salt leaching is required. On the contrary, the depth could be smaller, thus leaving some soil water holding capacity unfilled which may store rainfall in the days after irrigating. This strategy may improve rainfall use at the expense of increasing the number of irrigations.

Example 20.3 Different strategies for date and depth of irrigation are applied to grain sorghum planted on April 15 in Hinojosa (Spain). The critical SWD is 94. Figure 20.1 shows the basic strategy (irrigated when SWD reaches the critical value) and apply a dose equal to SWD. In this case we apply three irrigations. In Fig. 20.2 a more conservative strategy is followed: irrigate before SWD reaches the critical value. The number of irrigations would be 4. If we adopt a strategy designed to take advantage of rainfall (do not bring the soil to zero deficit) the number of irrigations is also 4 (Fig. 20.3). In Fig. 20.4 we assume a rotational water supply of 10 days. The number of irrigations would be 5. Note that the farmer does not need to irrigate every 10 days but only in those days when he cannot wait until the next possible date for irrigation.

(continued)

Example 20.3 (continued)

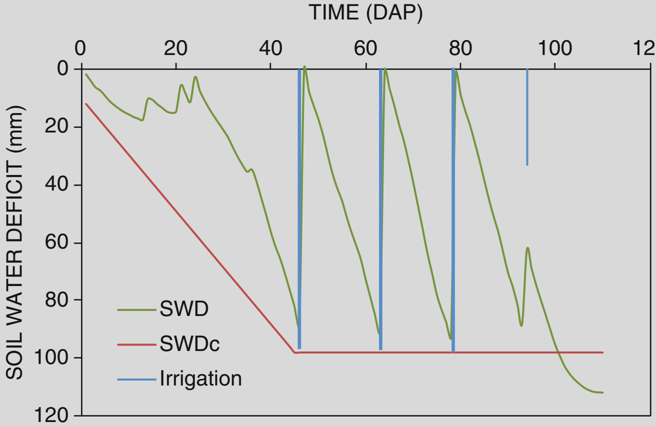

Fig. 20.1 Irrigation schedule of grain sorghum planted April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when SWD equals the critical SWD, and applying a depth equal to SWD

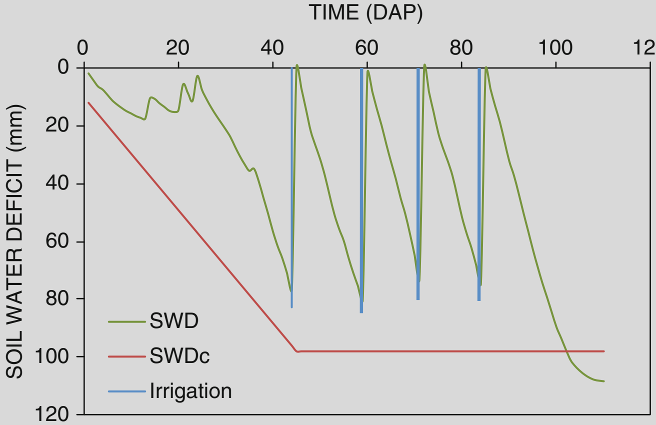

Fig. 20.2 Irrigation schedule of grain sorghum planted April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when SWD equals the critical SWD minus 20 mm, and applying a depth equal to SWD

(continued)

Example 20.3 (continued)

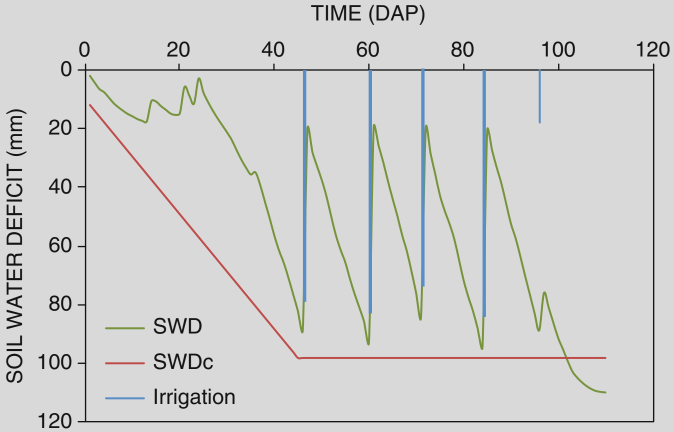

Fig. 20.3 Irrigation schedule of grain sorghum planted April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. The strategy followed is to irrigate when SWD equals the critical SWD, and applying a depth equal to SWD minus 20 mm

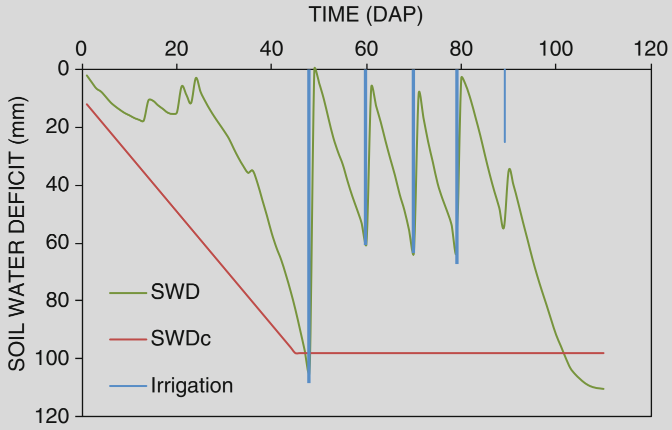

Fig. 20.4 Irrigation schedule of grain sorghum planted April 15 in Hinojosa (Spain). The curves of soil water deficit and critical water deficit are shown. Here a fixed rotation water delivery is assumed and water is available at 10-day intervals. The strategy followed is to irrigate when the expected SWD 10 days later will exceed the critical SWD, and applying a depth equal to SWD

The rules about irrigation depths have to be corrected near the end of the crop cycle in order to leave the soil as dry as possible to allow rainfall storage during fallow and to prevent excessive deep percolation and thus, nitrate leaching. To achieve such an objective, the soil water deficit at harvest should approach 80–90 % of available water in the profile. This can be achieved by solving the water balance equation since the date of the last irrigation until harvest, which allows calculating the depth for the last irrigation as:

$$I = SWD_{t_L} - SWD_{t_H} + \sum_{t_L}^{t_H} ET_i \tag{20.6}$$

where t_L and t_H refer to the dates of the last irrigation and harvest, respectively.

Example 20.4 We are irrigating a crop whenever SWD reaches a critical value of 96 mm, which results from determining it based on a soil depth 1 m, PAW 160 mm/m and AD 0.6. We need to irrigate on September 1 and want to end the irrigation season on October 1, after using 90 % of the PAW. Therefore the final SWD should be 144 mm. Average ET during September is 3 mm/day. Applying Eq. 20.5 we calculate the irrigation depth as:

$$I = SWD_{t_L} - SWD_{t_H} + \sum_{t_L}^{t_H} ET_i = 96 - 144 + 30 \times 3 = 42\ mm$$

Note that by applying the correction we could save 54 mm of irrigation water.

20.6 Irrigation Schedules

The dates and depths of irrigation have to be decided on real time according to the specific weather of each year by updating the soil water deficit day after day according to crop ET and rainfall. In arid areas where rainfall is negligible during the irrigation season an average irrigation calendar may be defined a priori using mean ET values. This approach was originally developed in California and allows a better planning of the irrigation season as the dates and depths of irrigation for each crop in the farm are calculated at the start of the season so the allocation of labor and irrigation equipment can be optimized.

When irrigation systems are permanent (microirrigation or solid-set sprinkler systems), and there is no labor cost associated with applying an irrigation, timing is unimportant and irrigation is applied as frequently as desired. Thus, when using the water balance under high frequency irrigation (e.g. drip), we may ignore, in principle, the soil water storage, so that the scheduling strategy is to simply replace the ET accumulated since last irrigation. As explained in Example 20.4, some irrigation water may also be saved at the end of the season under high frequency irrigation by safely using some of the stored soil water.

Example 20.5 We are scheduling the irrigation of a tomato crop with crop coefficient 1.2, and a drip irrigation system with emitters of 2 L/h spaced 1 × 0.75 m. We will calculate the operation time of the system if yesterday's ET_0 was 7 mm/day.

The previous day's ET was:

$$K_c\ ET_0 = 1.2 \times 7\ \text{mm d}^{-1} = 8.4\ \text{mm d}^{-1}$$

Each hour of operation of the irrigation system is equivalent to an applied depth:

$$2\ \text{L/h}/\left(0.75\ \text{m}^2\right) = 2.67\ \text{mm h}^{-1}$$

Therefore the operation time should be:

$$8.4/2.67 = 3.15\ \text{hours d}^{-1}$$

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Chapter 21
Deficit Irrigation

Elias Fereres and Francisco J. Villalobos

Abstract When the level of irrigation supply is less than crop ET, deficit irrigation (DI) programs are needed to optimize the use of the limited water. In annual crops where yield and transpiration are linearly related, DI aims at achieving maximum profits by minimizing application losses and maximizing use of stored soil water. Crops that respond positively to mild water deficits are good candidates for DI programs that decrease irrigation water use while maintaining yield. DI programs for fruit trees and vines aim at inducing water deficits at periods where they are least harmful to yields, including high evaporative periods. Achieving optimal use of limited water is accomplished by solving an optimization problem using knowledge of water costs and crop prices.

21.1 Introduction

For many decades, the paradigm of irrigation development was to supply crops with sufficient water to meet their full water requirements. This approach was taken because the investments associated with the large costs of irrigation networks, from dams to on-farm equipment, were best justified if farmers would achieve maximum yields, normally associated with maximum transpiration. However, there were irrigation development cases where, in order to reach a maximum number of farmers, the irrigation supply was less than that needed to meet the full crop demands. In other cases, the capacity of the system was inadvertently less than needed or the crop rotation scenarios upon which the irrigation design was based, had changed over time and different crops or most intensive rotations were introduced that required more water than what the original system could supply.

More recently, water allocation to irrigation has been challenged by other sectors of society with the result that irrigation in many areas receives less supply now than

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what was originally assigned. Furthermore, water scarcity due to periodic droughts in many areas is increasing thus reducing the original irrigation supply or making it more unreliable. Under all these conditions, farmers do not have sufficient irrigation water to meet the full crop water requirements and the consequence is that crop transpiration is reduced below its maximum potential. Normally, this results in a reduction in crop production of variable magnitude depending on many factors (Chap. 14). Deficit irrigation (DI) is thus defined as an irrigation management practice that by applying insufficient water causes crop transpiration to be below its maximum unstressed value. This chapter discusses how to manage DI to minimize yield reductions and to maximize farmers' productivity and profits in situations of water scarcity.

21.2 The Yield Response Function to Water

The use of DI forces farmers to solve an optimization problem: what is the optimum level of irrigation water that a farmer should use to maximize its goals? Normally, farmers aim to obtain the maximum revenue or net income from their operations which is not necessarily the same as the maximum production. The initial information needed to optimize the use of a limited water supply through DI is the relation between water and yield. If the Y-I relationship is known for a specific situation at the field scale, the manager can determine the optimum amount of I to reach maximum net profits. This I_{opt} will be the level of I above which, the value of the additional crop produced would be less than the cost of one additional water unit. Given the close, linear relationship between transpiration and biomass production discussed in Chap. 14, and because of the conservative nature of the harvest index of many crops, the relationship between transpiration and crop yield is linear for the major crops over a wide range of transpiration, starting with the maximum yield at the maximum, unstressed transpiration value. However, the relation between yield and irrigation water (Y-I) is not linear, and is affected by the uniformity of distribution of irrigation water over the field.

To better understand the Y-I relationships at the field scale, Fig. 21.1 shows the variation in irrigation depth in different parts of the field, going from the areas that receive more water than the required depth to the areas that receive less water than required. Such spatial differences are caused by variations within the irrigation system that delivers different amounts in different parts of the field due to manufacturer and pressure variations, wind effects, and other factors that cause lack of uniformity in the distribution of water. The shape and slope of the line that describes the actual distribution of water in the field (Fig. 21.1) is indicative of the distribution uniformity. If the slope is mild, water distribution is similar in different areas of the field while if the slope is steep, the uniformity is low with some areas receiving much more water than others. In this case, much excess water

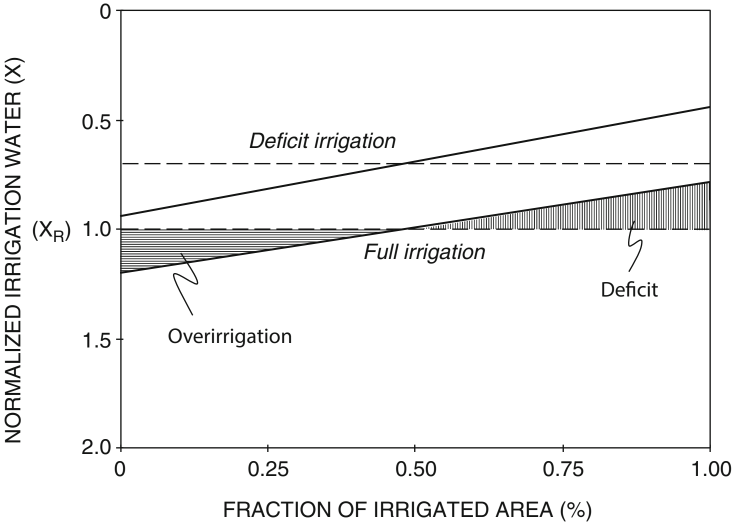

Fig. 21.1 Relations between normalized irrigation water and the fraction of the irrigated area that receives such water. X_R indicates the level of water required as shown by the *horizontal dotted line* at 1.0, and another *dotted line* at 0.7 indicates a level of DI that is 30 % less than X_R. The actual water distribution across the field is shown by the *solid lines* for full and deficit irrigation, going from the areas which receive the most water to the areas that receive the least

will be required to supply the required depth to the areas that received the least water. In the case of DI where the amount of water applied is less than what is required (see Fig. 21.1), given the same level of uniformity there will be areas within the field that will receive much less water than what is required and where yields could be seriously diminished by insufficient irrigation.

As it is not physically possible to achieve perfect uniformity of water application (100 %), additional water must be applied to arrive at the required depth in the areas that receive the least water. Figure 21.2 represents a generic yield response function with two levels of irrigation uniformity, high and low. Also represented is the linear function between yield and ET. As irrigation increases, more of the irrigation water in not used in ET and is lost to runoff or deep percolation. If irrigation uniformity is high, losses would be small and maximum yields will be achieved with little excess water (Fig. 21.2). However, if uniformity is low, irrigation application has to increase to meet the needs of the areas that receive the least water while others will be getting excessive. In the case of Fig. 21.2, water application must double the required amount to achieve maximum yields under low irrigation uniformity.

Constructing the Y-I function for a given crop and field needed to quantify I_{opt}, requires knowledge of the relation between Y and ET and of the actual uniformity of distribution of irrigation water over the field. Section 21.6 presents an advanced example where the Y-I function is developed and an expression for I_{opt} is derived based on some assumptions.

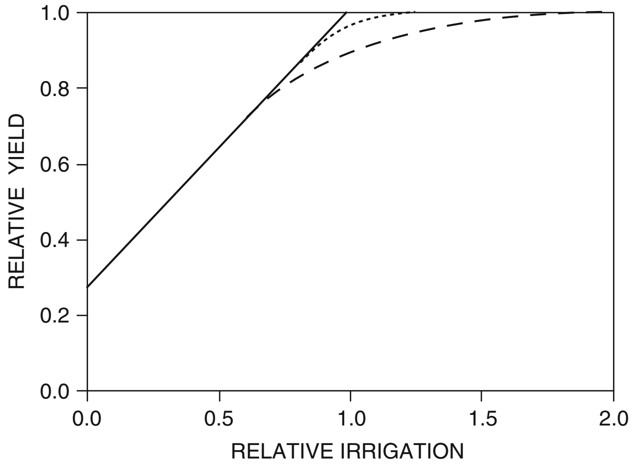

Fig. 21.2 Generic relations between relative irrigation and relative yield under two levels of uniformity. Also shown is the relation between relative yield and relative ET (*solid line*). High uniformity is represented by the *dotted line* and low uniformity is represented by the *dashed line*

21.3 Deficit Irrigation in Annual Crops

To define the Y-I function, the relations between yield and T must be known. While the B-T relationship is unique for a given crop and is only affected by the environment in which the crop is grown, the Y-T relationship of a crop can vary depending on the timing and intensity of the T deficits. This is because of the differential sensitivity to water stress of the different crop developmental stages. Water deficits imposed at sensitive stages affect disproportionally more the harvest index (HI) than biomass production, while the HI does not vary if water deficits during the sensitive stages are avoided or are not severe. As a general rule, when T deficits are imposed progressively and are moderate, HI stays constant and the reduction in Y is proportional to the reduction in B. Figure 21.3 shows the typical Y responses of an annual crop as ET is decreased by water deficits. The thick line represents the response to uniform, progressive water deficits and the two steeper lines represent the responses when water deficits are more severe and/or occur at the most sensitive stages of crop development. In most annual crops, the most sensitive stages are those at which yield determining processes (flowering, fruit set and fruit growth) occur. For instance, in the case of grain crops, the reproductive stages are more sensitive than the vegetative phase, as discussed below.

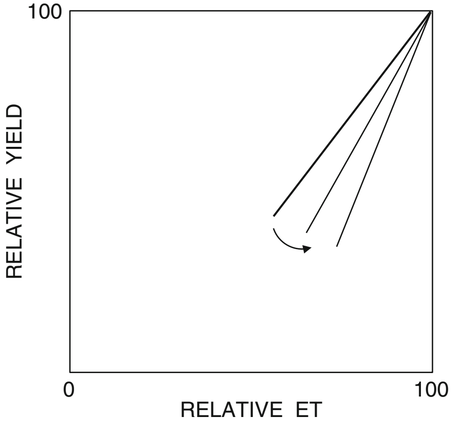

Fig. 21.3 Relations between relative crop yield and relative ET influenced by the severity of water deficits during sensitive developmental stages. The *arrow* indicates the response trend as water deficits are applied at the most sensitive stages and with increased severity

21.3.1 Maize

The most sensitive period to water deficits is flowering, the period that goes from tasseling to silking. In fact, severe water deficits during that period delay or prevent silk emergence, impairing pollination and resulting in a very low grain number. Following in sensitivity is the early grain filling period where severe stress results in grain abortion. Late grain filling is less sensitive and the least sensitive is the vegetative phase, as growth recovers after the release of water deficits. Note that during the vegetative phase, the goal is to develop a canopy that intercepts maximum radiation, thus severe irreversible reductions in canopy expansion also limit yield substantially. In general, maize is not a crop conducive to DI, as any measurable reduction in T has a negative impact on Y. Mild T deficits, around 10 % or less, during the mid to late vegetative phase have the least impact on production and may be a viable DI strategy in case of water scarcity.

21.3.2 Wheat

As in other winter cereals, flowering is the most sensitive period, in particular the pollination to grain set period. However, the stages of development which take place before and after pollination are also quite sensitive. In the pre-flowering phase, when the number of florets in the spikes is being determined, water deficits may cause a reduction in grain numbers. After pollination, abortion of grains also reduces grain numbers under water stress. Grain filling in its early stages is also quite sensitive to water deficits which affect negatively grain weight. During the early vegetative phase, wheat is quite tolerant to water deficits but at the tillering stage, water deficits may reduce tiller numbers. Winter cereals have compensatory mechanisms, and a reduction in grain numbers may be partially compensated by increased grain weight if conditions during grain filling are favorable. Thus, deficit irrigation of wheat is a viable strategy if deficits are restricted to the early vegetative and late reproductive stages, with mild reductions in transpiration. There are situations, however, where farmers have limited access to irrigation water, sufficient to apply one irrigation only. In that case, depending on rainfall probability and soil water storage capacity, the most profitable time to supplement rainfall would be around flowering. In shallow soils and very low post-flowering rainfall probabilities, it should be delayed as much as possible to avoid severe stress during grain filling, while in the opposite case, the single irrigation would be most profitable at the pre-flowering stage to maximize the number of grains which could then be filled based on stored soil water.

21.3.3 Rice

This crop is generally grown under flooded conditions thus it is not subjected to soil water deficits. However, there are newer methods of growing rice that are based on wetting and drying of the soil. Rice is an extremely sensitive plant to water deficits, has a small, shallow root system and does not tolerate water stress. Research has shown that the few days (2–3) around pollination time are the most sensitive to water deficits and can cause almost complete crop failure. Rice is not a crop that can be subjected to deficit irrigation and the water supply must be concentrated on an area which permits supplying the crop with its full requirements.

21.3.4 Soybean

Although it is an indeterminate-type plant, flowering of most modern varieties is determinate, normally occurring during a short period of 2–3 weeks. Water deficits during flowering and fruit set are most detrimental to yield. The next, most sensitive period is seed filling, where water deficits cause premature leaf senescence and reduce the plant's capacity to fill the seeds. Water stress during the vegetative period affects canopy cover and hence radiation interception, while if it occurs during the late part of such period, it is less detrimental, provided it can recover before it becomes severe enough to cause premature, irreversible leaf senescence. Soybean is mostly produced under rainfed conditions, thus the likelihood of using deficit irrigation is small; nevertheless, in terms of relative sensitivity, soybean is quite sensitive to water deficits, about the same as maize, thus the DI strategy should be quite conservative, aiming at producing at least 80–90 % of full yields.

21.3.5 Potato

It is very sensitive to water deficits and thus a candidate for DI strategies that only induce mild water stress. The most sensitive stage is the time during stolon formation and tuber initiation where the impact on yield is most important. Early canopy development is also sensitive and where water deficits that have irreversible effects on canopy expansion should be avoided. The period of tuber growth is less sensitive but yields are also affected, in particular if canopy senescence is hastened by water deficits. The relative sensitivity to water stress varies somewhat among the wide range of varieties that exist.

21.3.6 Sorghum

It is tolerant to water deficits and is a good substitute for maize when water shortages force the use of DI. Mild to moderate water deficits have little or no impact on yields due to an increase in harvest index when subjected to water deficits relative to full irrigation supply. The most favorable DI strategy is to sustain the level of water deficit throughout the season, for example applying 75 % of full ET needs, aiming to reach harvest time with the root zone profile exhausted of available water. It has been shown that severe stress that reduces ET below 50–60 % of maximum causes a decrease in HI in this crop and is detrimental to yield. Thus DI strategies in sorghum should aim at reducing ET not more than 60 % of maximum, and the optimal economic level would be between 70 % and 80 % of maximum depending on water availability and irrigation costs.

21.3.7 Tomato

As many other vegetable crops it is not amenable to deficit irrigation as yields are reduced with reductions in ET. However, experimental work in processing tomatoes showed that mild deficits at ripening reduce slightly ET (by about 10 % or less) without impacting yield. Thus, the least sensitive stage for imposing water deficits is the late ripening stage. Stress imposed during other developmental stages reduces canopy growth, fruiting and yields.

21.3.8 Sugarcane

It is very sensitive to water deficits during the period of stalk growth early in the crop cycle. The least sensitive period is maturation where mild to moderate deficits lead to increase sucrose accumulation in the stalk and reduction in harvest fresh weight (and costs). Therefore, DI should aim at imposing some ET deficits during the maturation period with reductions of ET of no more than 10–15 % of seasonal value. On the other hand, water supply should not limit the canopy development processes until the crop reaches maximum canopy cover.

21.3.9 Cotton

It is a good candidate for DI in areas where the season length is limited by low temperatures at the beginning and end of season. Water deficits can be used to adjust the crop to those environments by imposing deficits during the late vegetative growth period to hasten flowering and boll formation, and during the maturation phase to enhance boll opening and synchrony for effective mechanical harvest. Moderate water deficits applied during those two phases result in an increase of HI relative to that of fully irrigated crops and a reduction in season length that better fits the environment. Again, as in sorghum, severe water stress is detrimental and has a negative effect on HI, thus DI should aim at ET deficits that do not reduce the crop ET below 60–70 % of maximum. The most sensitive period where water deficits should be avoided is during fruit set to prevent fruit abortion.

21.3.10 Sunflower

It is a drought avoiding species that has very high growth rates during the vegetative phase but, during reproductive development accumulates dry matter much more slowly as it concentrates it in seeds that have high-energy fats and protein content. The period that goes from end of flowering to early fruit set is the most sensitive to water deficits, followed by early seed filling, late seed filling, early vegetative, and late vegetative, as the least sensitive. This is because sunflower has a strong compensatory growth capacity following water deficits during the vegetative phase. DI strategies should aim at imposing moderate deficits during the vegetative phase, well after crop establishment but ending it before leaf growth is completed. Such a period is not very long relative to the crop cycle; thus, ET reductions should not exceed 10–15 % of seasonal ET for optimum production.

21.4 Deficit Irrigation of Fruit Trees and Vines

The most powerful measure to respond to water scarcity in annual crops is to adjust the planted area to the available supply. This is not possible in permanent crops where the investment costs are substantial and maintenance of the plantations is the primary objective. Occasionally, farmers take advantage of drought years to replace old orchards with new ones of different species or cultivars. With that exception, the rest of the time there would be the need to use some form of DI to cope with the limited supplies and to minimize the impact of water deficits. This is particularly important because of the impact of water deficits on subsequent years' production in permanent crops, and furthermore to avoid the possibility of tree death with the economic consequences due to the multi-year investment losses if the plantation is lost.

The responses of fruit trees and vines to water deficits are much more complex than those of annual crops. The yield determining processes are less well understood than those of annual crops, and commonly, yields oscillate with time even under optimal growing conditions, a feature known as alternate bearing that varies in importance among the different fruit tree species and cultivars. Water deficits in the current season affect yields of the subsequent season/s, depending on its timing and severity. Knowledge of the differential sensitivity of the different processes to water deficits thus become important to allocate the application water in such a way that avoids impacting negatively on current year and/or subsequent year's yield.

Experiments with peach and pear trees demonstrated that irrigation may be restricted in periods when yields are insensitive to water stress and water can be saved with minimal or no yield loss, and sometimes producing more net profits than under full irrigation. This approach of purposely stressing tree crops and vines at certain developmental stages considered the least sensitive to water deficits has been called regulated deficit irrigation (RDI), a term now used for any DI approach followed in trees. However, there is another DI approach which consists in applying a fraction of the ET throughout the irrigation season. This sustained or continuous DI strategy (CDI), generates a stress pattern which is different than that of RDI, at least in temperate environments, where ET_0 varies widely during the growing season. The usual stress pattern in CDI starts early in the season when a fraction of ET is applied, but trees extract additional water from the wet soil with the consequence that water deficits seldom develop. Depending on the magnitude of the deficit and on the water storage capacity of the root zone, water deficits will increase in magnitude in CDI as the season progresses, reaching the highest level when ET_0 is highest close or near the end of the season, in the absence of rainfall.

21.4.1 Regulated Deficit Irrigation

In RDI, the physiological basis for imposing water stress at specific developmental stages resides in the differential sensitivity of vegetative growth and of photosynthesis to water stress (Chap. 14). Expansive growth is more sensitive to water deficits than is carbon assimilation, thus mild to moderate water stress slows down or stops leaf and stem growth before it impacts photosynthesis. During fruit growth of some tree species, there are periods when vegetative growth takes place and fruit growth slows down almost to a stop. In those periods, water stress reduces growth in general but fruit growth can fully recover upon release of stress while vegetative growth has been curtailed. The result is less vegetative growth (and less pruning costs) while fruit size is unaffected. There are some species where moderate water deficits change the partitioning of assimilates in favor of the fruits and this also results in beneficial effects in terms of yield and fruit quality. In deciduous trees, the period after fruit harvest is another insensitive period where water deficits may be applied without impacting yield, provided that next year's bud development processes have been completed.

One important benefit of DI in fruit trees and vines is related to the enhancement of fruit quality features caused by moderate water deficits. The most important case is that of wine grapes. Plants grown under moderate water deficits applied both early during berry growth and late after the berries changed color, promote the synthesis of a number of biochemical compounds that are essential wine quality components. In fact, high-quality wines are produced mostly in rainfed environments or under substantial DI programs, while wines produced from grapes grown under unlimited supply are seldom of good quality. Other fruits benefit from an increase in the content of sugars or other positive changes in composition induced by DI, although, contrary to wine production, the quality features of most fruits are not determinants of the price that farmers receive for their produce. In fact, fruit size is a factor that is appreciated in many markets and DI tends to reduce fruit size relative to that of full irrigation. In this particular case, the economic loss of DI makes its use not viable, such as in the case of apple.

The yield response to ET deficits generated by RDI strategies may be generalized in Fig. 21.4. Three different response regions may be defined; Region A, where small reductions in ET applied through RDI during insensitive periods do not impact yields. As ET deficits increase in magnitude, yield decreases (Region B) albeit at a low rate. If water stress becomes more severe, yield decline decreases

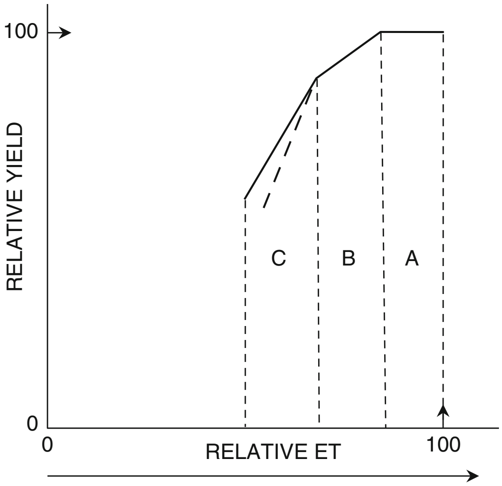

Fig. 21.4 Generalized yield responses to ET deficits induced by RDI strategies in fruit trees expressed in relative terms

steeply (Region C) and water deficits of that magnitude can impact yields very severely if they occur partly in more sensitive periods (Dashed line in Fig. 21.4).

The magnitude of the response in Region A varies depending on the species; from the very sensitive ones such as avocado, walnut and apple where it has not been found, to about 5–15 % ET reductions in citrus (depending on species and cultivars), pears, almonds, among others, raising to 10–20 % ET reductions in peach, plum, apricot, pistachio, up to 20–30 % ET reductions without impacting yields as in the olive.

Region B also varies in magnitude with species and cultivars but follow the differential sensitivities indicated for the different species in Region A. The mild slope indicates that the water savings must be compared against yield losses to find an optimum net income under DI. On the contrary, the steep slopes of Region C suggest that ET deficits of such magnitude will have detrimental effects on net income and should be avoided at all costs.

21.5 Deficit Irrigation at Farm Level

Water restrictions that occur at farm level force managers to make strategic decisions before planting. They must decide what crops to grow, and how to allocate different water amounts to each of the crops to make best use of the limited supply available. Different crops need different irrigation amounts and their irrigation timing is also different. Economic issues (markets and subsidies) are critical in determining the farm net profits once the total supply available is known. The goal would be to optimize the use of land and irrigation water given the supply restrictions, and this is achieved through the use of economic optimization models. These models provide optimal cropping patterns and optimal irrigation amounts for each of the crops that maximize the objective function which normally is the total farm income. Once the model is built, it can be used to explore different scenarios of varying crop and water prices and of other factors, such as the impact of changing subsidies on the strategic decisions by farmers, for example. One complicating factor at the farm level is the uncertainty of the level of water restrictions. Too often, water authorities delay too much the communication of the restriction to farmers after some of the best options for using the limited water (for example, early planting) are no longer viable. In the event of a drought, farmers must be proactive in securing their water supplies and should maintain open communication with the water authority to be able to make the best decisions under uncertainty.

21.6 Quantitative Optimization of Deficit Irrigation

We start with the assumption that biomass production is proportional to transpiration and that Harvest Index does not change with the level of water stress. This is valid for mild to moderate stress. Therefore yield will proportional to transpiration in any location of the irrigated field. We also assume that evaporation from the soil surface (E_s) is equal in all points of the field and that excess irrigation has no penalty on yield.

Then we need to consider the variation of irrigation applied. We assume that applied irrigation follows a uniform (i.e. rectangular) distribution. Therefore applied irrigation (I) will lie between a minimum $I_{min} = I_{mean}$ (2 U_{cc}-1) and a maximum $I_{max} = I_{mean}$ (3–2 U_{cc}), where I_{mean} is the mean irrigation applied and U_{cc} is the uniformity coefficient (Chap. 19). The irrigation crop water requirement was defined in Chap. 10 as:

$$\mathrm{IWR_n} = ET - \mathrm{P_e} - \mathrm{SWE} \tag{21.1}$$

where ET is unstressed (i.e. maximum) seasonal crop ET, P_e is effective precipitation and SWE is water uptake from the soil between planting and harvest.

We have three possible situations:

(a) $I_{max} < IWR_n$ the whole field is under-irrigated as even where the maximum application occurs it does not satisfy the net irrigation requirement. In this case yield will be proportional to transpiration, and thus to the irrigation applied in each point of the field.

(b) $I_{min} > IWR_n$ the whole field is over-irrigated as even where the minimum application occurs it exceeds the net irrigation requirement. In this case yield will be the same in the whole field and equal to Y_x (maximum yield).

(c) $I_{min} < IWR_n < I_{max}$ parts of the field are over-irrigated and parts are under-irrigated, thus parts of the field will reach Y_x while others will yield in proportion to irrigation received in that location.

To calculate average yield in the whole field we calculate the integral of yield using applied irrigation (I) as integration variable. For instance for case c we calculate:

$$\overline{Y} = \frac{1}{I_{max} - I_{min}} \left[\int_{I_{min}}^{IWR_n} Y_x \frac{ET - E_s - IWR_n + I}{ET - E_s} dI + \int_{IWR_n}^{I_{max}} Y_x dI \right] \tag{21.2}$$

And after integration we get the relationship between actual yield (kg/ha) and mean applied irrigation (I_{mean}, mm):

$$\overline{Y} = Y_x \left(A - \frac{B}{I_{mean}} - C\, I_{mean} \right) \tag{21.3}$$

where

$$A = \frac{3 - 2\,U_{cc}}{4\,(1 - U_{cc})} - \frac{(2\,U_{cc} - 1)(SWE + P_e - E_s)}{4\,(1 - U_{cc})(ET - E_s)} \tag{21.4}$$

$$B = \frac{IWR_n{}^2}{8\,(1 - U_{cc})(ET - E_s)} \tag{21.5}$$

$$C = \frac{(2\,U_{cc} - 1)^2}{8\,(1 - U_{cc})(ET - E_s)} \tag{21.6}$$

For case a ($I_{max} < IWR_n$):

$$\overline{Y} = \frac{Y_x}{ET - E_s}(SWE + P_e - E_s + I_{mean}) \tag{21.7}$$

And for case b ($I_{min} > IWR_n$) : $\overline{Y} = Y_x$

The model illustrates several interesting points:

(a) To achieve maximum yield it is necessary to apply $IWR_n/(2\ U_{cc}-1)$. For instance, with $U_{cc} = 0.75$ the gross irrigation amount should double the irrigation requirement.

(b) It is clear that the best strategy to achieve maximum profits will likely be to apply less water than that required for maximum yield. The optimum value will depend on the price of the crop at harvest (P_H, €/kg) and the cost of irrigation water (Q_I, €/m^3):

$$I_{opt} = \sqrt{\frac{B}{\frac{10\,Q_I}{P_H\,Y_x} + C}} \tag{21.8}$$

From that we may calculate an apparent optimum efficiency (AOE) of irrigation as:

$$\frac{IWR_n}{I_{opt}} = \sqrt{\frac{10\,Q_I(ET - E_s)\,8\,(1 - U_{cc})}{P_H\,Y_x} + (2\,U_{cc} - 1)^2} \tag{21.9}$$

This equation indicates that AOE is related to the irrigation system (U_{cc}), to the crop species and location (ratio $(ET\text{-}E_s)/Y_x$) and to external economic factors (ratio Q_I/P_H). As the difference $ET\text{-}E_s$ is equal to seasonal transpiration, the ratio $(ET\text{-}E_s)/Y_x$ is proportional to the inverse of Water Use Efficiency (Chap. 14) so it should be proportional to VPD and differ between C3 and C4 species.

Example 21.1 We are growing maize with maximum yield of 12,000 kg/ha and seasonal ET of 750 mm with E_s=150 mm. The values of P_e and SWE are 150 and 100 mm, respectively. The irrigation system is sprinkler with $U_{cc} = 0.75$. The price of maize is 0.3 €/kg. If the water price is 0.05 €/m^3 the apparent optimum efficiency will be 0.645 so we should apply IWR_n/AOE = 500/0.645 = 775 mm. In this case yield would be 11,836 kg/ha (from Eq. 21.3). With water price of 0.15 €/m^3 we should apply 577 mm (AOE = 0.866) to get a final yield of 11,226 kg/ha.

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Chapter 22
Control of Salinity

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Abstract Salinity is a threat to the sustainability of many agricultural systems and especially for irrigated areas in arid and semi-arid zones. Besides the possible specific toxicity the main effect of salts is the reduction of soil osmotic potential causing an effect similar to that of water deficit. The expected yield under saline conditions can be calculated with a simple model whose parameters are the threshold EC_e and the yield loss per unit increase in EC_e. The salt balance equation allows us to deduce soil salinity based on the EC of the irrigation water and the leaching fraction. The Leaching Requirement is calculated taking into account the irrigation frequency, the EC of the irrigation water and the desired EC_e. The presence of Sodium deteriorates soil structure but the effect depends on other factors, in particular the salinity of irrigation water. The reclamation of saline soils is performed by salt leaching while sodic soils are usually reclaimed adding gypsum and leaching Na.

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22.1 Introduction

According to FAO around 20 % of irrigated land occupies salt-affected soils while salts affect less than 3 % of dryland agricultural area. Salt-affected land is mainly located in irrigated arid and semi-arid areas. Preventing the buildup of salts in soils and waters with adequate management is crucial for avoiding land degradation and thus for ensuring the sustainability of agriculture. In the case of irrigated areas, sustainability relies on maintaining an appropriate salt balance in the soil which depends on the salt concentration of irrigation water and the soil water balance.

The primary source of salts is the weathering of minerals, but this source hardly causes soil salinization of agricultural soils. Soil salinization is the consequence of an external supply of salts which in irrigated agriculture is associated with the application of waters that contain salts, while in rainfed agriculture, it is related to secondary salinization phenomena, usually caused by upward movement of water and salts from the subsoil effected by changes in hydrology. Therefore, the salt and water balances are tightly coupled. The salt concentration in the soil solution is greater than that of the water that infiltrates. This difference is a result of soil evaporation not carrying salts while root water uptake only does so very selectively. Therefore, salinity is a real threat in agricultural areas of arid or semi-arid regions due to the high ET rates and by the scarcity of water needed for leaching the salts out of the root zone.

The contribution of salts from rain water is insignificant but can be important in coastal areas when winds from the sea carry salts in aerosols. Irrigation water itself is often the cause of salinization, as all irrigation waters contain salts in varying concentrations. On the other hand, excess of irrigation causes percolation that leaches salts which may eventually reach the sea. The sea can also be the direct source of salinization in some cases: the soils originating from marine sediments can be saline or marine intrusions can cause salinization of groundwater origin, i.e. by upward movement of water from a saline water table. In addition to the natural sources of salt, excessive application of fertilizers can also contribute to salinization.

22.2 Effects of Salinity on Crops

Salinity is quantified as the electrical conductivity of the soil solution (EC, dS/m) or by the salt concentration (C_S, g L^{-1}) which are approximately related by $EC = 0.64\ C_S$. The concentration of cations (CC, or anions) in meq/L is also related to the EC by $CC = 10\ EC$. The osmotic potential (Ψ_o, kPa) may be estimated from the salt concentration as $\Psi_o = 56.25\ C_S$. The electrical conductivity is commonly measured in a saturated soil extract (EC_e) which is approximately half the value of the EC at field capacity (EC_{FC}).

The effects of a high salt concentration in the soil on crop performance are due to: (i) the reduction of osmotic potential in the soil solution, which in many aspects mimics that of water deficits, and (ii) the toxicity and nutrition disorders (antagonistic effects) caused by major ions present in salts (Cl, Na, B). The negative effects of salinity on crops depend on the particular species and the developmental stage. An additional problem occurs with sodium accumulation in soil, a problem defined as soil sodicity, that causes degradation of soil structure.

The main difference between soil water deficit and the osmotic effects due to salts is that a low soil water content has two effects. The first one is to lower the soil water potential, so roots will in turn need a lower water potential for water uptake to occur. The second is the decrease in hydraulic conductivity of dry soil, so that even with a lower potential in the roots, water movement to the root surfaces is limited by the low hydraulic conductivity. The effect of salinity corresponds to the first effect of low soil water content, but the hydraulic conductivity is not affected in the case of salinity.

Example 22.1 A non-saline soil (called A) at wilting point has a matric potential of −1500 kPa and soil water potential is −1500 kPa. We have another soil (called B), with the same texture, but saline. Soil B is at field capacity (matric potential −20 kPa) and has $EC_e = 8.4$ dS/m (so $EC_{FC} = 16.8$ dS/m). Therefore soil B has osmotic potential −1480 kPa and soil water potential −1500 kPa. Despite having the same soil water potential transpiration is zero for soil A, while in the case of soil B it can be significant for several crop species (e.g. rye).

22.2.1 Impacts of Salinity on Crop Productivity

A soil is classified as saline when the electrical conductivity of the saturation extract is greater than 4 dS/m. This level represents less than 10 % of the salinity of seawater (50–60 dS/m), but is sufficient to affect negatively the growth of many crop plants. Increasing the concentration of salts in the soil involves a decrease of osmotic potential, and therefore a decrease in the soil water potential and thus, in shoot water potential, which ultimately leads to reduced expansive growth.

There is a wide variability in the sensitivity of crops species to salinity, and also among cultivars within a species. A simple response model has been proposed where the sensitivity or tolerance is quantified by two parameters. The first is a threshold salinity value, EC_{eu} (measured as EC of the soil saturation extract) above which yield decreases. The second parameter (B_s) is the percentage of yield loss per unit increase in EC_e. The relative yield (Y/Y_x) expressed as a fraction of the maximum yield can then be calculated as:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}\left(EC_e - EC_{eu}\right) \qquad (22.1)$$

Maas and Hoffman published in 1977 a review on the crop tolerance to salinity, which results are summarized in Table 22.1. The crops are classified as sensitive, moderately sensitive, moderately tolerant and tolerant according to the values of the parameters EC_{eu} and B_s (Table 22.2). Most fruit trees are sensitive, most horticultural crops are moderately sensitive and most field crops lie between moderately sensitive to moderately tolerant.

Table 22.1 Sensitivity of different crop species to salinity

Common name	EC_{eu}	B_s	Type	Na or Cl in water	B in soil	Na in soil (ESP)
	dS/m	%/dS/m		meq/L Na or Cl	mg/L saturated extract	%
Alfalfa (hay)	2	7.3	MS	10.0–20	4.0–6.0	>40
Apple	1	18	S			<15
Barley	6	7.1	T	10.0–20		
Bean (Phaseolus) (dry seed)	1	18.9	S			<15
Cotton	7.7	5.2	T	>20	6.0–15.0	>40
Grapes (wine)	1.5	9.5	MS	5–10.0	0.5–0.75	
Lettuce	1.3	13	MS	–	2.0–4.0	15–40
Maize (grain)	1.7	12	MS	10.0–20	2.0–4.0	<15
Millet			MS			
Olive	5.00	7	MT			
Orange	1.3	16	S	<5	0.5–0.75	<15
Palm trees	4	3.6	T			
Peach	1.7	21	S	–	0.5–0.75	<15
Peas (dry harv.)	2.5		MS		1.0–2.0	<15
Potato	1.7	12	MS	5.0–10	1.0–2.0	
Rapeseed, Canola	10.5	13.5	T			
Rice	11.4	10.8	MT			15–40
Sorghum (grain)	6.8	16	MT	10.0–20	4.0–6.0	15–40
Soybeans	5	20	MT			
Sugar beet	7	5.9	T	>20	4.0–6.0	>40
Sugar cane (virgin)	1.7	5.9	MS			15–40
Sunflower	5.5	25	MS	>20	0.75–1.0	
Tomato	2.5	9.9	MS	5.0–10	4.0–6.0	15–40
Winter wheat	6	7.1	MT	–	0.75–1.0	15–40

For the response to total salt concentration two parameters are shown: EC_{eu} (dS/m) is the value of EC_e below which yield is not affected. B_s (%/(dS/m)) is the slope of the linear relationship between yield (% of maximum) and EC_e. Crops are classified as sensitive (S), moderately sensitive (MS), moderately tolerant, (MT) and tolerant (T). Concerning the foliar damage by sprinkler irrigation, the threshold concentration of Na or Cl is shown (meq/L). The maximum concentration of B (mg/L in soil saturated extract) and Na (ESP, %) in the soil above which toxicity may occur are also shown

Adapted from Ayers and Westcott (1989)

Table 22.2 Examples of species in the four groups of response to salinity and typical parameters of the response

	Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
EC_{eu} (dS/m)	6.0–10	3.0–6.0	1.3–3.0	0–1.3
Slope Bs (typical) (%/(dS/m))	12	13	17	30
EC_e for zero yield (dS/m)	<32	<24	<16	<8
Fibre, seed and sugar crops	Barley	Winter cereals (wheat, oat, rye, triticale)	Sugarcane	Bean
	Cotton	Legumes (cowpea, soybean)	Legumes (faba bean, peanut)	Guayule
	Sugarbeet	Sorghum	Summer cereals (maize, rice, millet)	Sesame
		Safflower	Oilcrops (castorbean, flax, sunflower)	
Forage crops	Wildrye (some spp.)	Wildrye (some spp.)	Alfalfa	
	Wheatgrass (some spp.)	Wheatgrass (some spp.)	Common vetch	
	Bermuda grass	Barley, wheat	Oats, rye, maize	
		Ryegrass, fescue, sudangrass	Brome	
		Clover (Melilotus spp.)	Clover (Trifolium spp.)	
Vegetable crops	Asparagus	Red beet	Solanaceae (potato, tomato, pepper, eggplant)	Carrot
		Zucchini squash	Cucurbitaceae (cucumber, melon, watermelon, squash)	Onion
			Brassicaceae (cabbage, cauliflower, kale, turnip, broccoli)	Parsnip
			Other (lettuce, spinach, celery, radish, sweet potato)	
Fruits and nuts	Date palm	Olive, fig, pomegranate	Grape	Citrus spp. (orange, lemon, tangerine, etc.)
		Pineapple		Prunus spp. (peach, almond, cherry, etc.)

(continued)

Table 22.2 (continued)

	Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
		Papaya		Berries (Rubus spp., Ribes spp.)
				Pome fruits (apple, pear)
				Other (strawberry, avocado
				Tropical fruits (cherimoya, mango, passion fruit)

The information in Table 22.1 has to be taken with caution since the response of plants varies with development stages and growing conditions (climate, soil management and irrigation, cultivar, etc.). Furthermore, it should be noted that the data in Table 22.1 were determined with surface irrigation following conventional management, including the application of excess water to obtain a steady state and uniform distribution of salts throughout the root zone. However, soil EC_e may vary substantially in space and during the growing season, so the application of Eq. 22.1 is not straightforward, but would represent the response of a given crop to the long term, uniform application of an irrigation water of a given EC.

22.2.2 *Specific Toxicity*

Toxicity occurs when certain ions are absorbed by the plant and accumulate to concentrations high enough to cause crop damage. Toxicity related to saline conditions is ascribed to ions usually present in soluble salts, mainly Na and Cl, and to B, frequently found in saline irrigation waters. The first symptoms are usually marginal leaf burn and interveinal chlorosis. The sensitivity of crops to ion toxicity is quite variable with tree crops being the most sensitive, which may be affected by very low ion concentrations (see Table 22.1). Under high evaporative demand ion accumulation is faster, thus enhancing the toxic effect.

Toxicity can also be due to direct absorption of Cl or Na through the leaves (e.g. sprinkler irrigation). This may be an important problem in certain sensitive crops such as citrus.

22.3 Irrigation Systems and Distribution of Salts

In general, salts accumulate in lands where the leaching is limited, i.e. they tend to concentrate close to the soil surface, and the depth at which salts accumulate depends on the amount of drainage water. Lack of drainage causes the build up of a water table near the surface from where water evaporates, bringing salts to the uppermost soil layers causing salinization. This is shown in Fig. 22.1 where a saline water table at a depth of 100 cm and EC=10 dS/m is the source of water that evaporates, resulting in a high concentration of salts on the surface. A situation of this type has also occurred under rainfed conditions, for example in the Murray Basin and other areas in Australia. The substitution of evergreen forests that have high rates of ET for crops that use less water, has changed the hydrology of basins, leading to the accumulation of excess water in the low lands where the water table rose with the consequent soil salinization. The problem is of such magnitude that it is estimated that in 50 years it could affect 25 % of the cultivated area of Australia unless specific measures are adopted to alleviate the problem.

Figure 22.2 shows a different profile of salt concentration. In this case the salts were accumulated in the lower layers due to leaching. A period of heavy rainfall during winter helped in salt leaching and the EC decreased across the soil profile. This would be the typical profile of salts in irrigated semiarid areas without the presence of a water table.

Since salt movement is related to water movement in soil, the irrigation method affects the distribution of salts in the soil. Figure 22.3 distinguishes areas where salts concentrate more or less depending on the method of irrigation. Furrow irrigation provides leaching in almost the entire surface of the ground, except in the ridges. Drip irrigation wets only part of the ground and therefore leaching

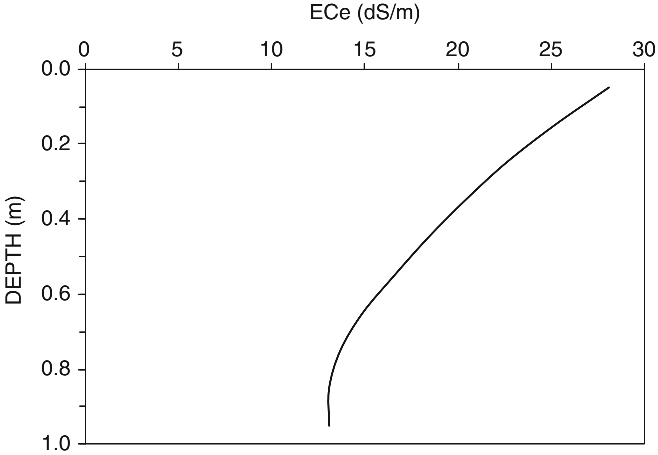

Fig. 22.1 Soil salinity profile above a saline water table ($EC_w = 10$ dS/m) at the end of a growing season of a sorghum crop

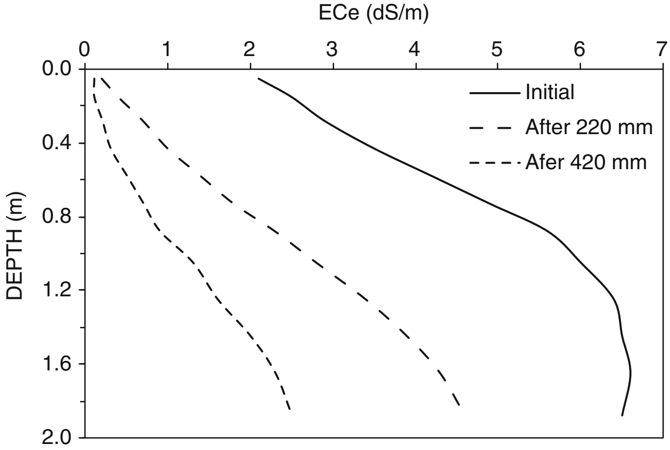

Fig. 22.2 Soil salinity profiles in a sandy loam soil before (initial) and after 220 and 420 mm of rainfall

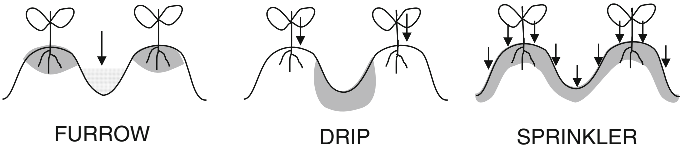

Fig. 22.3 Accumulation of salts from irrigation water for different methods of irrigation (Adapted from Rhoades and Loveday and Stewart and Nielsen 1990)

occurs only under the emitters while the remainder of the surface tends to accumulate salts, particularly at the edges of the wetted zones. Overhead sprinkler or flood irrigation leaches salts evenly throughout the field depending on the uniformity of irrigation.

The EC of the soil solution increases as the soil water is depleted so the osmotic effect of salts depends on the actual soil water content. This is illustrated in Fig. 22.4 where changes in EC of the soil solution are parallel to changes in soil water potential. Irrigation frequency also affects the concentration of the salts. High frequency irrigation keeps high soil water content and is therefore able to maintain a lower salt concentration in soil solution. In addition, a relatively constant high soil water content contribute to counteract the effect of salinity on water potential by avoiding low matric potentials in soil. On the contrary, low frequency irrigation involves drying cycles as those shown in Fig. 22.4, which may lead to very low soil water potential. This is one reason why drip irrigation in cotton with saline water is advantageous as compared to traditional furrow irrigation.

The potentially harmful salts in the soil are those in areas where root absorption takes place. This must be considered if we conduct a survey of soil salinity on a plot.

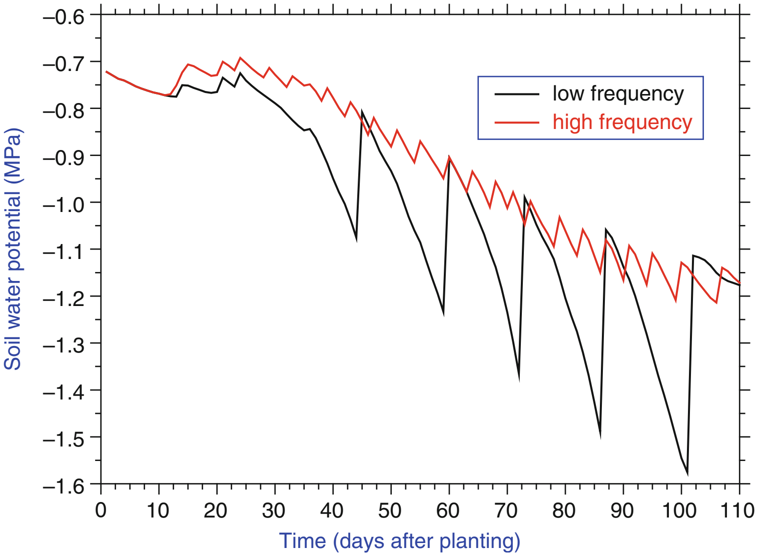

Fig. 22.4 Time course of soil water potential of a sorghum crop irrigated with water of $EC_w = 4$ dS/m with leaching fraction 0.2 and low or high irrigation frequency

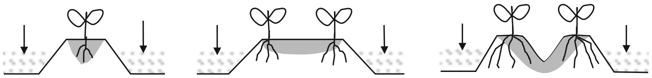

Fig. 22.5 Effects of bed shape and plant distribution on salt accumulation and emergence of furrow irrigated crops (Adapted from Rhoades and Loveday and Stewart and Nielsen 1990)

A special problem is that of seeds and seedlings. Germinating seeds and seedlings are especially sensitive to salinity so crop establishment is the most critical stage for some species, in particular under furrow irrigation. The seedbed configuration, the design of the irrigation system and the distribution of plants can have a huge impact on crop establishment in saline conditions. Figure 22.5 illustrates various situations for furrow irrigated crops. Planting on flat ridges with lateral furrow irrigation leads to an accumulation of salts in the center of the ridge. This can be avoided by widening the bed and creating a small furrow in the middle to separate the two central rows. The situation can be further improved if planting is performed on sloping beds with a central furrow which is watered until crop establishment.

In sodic soils (see Sect. 2.4.4), surface crusts develop and prevent seedling emergence. This may be alleviated by sprinkler irrigation (small doses, high frequency) which also would reduce salt concentration close to the seeds.

Alternatively, mechanical removal of the crust in the rows could be beneficial although it is impractical except for small plots.

22.4 Salt Balance and Leaching Fraction

To quantify the risk of soil salinization it is necessary to evaluate its salt balance. This balance implies that the quantity of salts entering the system minus the amount going out must equal the increase in the salt content of the soil (ΔS):

$$V_w C_w + V_r C_r + S_s + S_f - \left(V_d C_d + S_p + S_c\right) = \Delta S \tag{22.2}$$

where V and C refer to volume and concentration, respectively, corresponding to the irrigation water (w), rain (r) and drainage (d). S_s, S_f, S_p and S_c refer to the amounts of salts released from the soil (by dissolution or weathering), provided as fertilizer, precipitated and absorbed by the crop, respectively, during the period.

To prevent soil salinization the amount of salts in the soil should be constant ($\Delta S = 0$). In order to simplify Eq. 22.2, assuming $S_s+S_f=S_p+S_c$ and neglecting the term related to rainfall, we may write:

$$V_w C_w = V_d C_d \tag{22.3}$$

On the other hand, the Leaching Fraction (LF) is defined as the ratio of the drainage volume to the irrigation volume. Using Eq. 22.3, and replacing concentration by electrical conductivity, LF can be expressed as:

$$LF = V_d / V_w = EC_w / EC_d \tag{22.4}$$

Example 22.2 The electrical conductivity of irrigation water is 1 dS/m. Drainage is 25 % of applied irrigation. The leaching fraction is thus 0.25 and the EC of the drainage water is obtained by dividing EC_w by 0.25, i.e. $EC_d = 4$ dS/m.

Therefore, by changing the LF, it is possible to control the concentration of salts in the soil water within values above the salt concentration in the irrigation water. This is shown in Fig. 22.6 for different Leaching Fractions. Note that the soil EC increases with increasing depth, taking values similar to that of the irrigation water at the top. As LF decreases this variation with depth is more pronounced.

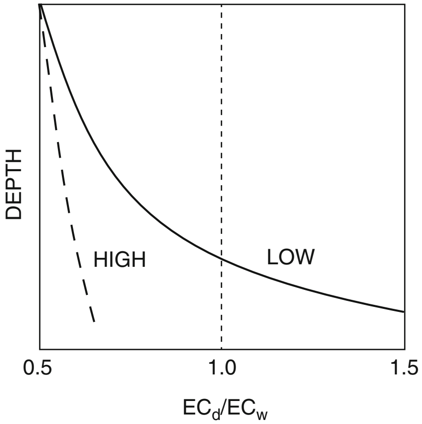

Fig. 22.6 Generic profiles of soil salinity for high and low leaching fractions. Salinity is shown as the ratio of EC of the saturation extract and irrigation water EC

22.5 Salinity Profiles and Crop Yields

The profiles of EC in the soil are affected by the EC of irrigation water and the LF as we have seen above. This EC refers to the soil with its water content at Field Capacity. To convert to EC of saturation extract (which is required to apply Eq. 22.1) we use a factor of 0.5, as EC_e is roughly half of EC at Field Capacity (EC_{FC}).

We will now show how EC varies with depth in the soil with the following example.

Example 22.3 A bean crop ($EC_{eu} = 1.0$ dS/m, $B_s = 19$ %/dS/m) is irrigated with water of 1.5 dS/m with a leaching fraction of 0.2. We assume a water uptake distribution of the type 40–30–20–10 (the soil is divided into four parts of equal depth from where 40 %, 30 %, 20 % and 10 % of the total water extraction occurs, respectively).

For every 100 mm applied as irrigation, 80 mm are absorbed by the root system and 20 mm are drained. Applying Eq. 22.4 to each of the four layers in which we have divided the profile we may deduce the average EC (at Field Capacity) for each layer.

In the first layer water uptake is 40 % of total (0.4 × 80 mm) so the amount of water draining from this layer is the difference between the water applied (100 mm) and that absorbed, i.e. drainage is $100 - 32 = 68$ mm. Therefore for the first layer, LF and the calculated EC are:

$$LF_{0-1} = (100 - 0.4 \cdot 80)/100 = 68/100 = 1.5/EC_{FC1}; \quad EC_{FC1} = 2.2$$

(continued)

Example 22.3 (continued)

And for the other layers:

$$\mathrm{LF}_{1-2} = (68 - 0.3 \cdot 80)/68 = 44/68 = 2.2/\mathrm{EC}_{\mathrm{FC2}}; \quad \mathrm{EC}_{\mathrm{FC2}} = 3.4$$
$$\mathrm{LF}_{2-3} = (44 - 0.2 \cdot 80)/44 = 28/44 = 3.4/\mathrm{EC}_{\mathrm{FC3}}; \quad \mathrm{EC}_{\mathrm{FC3}} = 5.35$$
$$\mathrm{LF}_{3-4} = (28 - 0.1 \cdot 80)/28 = 20/28 = 5.35/\mathrm{EC}_{\mathrm{FC4}}; \quad \mathrm{EC}_{\mathrm{FC4}} = 7.5$$

The values of EC of the saturation extract will be half of those values: 1.1, 1.7, 2.7 and 3.75 dS/m.

The arithmetic mean of $\mathrm{EC_e}$ will be 1.93 dS/m.

The weighted EC average considering water uptake will be:

$$\begin{aligned}&0.4(0.75 + 1.1)/2 + 0.3(1.1 + 1.7)/2 + 0.2(1.7 + 2.7)/2\\ &\quad + 0.1(2.7 + 3.75)/2\\ &\quad = 1.56\,\mathrm{dS/m}\end{aligned}$$

If we use the weighted average which is recommended for high frequency irrigation we would predict a relative yield of 89 % of the maximum. Using the arithmetic mean (recommended for low frequency irrigation) we would predict a relative yield of 82 %.

It is possible to deduce analytically the profile of soil EC and then the mean values of EC may be computed as a function of EC of the irrigation water and the LF (Fig. 22.7):

(a) The weighted average does not depend on the distribution of root water uptake and may be calculated as:

$$EC_{em1} = 0.5\ EC_w \frac{\ln(LF)}{1 - LF} \tag{22.5}$$

(b) If water uptake decreases linearly with depth like in Example 22.3 then the arithmetic mean will be:

$$EC_{em2} = EC_w \frac{arc\cos\sqrt{LF}}{\sqrt{LF(1 - LF)}} \tag{22.6}$$

where the arccos function is given in rad.

A simpler equation may be deduced from the Leaching Requirement (see below) equation commonly found in the salinity literature:

$$EC_{em2} = EC_w \frac{1 + LF}{5LF} \tag{22.7}$$

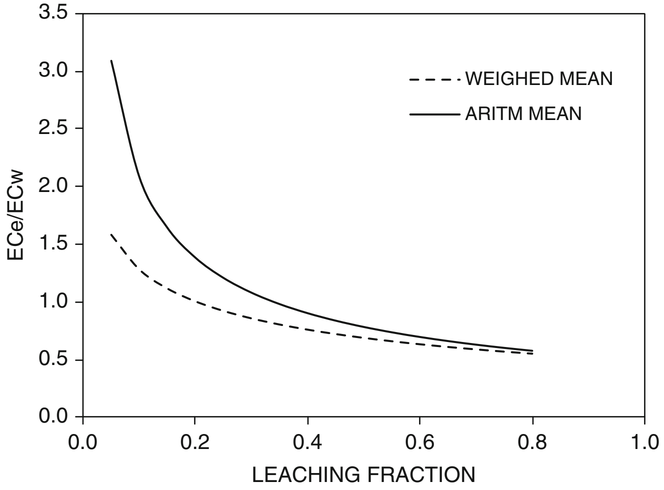

Fig. 22.7 Mean soil salinity (relative to irrigation water EC) as a function of the Leaching Fraction computed as a weighed (of root water uptake) or arithmetic average

Example 22.4 Following example 22.3 of the bean crop ($EC_{eu} = 1.0$ dS/m, $B_s = 19$ %/dS/m) irrigated with water of $EC_w = 1.5$ dS/m and $LF = 0.2$ we can evaluate the average EC_e using Eqs. 22.5 and 22.7.

Weighted average:

$$EC_{em} = -0.5\ EC_w \ln(LF)/(1 - LF) = -0.51.5 \ln(0.2)/0.8 = 1.51\ dS/m$$

Relative yield would be:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}(EC_e - EC_{eu}) = 1 - \frac{19}{100}(1.51\ -\ 1) = 0.90$$

The result would be very close to that obtained using a numerical approach (Example 22.3).

Arithmetic mean:

$$EC_{em2} = EC_w \frac{1 + LF}{5LF} = 1.5\ \frac{1 + 0.2}{5 \cdot 0.2} = 1.8\ dS/m$$

And the expected yield (as fraction of the maximum) is:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}(EC_e - EC_{eu}) = 1 - \frac{19}{100}(1.8 - 1) = 0.85$$

22.6 Leaching Requirement

The Leaching Requirement (LR) is the LF desired to keep a given EC_e (EC_{em}) and will depend on the crop sensitivity (Eq. 22.1) and the EC of irrigation water. Then the amount of irrigation to be applied would be:

$$AW = \frac{ET}{1 - LR} \tag{22.8}$$

The LR could be obtained by solving Eqs. 22.5 and 22.6 for LF but no analytical solution is possible. Then approximate equations may be used:

For low irrigation frequency:

$$LR = 0.31\left(\frac{EC_w}{EC_{em}}\right)^{1.7} \tag{22.9}$$

Or, alternatively, the following equation is commonly found in the literature:

$$LR = \frac{EC_w}{5EC_{em} - EC_w} \tag{22.10}$$

For high irrigation frequency:

$$LR = 0.18\left(\frac{EC_w}{EC_{em}}\right)^{3} \tag{22.11}$$

Example 22.5 A barley crop is irrigated with water of EC_w 5 dS/m. To reach a relative yield of 90 % of the maximum we should keep an average EC_{em} that satisfies the following equation:

$$90 = 100 - 5.0(\mathrm{EC_{em}} - 8.0)$$

Thus $EC_{em} = 10$ dS/m.

Therefore the LR for high frequency irrigation will be:

$$LR = 0.18\left(\frac{5}{10}\right)^{3} = 0.022$$

And for low frequency:

$$LR = 0.31\left(\frac{5}{10}\right)^{1.7} = 0.095$$

(continued)

Example 22.5 (continued)

or

$$LR = \frac{5}{5 \times 10 - 5} = 0.11$$

Example 22.6 A farm has a limited amount of irrigation water from a canal (EC = 0.4 dS/m). It also has a well of unlimited water supply with 2.5 dS/m. We want to grow peppers ($EC_{eu} = 1.5$, B = 14) with a low frequency irrigation system that has a leaching fraction LF = 0.2. How can the irrigated area be expanded by using water from the well?

Using only water from the canal:

$$EC_{em} = EC_w \frac{1 + LF}{5LF} = 0.4 \ \frac{1 + 0.2}{5 \times 0.2} = 0.48 \ dS/m$$

This value is lower than the threshold EC (1.5 dS/m) thus yield would be maximum.

With water from the well:

$$EC_{em} = 2.5 \ \frac{1 + 0.2}{5 \times 0.2} = 3.0 \ dS/m$$

And the relative yield would be:

$$\frac{Y}{Y_x} = 1 - \frac{B_s}{100}(EC_e - EC_{eu}) = 1 - \frac{14}{100}(3 - 1.5) = 0.79$$

The two waters could be blended to obtain a given EC_{em}. For instance if we want to obtain the maximum yield then the average EC_e should be 1.5 dS/m, which implies the following equation:

$$[f \ EC_{well} + (1 - f)EC_{canal}]\frac{1 + LF}{5 \ LF} = 1.5$$

Where f is the fraction of water taken from the well. In our case we may deduce f = 0.4, i.e. by mixing 60 % of water from the canal and 40 % from the well we could achieve maximum yield while increasing the irrigated area by 67 %.

We could also change the LF. For instance, by increasing LF up to 0.3 we could use 63 % of water from the well thus further increasing the irrigated area.

22.7 Optimum Leaching Requirement

From the sections above it is clear that to maintain crop productivity we may increase the LF, and thus water applied. In other words irrigation water of poor quality (high EC_w) is equivalent to having a smaller amount of fresh water in terms of crop productivity.

In the previous section we determined the Leaching Requirement when the objective yield is known. This may lead to unreasonably high values of LR when EC_w and irrigation costs are high. In this case we may be interested in maximizing the Crop Water Productivity (yield per unit of irrigation applied). To do that we may apply Eq. 22.1 for different values of LR until a maximum CWP is found. In the case of low irrigation frequency it is also possible to deduce an analytical solution for LR_{opt} by maximizing the function:

$$f(LR) = (1 - LR)\left\{1 - B'\left[EC_w \frac{1 + LR}{5LR} - EC_{eu}\right]\right\} \tag{22.12}$$

Where $B' = B_s/100$. The function is maximized when:

$$LR_{opt} = \sqrt{\frac{0.2\,B' EC_w}{1 + B'(EC_{eu} - 0.2EC_w)}} < \frac{1}{5\frac{EC_{eu}}{EC_w} - 1} \tag{22.13}$$

As the inequality indicates, the solution is valid below the value of LR at which maximum yield is achieved.

Example 22.7 We want to irrigate peach ($EC_{eu} = 1.7$, $B_s = 21$) with irrigation water of $EC_w = 3$ dS/m.

Using Eq. 22.13 we deduce $LR_{opt} = 0.35$. The solution is valid as it is lower than the limit LR to get maximum yield:

$$\frac{1}{5\frac{EC_{eu}}{EC_w} - 1} = \frac{1}{5\frac{1.7}{3} - 1} = 0.54$$

If we had water with $EC_w = 1$ dS/m, a value of $LR_{opt} = 0.18$ would be deduced but now it would exceed the limit value (0.13). Therefore in this case the optimum LR would be 0.13.

The previous analyses are based on a steady state salt concentration in the soil solution which would be achieved after continuous use of a given irrigation water. However, EC_e may change during the season and from year to year. For instance, in Mediterranean areas rainfall is concentrated in winter which would provide for salt leaching (at least partial, depending on amount) and thus to EC_e below the steady state value. Therefore the calculation of Leaching Requirement based on the steady state solution leads to an upper limit for LR. The desired LR would vary depending on the amount of winter leaching, and thus, on the actual EC_e at the start of the irrigation season, which should be measured routinely to keep track of soil salinity trends.

22.8 Sodicity and Soil Structure

Sodium-affected soils, referred to as sodic soils, are those with high levels of adsorbed (exchangeable) Na in soil. High exchangeable Na promotes the dispersion of soil colloids and consequently the degradation of soil structure. This degradation involves deterioration in aggregate stability, soil water transmission capacity due to soil surface sealing, and increased susceptibility to crust formation. Crusting is particularly relevant since, in addition to limit crop establishment, it affects the water balance by decreasing infiltration and enhancing runoff, and subsequently increasing erosion risk.

Crusting is the consequence of the breakdown of aggregates and the closing of the pores in soil surface resulting from rapid soil wetting accompanied by a dispersive effect of the impact of raindrops. In sodic soils the problem is exacerbated because of the dispersing effect of sodium, which leads to a lack of aggregate stability and large reduction in the infiltration rate, with the attendant problems of waterlogging and increased runoff.

A soil is classified as sodic when the Exchangeable Sodium Percentage (ESP) exceeds 15 % of cation exchange capacity. In practice, an indicator used is the Sodium Adsorption Ratio (SAR, $meq^{0.5}/L^{0.5}$) in the soil saturation extract which is approximately equal to ESP:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \tag{22.14}$$

where all the concentrations are expressed in meq/L.

ESP can be more precisely estimated from SAR in the saturation extract following the empirical equation:

$$ESP = \frac{(100 - 0.0126 + 0.01475 \cdot SAR)}{1 - 0.0126 + 0.01475 \cdot SAR} \tag{22.15}$$

SAR is an index applied to solutions, and also for irrigation water. It is also used to assess the effect of the sodium content of the irrigation water on soil structure and hydraulic conductivity due to an excess of sodium in relation to calcium and magnesium. However, this negative effect depends on the EC of irrigation water as the dispersing effect of Na is counteracted by the aggregating effect of a high salt

Table 22.3 Quality criteria for irrigation water

Potential irrigation problem			Units	Degree of restriction on use		
				None	Slight to moderate	Severe
Salinity reduces crop growth and transpiration						
EC$_w$			dS/m	<0.7	0.7–3.0	>3.0
Specific ion toxicity (*affects sensitive crops*)						
	Sodium (surface irrigation)		SAR	<3	3–9	>9
	Sodium (sprinkler irrigation)		meq/L	<3	>3	
	Chloride (surface irrigation)		meq/L	<4	4–10	>10
	Chloride (sprinkler irrigation		meq/L	<3	>3	
	Boron		mg/l	<0.7	0.7–3.0	>3.0
Infiltration is reduced						
SAR	=0–3	**And EC$_w$**	dS/m	>0.7	0.7–0.2	<0.2
	=3–6		dS/m	>1.2	1.2–0.3	<0.3
	=6–12		dS/m	>1.9	1.9–0.5	<0.5
	=12–20		dS/m	>2.9	2.9–1.3	<1.3
	=20–40		dS/m	>5.0	5.0–2.9	<2.9
Miscellaneous effects						
Bicarbonate (whitewash, sprinkler)			meq/L	<1.5	1.5–8.5	>8.5
pH				Normal range 6.5–8.4		

concentration in solution (Table 22.3). In addition, it is necessary to take into account changes in Ca in the soil water that take place resulting from precipitation (as calcium carbonate) or dissolution during or following irrigation. Sodium remains soluble and in equilibrium with exchangeable soil sodium at all times, whereas calcium concentration, however, varies until the equilibrium is established. Dissolution is promoted by dilution and by carbon dioxide dissolved in the soil solution. Precipitation may take place when the presence of calcium is accompanied by enough carbonate, bicarbonate or sulfate to exceed the solubility of calcium carbonate (limestone) or calcium sulfate (gypsum). This is why different corrections of the SAR value in irrigation water have to be considered for a more realistic estimation of the potential effects of irrigation water on soil structure and hydraulic conductivity. The most common correction is done by estimating a corrected Ca concentration (Ca$_x$):

$$Ca_x = exp\left[0.552 + 0.1637\sqrt{EC_w} - 0.668\ ln\left(\frac{HCO_3 + CO_3}{Ca}\right)\right] \tag{22.16}$$

which is used to calculate an adjusted SAR (now called Adjusted Sodium Ratio, SAR$_x$):

$$SAR_x = \frac{Na}{\sqrt{\frac{Ca_x + Mg}{2}}} \tag{22.17}$$

Example 22.8 The composition of irrigation water is:

Ca: 1.3 meq/l, Mg: 1.6 meq/l, Na: 6.6 meq/l, CO_3: 0.4 meq/l, HCO_3: 4.00 meq/l, EC_w: 0.90 dS/m

The ratio $(CO_3+HCO_3)/Ca$ is $(4.0 + 0.4)/1.3 = 3.38$

The adjusted Ca concentration is:

$$Ca_x = exp[0.552 + 0.1637\sqrt{0.9} - 0.668\ ln(3.38)] = 0.90$$

And the adjusted Sodium Ratio:

$$SAR_x = \frac{6.6}{\sqrt{\frac{0.9+1.6}{2}}} = 5.9$$

According to Table 22.3 which summarizes the possible problems related to the quality of irrigation water, this water would cause almost no problem in terms of water availability, slight to moderate problems of infiltration, toxic effects in sensitive crops and slight to moderate problems of "whitewash" due to bicarbonate when applied by sprinkler irrigation.

22.9 Reclamation of Saline Soils

In general a soil is classified as saline when its EC_e is greater than 4 dS/m although the Soil Science Society of America uses a threshold of 2 dS/m. Soluble salts most commonly present are the chlorides and sulfates of Na, Ca and Mg. Sodium and chloride are the most dominant ions, especially in highly saline soils, but Ca and Mg concentrations are usually enough to meet the crop needs. Many saline soils contain appreciable quantities of gypsum ($CaSO_4 \cdot 2H_2O$) while soluble carbonates are never present. The pH of the saturated soil paste is always lower than 8.2 and is usually close to 7.

Saline soils usually have good physical properties as excess salts keep the clay in a flocculated state. Some saline soils, in special heavy clays, tend to disperse when leached with low salt water.

Saline soils can be recognized by the spotty growth of crops (irregular plant size, barren spots) and often by the presence of white salt crusts on the surface. This is because there is always substantial spatial variability in the soil water properties that leads to wide spatial variations in soil salinization. If salinity is moderate and in the few cases where it is more uniform across the field it may go undetected as it may not cause visible symptoms other than reduced growth rate, with the exception of a blue-green tinge in some cases. Symptoms of salinity stress may resemble those of water deficit without wilting due to gradual osmotic adjustment. Symptoms of specific toxicities (marginal or tip burn of leaves) are typical in woody plants.

The reclamation of saline soils is performed by salt leaching. The important question is the amount of water required and the best application strategy. Evacuation of drained water must be guaranteed, and if required to this end, a drainage network should be installed.

Theoretically, if the soil behaves as a perfect porous medium and assuming that there is no precipitation or dissolution of salts, the change in salts stored in the soil after applying an amount of water (AW) with EC_w are given by:

$$\begin{aligned} EC_{efinal} &= EC_{einit}\exp\left(\frac{-AW}{Z(\theta_{sat}-\theta_{init})}\right) \\ &\quad + 0.5\,EC_w\left[1-\exp\left(\frac{-AW}{Z(\theta_{sat}-\theta_{init})}\right)\right] \end{aligned} \tag{22.18}$$

where Z is the soil depth being considered and subscripts sat and init refer to saturation and initial conditions, respectively.

Example 22.9 The soil has $EC_e = 10$ dS/m with drains at 1 m depth. We apply 1000 mm with $EC_w = 0.1$ dS/m when the soil is at PWP (0.10 $m^3\ m^{-3}$). Soil water content at saturation is 0.40 $m^3\ m^{-3}$.

$$\begin{aligned} EC_{e\,final} &= 10\exp\left(\frac{-1}{1(0.4-0.1)}\right) + 0.5EC_w\left[1-\exp\left(\frac{-1}{1\,(0.4-0.1)}\right)\right] \\ &= 0.357 + 0.048 = 0.40\ dS/m \end{aligned}$$

Several empirical models have been proposed to estimate the volume of water required. Each soil differs in behavior and the same amount of water has different leaching efficiencies in different soils, so field experiments are usually performed to determine the amount of water required. We have seen before (Example 22.9) that an amount of water equal to the depth of the soil, would leach theoretically 96 % of the salts. However in practice such an amount which is equivalent to 1.5–2 times the pore volume removes only around 70 % of soluble salts.

Sprinkler irrigation is more efficient in salt leaching than surface irrigation. This is mainly due to preferential flow occurring under saturated conditions, leaving part of the soil without leaching. For the same reason, intermittent application of surface irrigation is more efficient (although slower) than continuous application. To calculate the depth of water required (I_w, mm) to reclaim a given soil depth Z (mm) to go from an initial EC (EC_{init}) to a final desired EC (EC_{final}) we may use the following formula:

$$\frac{I_w}{Z} = k_{leach}\frac{EC_{einit} - 0.5\,EC_w}{EC_{efinal} - 0.5\,EC_w} \tag{22.19}$$

where the parameter k_{leach} depends on soil properties (soil water content at saturation and texture) and irrigation method. For continuous ponding $k_{leach} = 0.45$ in peat soils, 0.30 in clay loams and 0.1 in sandy loams. For intermittent ponding or sprinkler irrigation $k_{leach} = 0.10$.

Example 22.10 The soil has $EC_e = 10$ dS/m with drains at 1 m depth. We plan to reclaim the whole soil depth ($Z = 1000$ mm) to reach a final $EC_e = 2$ dS/m using sprinkler irrigation (so $k_{leach} = 0.1$) and water with $EC_w = 1$ dS/m. Using Eq. 22.19:

$$\frac{I_w}{Z} = k_{leach} \frac{EC_{einit} - 0.5\ EC_w}{EC_{efinal} - 0.5\ EC_w} = 0.1 \frac{10 - 0.5 \cdot 1}{2 - 0.5 \cdot 1} = 0.633$$

Therefore the amount of irrigation to apply will be 633 mm.

In the case of saline-sodic soils the addition of gypsum may help in improving water infiltration and thus accelerate both desalinization and desodification of the soil, in special in heavy textured soils, or when low electrolyte water is applied. The application of amendments should be tested by trials on an experimental scale for large scale reclamation projects.

22.10 Reclamation of Sodic Soils

The main characteristic of sodic soils is the high content of exchangeable Na that adversely affects soil properties and the growth of most crop plants. By definition, sodic soils are those with Exchangeable Sodium Percentage greater than 15. In many cases the EC_e is not too high (less that 4 dS/m). The pH is 8.2 or higher and in extreme cases it may be above 10.5. Dispersed and dissolved organic matter in the soil solution may be deposited on the soil surface by evaporation generating a dark surface which is why these soils have also been termed black sodic soils.

The objective of reclamation of a sodic soil will be decreasing the amount of Na in the exchange complex and/or increasing the amount of Ca. Leaching of Na alone may be difficult because of the low permeability of sodic soils. This may be improved by adding electrolytes (chemical amendments added to the irrigation water) and tillage.

Calcium is usually added as calcium chloride, calcium carbonate or gypsum, the latter being the most frequently used. The availability of gypsum has increased in recent years as it is the by-product of scrubbing sulfur dioxide gases from the emissions of coal-fired power plants. Although gypsum is not a liming agent, it reduces the Aluminum toxicity that often accompanies soil acidity.

Gypsum amendments are normally applied broadcast and then incorporated with the soil by disking or ploughing. Fine ground gypsum is more quickly solubilized. When the problem is a surface crust, gypsum needs are reduced. If the problem is in deeper layers, gypsum contributions should be much larger. Gypsum may also be applied dissolved in the irrigation water which increases the efficiency.

In general the reclamation process with gypsum is performed in several stages. The common practice is to make a first application of approximately 10 t/ha of gypsum in the first year with 1.5 m of water. In subsequent years (2 or 3) applications of gypsum of 4 t/ha accompanied by some leaching may be performed.

According to the USDA the amount of gypsum to apply (kg/ha) may be calculated as:

$$Gypsum\ amount = 860 \cdot F_g \cdot \rho_b \cdot Z \cdot CEC\ \ (SAR_i - SAR_f) \tag{22.20}$$

where ρ_b is soil bulk density (t/m^3), Z is soil depth (m) to be restored, CEC is the Cation Exchange Capacity (mmol/kg), SAR_i and SAR_f are the initial and final values of SAR in the saturation extract of soil, respectively, and F_g is an efficiency factor that varies from 1.1 ($SAR_f = 0.15$) to 1.3 ($SAR_f = 0.05$).

Example 22.11 Soil bulk density is 1.3 t/m^3, CEC is 400 mmol/kg. The initial SAR is 0.20 and we want a final value of 0.10. The amount of gypsum to recover the top 0.3 m layer of soil will be:

$$\begin{aligned} Gypsum\ amount &= 860 \cdot F_g \cdot \rho_b \cdot Z \cdot CEC\ (SAR_i - SAR_f) \\ &= 860 \cdot 1.2 \cdot 1.3 \cdot 0.3 \cdot 400 \cdot (0.2 - 0.10) = 16099\ kg/ha \end{aligned}$$

Appendix 22.1: Sensitivity of Different Crop Species to Salinity

For the response to total salt concentration two parameters are shown: EC_{eu} (dS/m) is the value of EC_e below which yield is not affected. B_s (%/(dS/m)) is the slope of the linear relationship between yield (% of maximum) and EC_e. Crops are classified as sensitive (S), moderately sensitive (MS), moderately tolerant, (MT) and tolerant (T). Concerning the foliar damage by sprinkler irrigation, the threshold concentration of Na or Cl is shown (meq/L). The maximum concentration of B (mg/L in soil saturated extract) and Na (ESP, %) in the soil above which toxicity may occur are also shown.

	Response to salinity			Toxicity		
Species	dS/m	%/dS/m		meq/L Na or Cl	mg/L saturated extract	%
Cereals and pseudocereals	**EC$_{eu}$**	**B$_s$**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Barley, grain	8	5	T	10.0–20	0.75–1.0	>40
Maize (grain, sweet)	1.7	12	MS	10.0–20	2.0–4.0	<15
Millet			MS			
Oats	5	20	MT		2.0–4.0	15–40
Rice, paddy	3	12.2	S			15–40
Rye	11.4	10.8	MT			15–40
Sorghum	6.8	16	MT	10.0–20	4.0–6.0	15–40
Wheat	6	7.1	MT	–	0.75–1.0	15–40
Wheat, durum	5.9	3.8	T	–	0.75–1.0	15–40
Forages	**EC$_{eu}$**	**B$_s$**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Alfalfa	2	7.3	MS	10.0–20	4.0–6.0	>40
Barley, forage	6	7	T	10.0–20		
Barley, hay	6	7.1	T	10.0–20		
Bermuda grass	6.9	6.4	T			>40
Clover (red)	1.5	12	MS			
Clover, berseem	2	10.3	MS			15–40
Clover, white	1.5	12	MS	–	2.0–4.0	15–40
Cowpea (vegetative)	2.5	11	MS			
Fescue	3.9	5.3	MT			15–40
Lovegrass	2	8.5	MS			
Maize (forage)	1.8	7.4	S	10.0–20		
Meadow foxtail	1.5	9.7	MS			
Orchard grass	1.5	6.2	MS			
Paspalum	1.8	9	MS			15–40
Phalaris	4.2		MT			
Ryegrass	5.6	7.6	MT			15–40
Sesbania	2.3	7	MS			
Setaria	2.4	12.2	MS			
Siratro	2	7.9	MS			
Sudan grass	2.8	4.3	MS			
Townsville stylo	2.4	20.4	MS			
Trefoil, big	3	11.1	MS			
Trefoil, birdsfoot	5	10	MT			
Vetch	3	11	MS		4.0–6.0	15–40
Wheatgrass, crested	3.5	4	MT			>40

(continued)

	Response to salinity			Toxicity		
Species	dS/m	%/dS/m		meq/L Na or Cl	mg/L saturated extract	%
Wheatgrass, fairway	7.5	6.9	T			>40
Wheatgrass, tall	7.5	4.2	T			>40
Fruit trees, vines and shrubs	**EC_{eu}**	**B_s**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Almond	1.5	18	S	<5		<15
Apple	1	18	S			<15
Apricot	1.6	24	S	<5	0.5–0.75	<15
Avocado	1.3	21	S	–	0.5–0.75	<15
Banana			MS			
Blackberry	1.5	22	S		<0.5	<15
Boysenberry	1.5	22	S			<15
Cherry	–	–	S	<5	0.5–0.75	<15
Coconut			MT			
Date palm	4	3.6	T			
Fig	4.2		MT		0.5–0.75	<15
Grape	1.5	9.5	MS	5–10.0	0.5–0.75	
Grapefruit	1.8	16	S	<5	0.5–0.75	<15
Lemon	1	–	S	<5	<0.5	<15
Orange	1.3	16	S	<5	0.5–0.75	<15
Peach	1.7	21	S	–	0.5–0.75	<15
Pear	1		S			<15
Pineapple			MT			
Plum	1.5	18.2	S		0.5–0.75	<15
Pomegranate	4		MT			
Prune	1.5	18	S	<5		<15
Raspberry	1		S			<15
Rosemary	4.5		MT			
Walnut			S		0.5–0.75	<15
Horticultural crops	**EC_{eu}**	**B_s**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Artichokes	6.1	11.5	MT		2.0–4.0	
Asparagus	4.1	2	T		6.0–15.0	
Bean (green)	1	18.9	S			<15
Beet (table)	4	9	MT	>20	4.0–6.0	>40
Broadbean	1.6	9.6	MS			
Broccoli	2.8	9.1	MS			
Brussels sprouts	1.8	9.7	MS			
Cabbage	1.8	9.7	MS	–	2.0–4.0	
Cauliflower	1.8	6.2	MS	>20		

(continued)

	Response to salinity			Toxicity		
Species	dS/m	%/dS/m		meq/L Na or Cl	mg/L saturated extract	%
Celery	1.8	6.2	MS		2.0–4.0	
Cucumber	2.5	13	MS	10.0–20	1.0–2.0	
Eggplant	1.1	6.9	MS			
Kale	6.5		T			
Lettuce	1.3	13	MS	–	2.0–4.0	15–40
Melons	2.2	7.3	MS	–	2.0–4.0	
Pea	2.5		ms		1.0–2.0	<15
Pepper	1.5	14	MS	5.0–10	1.0–2.0	
Pumpkin, winter squash	1.2	13	MS			
Radish	1.2–2.0	7.6–13.0	MS		1.0–2.0	15–40
Spinach	2.0–3.2	7.7–16.0	MS			15–40
Squash	2.5		MT		2.0–4.0	
Squash, scallop	3.2	16	MS			
Squash, Zucchini	4.7	10	MT			
Strawberry	1	33	S	–	0.75–1.0	
Tomato	2.5	9.9	MS	5.0–10	4.0–6.0	15–40
Watermelon	–	–	MS			
Legumes	**EC_{eu}**	**B_s**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Bean (dry)	1	18.9	S			<15
Chickpea			MS			<15
Cowpea (seed)	4.9	12	MT		0.5–0.75	<15
Faba bean	1.6	9.6	MS			
Pea	1.5	14	S		1.0–2.0	<15
Peanut	3.2	29.4	MS	–	0.75–1.0	<15
Soybean	5	20	MT			
Roots, **tubers** and **bulbs**	**EC_{eu}**	**B_s**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Carrot	1	14	S	–	1.0–2.0	15–40
Onion	1.2	16.1	S	–	0.5–0.75	15–40
Parsnip	–	–	S			
Potato	1.7	12	MS	5.0–10	1.0–2.0	
Sweet potato	1.5	11.1	MS		0.75–1.0	
Turnip	0.9	9	MS		2.0–4.0	
Cassava			MS			
Garlic	3.9	14.3	MS		0.75–1.0	
Sugar, oil and fiber crops	**EC_{eu}**	**B_s**	**Type**	**Na or Cl in water**	**B in soil**	**Na in soil (ESP)**
Cotton	7.7	5.2	T	>20	6.0–15.0	>40

(continued)

	Response to salinity			Toxicity		
Species	dS/m	%/dS/m		meq/L Na or Cl	mg/L saturated extract	%
Castorbean	–	–	MS			
Flax/Linseed	1.7	12	MS			
Kenaf	8.1	11.6	T			
Olive	5.00	7	MT			
Rapeseed	10.5	13.5	T			
Safflower	6.5		MS	10.0–20		
Sesame			S	10.0–20	0.75–1.0	
Sugar beet	7	5.9	T	>20	4.0–6.0	>40
Sugarcane	1.7	5.9	MS			15–40
Sunflower	5.5	25	MS	>20	0.75–1.0	

Adapted from Ayers and Westcott (1989)

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Chapter 23
Fertilizers

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Abstract In this chapter we review the classification and main features of fertilizers. Among nitrogen fertilizers, nitric and ammonium are the most appropriate for topdressing and basal applications, respectively, while urea may be applied in both modes. Phosphorus fertilizers are distinguished mainly by their solubility which determines the application form. Potassium fertilizers are highly soluble. Deficiencies of micronutrients are often due to their conversion to insoluble forms in calcareous soils or the inability of plants to mobilize and transport them; their deficiency is usually solved with forms bound to organic compounds (complexes or chelates).

23.1 Introduction

Fertilizers are inorganic or organic products that are used to provide nutrient for plants. In general they have to comply with official regulations. For instance, the European Regulation 2003/2003, sets the rules that all EU must follow in their

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national directives to regulate properties, quality, and traffic of commercial fertilizers. According to the European regulation, different types of nutrients can be contained in fertilizers:

(a) Primary nutrients: nitrogen, phosphorus and potassium, which are usually the nutrients that have to be supplied in large amounts (tens or hundreds of kilograms per hectare).
(b) Secondary nutrients: calcium, magnesium, sodium and sulfur, also taken up by plants in high amounts, but not always have to be applied. Sodium is not an "essential nutrient" from a physiological point of view, but is required by some species such as C4 plants, and it is defined as "beneficial nutrient".
(c) Micronutrients: boron, cobalt, copper, iron, manganese, molybdenum and zinc, are required in small amounts compared with primary and secondary nutrients; all are "essential nutrients" except cobalt (e.g. beneficial for legumes). The European regulation does not include nickel and chloride, which are also essential but seldom required as fertilizer.

The fertilizer product and the application technique should be chosen to achieve the maximum efficiency in the use of applied nutrients by plants, which implies that the maximum fraction of applied nutrient should be taken up by plants. Fertilizers can be applied before planting (basal or preplant) or after it (topdressing or sidedressing). The application of fertilizer to soil can be done manually, using machines (fertilizer spreader), or through the irrigation system (fertigation). Fertilizers can also be applied to vegetative organs (foliar spray), particularly when soil conditions are not favorable for nutrient absorption (e.g. very dry) or to achieve a fast response under deficiency conditions. Fertilizer may be applied on the entire field or just on part of it (localized, preferable close to plants), the latter being preferred for nutrients that can be fixed in the soil, such as phosphorus or potassium, particularly in poor-nutrient soils or soils with a high fixing capacity.

Increased global use of fertilizers is partly responsible for the increase in food production (Fig. 23.1). Table 23.1 shows the variation in fertilizer use for the different continents. Fertilizer use has a decreasing trend in Europe except for N, while it shows a clear increasing trend in Asia and America (only for N). The values are very low and do not show any clear trend in Africa.

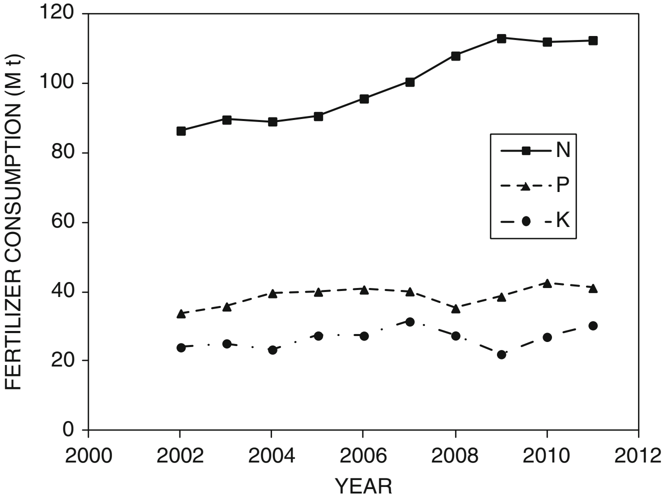

Fig. 23.1 Global use of N, P and K fertilizers (2001–2011)

Table 23.1 Fertilizer consumption by continents 2003–2011 (Source: FAO stats)

	Europe			Asia			Africa			America and Pacific		
Year	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
	M ton											
2002	12.9	4.0	5.2	52.0	18.6	9.3	2.6	1.0	0.5	18.8	10.2	9.1
2003	13.5	4.2	4.7	52.6	18.9	9.6	3.0	1.0	0.5	20.3	11.7	10.3
2004	13.1	4.2	4.8	52.5	22.2	7.1	3.1	1.1	0.5	20.2	12.2	11.0
2005	12.7	4.1	4.4	54.8	23.5	12.9	3.1	1.0	0.5	19.9	11.4	9.6
2006	12.8	4.0	4.6	59.8	24.2	12.6	2.8	1.0	0.6	20.2	11.4	9.6
2007	13.7	4.3	4.9	61.9	22.0	15.5	2.8	1.1	0.6	22.0	12.7	10.5
2008	13.1	3.2	3.7	71.1	20.9	13.6	3.3	1.0	0.5	20.5	10.2	9.7
2009	12.7	3.1	3.4	77.6	25.6	11.3	2.8	1.1	0.4	19.9	8.8	7.0
2010	13.3	3.4	4.1	73.6	27.2	12.7	3.2	1.2	0.4	21.8	10.7	9.8
2011	13.6	3.5	4.1	71.4	23.2	14.9	3.3	2.2	0.4	24.1	12.2	10.9
Agricultural land 2011 (M ha)	470			1634			1170			1626		
Average fertilizer use (kg/ha) 2011	28.9	7.4	8.8	43.7	14.2	9.1	2.8	1.9	0.3	14.8	7.5	6.7

23.2 Classification

Fertilizers can be classified according to different criteria:

(a) Depending on their nature: Organic and inorganic (also referred to as mineral or chemical). Inorganic fertilizers are those in which nutrients are mineral form obtained by extraction (mining) or by industrial processes. Calcium cyanamide, urea and its condensation and association products, and fertilizers containing chelated or complexed micro-nutrients can be classified as inorganic fertilizers by convention. Chelated and complexed micronutrients refer to a product in which the micronutrient is held by complexation reaction with organic molecules; depending on the type of organic molecule defined in the European regulation the product is considered "chelated" (synthetic organic molecules such as EDDHA) or "complexed" (natural organic molecules or present in by-products; not always a single compound, such as lignosulphonates). In organic farms only those from natural sources are allowed (e.g. farm organic residues or Chilean nitrate).

(b) According to their composition:

- Straight fertilizers, which are those containing only one primary nutrient, so they can be nitrogenous, phosphatic, or potassic.
- Compound fertilizers, which are fertilizers with a declarable content according to law of at least two primary nutrients obtained chemically or by blending or by a combination of both processes.
- Complex fertilizers, which are those obtained by chemical reaction, by solution, or in its solid state by granulation with a declarable content of a least two of the primary nutrients.

Compound and complex fertilizers can be binary, when they have a declarable content of two primary nutrients, or ternary or complete, when they have a declarable content of three primary nutrients.

Fertilizers with secondary nutrients or micronutrients, are those products of one of the three previous types with declarable amounts of these nutrients.

(c) According to its physical presentation, which often determines the conditions of its use and its effectiveness, fertilizers can be classified as:

- Solid fertilizers, with different types of presentation depending on its production, solubility, and method of application:

Powder or non-granular, when the product is presented as fine particles usually up to 3 mm diameter. Very few materials are sold now in this form as they present problems in handling (they tend to "cake") and cannot be applied with spreaders. Powder is a usual presentation for sparingly soluble products since low particle size enhances its solubilization.

Crystalline which are usually very soluble fertilizers for preparing fertigation or foliar spray solutions. They are not suitable for application with mechanical spreaders.

Granules which are designed to improve the uniformity of mechanical distribution. More than 90 % of the particles have to present diameters between 1 and 4 mm. The spherical shape is desirable. The distinction between granular and prilled refers to the industrial production method.

Pelletized or pelleted: They are granular fertilizers with very uniform size of spherical granules which improves the uniformity of distribution.

Macrogranules: granules of 1–3 cm to produce a slower release of the nutrients.

- Fluid fertilizers, which can be fertilizers in suspension or solution or both; fertilizers presented only in suspension as dispersed particles are called “suspension fertilizers”, while solutions free of solid particles are “solution fertilizers”. Pressure solutions are those including anhydrous ammonia in a concentration greater than that that can be maintained in equilibrium with the atmosphere.
- Gaseous fertilizers, with only one fertilizer in this category, anhydrous ammonia which must be injected to the soil.

23.3 Fertilizer Properties

23.3.1 Physical Properties

The physical properties of fertilizers are not regulated by law. However, these properties are critical for an accurate handling, storage, conservation, and correct and homogeneous application to crops. For solid fertilizers the following properties are most relevant:

(a) Hardness, i.e. the resistance to be broken, which is important to prevent the breaking of granules during handling and to avoid powder formation due to abrasion.
(b) Fluidity which means a low risk of caking after storage
(c) Particle size, which must be homogeneous to guarantee a correct application by mechanical spreading

(d) Humidity, must be low to avoid caking
(e) Density, which is relevant for storage and for segregation during application of blended fertilizers with different density; the distribution of a blend of several fertilizers could result heterogeneous if compounds with very different density are blended.

23.3.2 Chemical Properties

Chemical properties are important in the potential speed of action of the fertilizer and in the potential collateral effects on crops and soil properties. The main chemical properties to be considered in fertilizers are the following:

(a) Solubility determines the speed at which nutrients can pass to soil solution and thus be potentially available to plants. It is usually measured in water for nitrogenous and potassic fertilizers. For phosphate, usually less soluble, besides water, ammonium citrate or citric acid has been traditionally used to characterize its solubility trying to mimic the effect of plant roots in soil (exudation of low molecular weight acids). Solubility in water is critical for fertilizers used in fertigation to avoid clogging of drippers. Solubility increases with increasing temperature and acidity of solutions. Care should be taken with mixtures which can promote precipitation of compounds, such as fertilizers with Ca which can promote the precipitation of Ca phosphates.
(b) Reaction of fertilizer in the soil, acid or basic, depending on what's the fertilizer effect on soil pH. Traditionally it has been measured by the "acidity index" which is the equivalent amount of CaO which neutralizes the effect of fertilizer with acid reaction or to promote the same pH rising in soil in fertilizers with basic reaction. Fertilizer reaction can be the result of: (i) its chemical composition, e.g. anhydrous ammonia is a base, or base (e.g. Ca) which is the counterion in the nitric fertilizers; (ii) of its reactions in soil, e.g. nitrification of ammonium in the soil produces acidity, or the decomposition of calcic cyanamide forms $Ca(OH)_2$ which increases the soil pH, or (iii) presence of impurities such as sulfuric acid in ammonium sulfate.
(c) Salt index, which measures the effect of the fertilizer on the osmotic pressure; it is a relative value compared with sodium nitrate which receives an arbitrary value of 100.
(d) Hygroscopicity: It is the ability to absorb atmospheric moisture and is measured as the relative humidity value at which the fertilizer starts to absorb water. In many cases, hygroscopicity is proportional to the solubility of the fertilizer. Water absorption causes the dissolution of the particles, which melts the

physical structure of the fertilizer and converts it to clumps instead of the initial granules which worsens the mechanical distribution. Deliquescence is the property of being dissolved in the water retained by hygroscopicity. This extreme situation occurs with hygroscopic fertilizers very soluble in water, such as many of the nitrogenous fertilizers.

23.3.3 Nutrient Concentration in Fertilizers

The nutrient concentration in a fertilizer is the amount of nutrient per unit mass of product. After estimating crop requirement of nutrients, this information is basic to calculate the amount of fertilizers to be applied. The concentration of nutrients in fertilizers must be expressed in the following form, according to the legislation of many countries (e.g. Spain):

(a) Nitrogen, as elemental nitrogen (N)
(b) Phosphorus, potassium, calcium, magnesium, sodium, and sulfur as oxides (K_2O,P_2O_5, CaO, MgO, Na_2O, and SO_3)
(c) Other nutrients, such as micronutrients, in elemental form.

However, European regulation allows European countries to choose between oxides and elemental expression in the nutrients considered in the case (b). The current trend is to express the concentration of all nutrients in its elemental form. The concentration of primary nutrients of a compound or complex fertilizer or fertilizer grade is usually indicated by three numbers separated by hyphens that correspond to the percentages of N, P_2O_5 and K_2O.

Example 23.1 A ternary 15-15-15 fertilizer has concentrations of 15, 15 and 15 % of N, P_2O_5 and K_2O, respectively. If we express the concentration in elemental form we have:

N 15 %
P $15\% \times 62\ \text{kg}\ \ \text{P}/142\ \text{kg}\ \ \text{P}_2\text{O}_5 = 6.5\%$
K $15\% \times 78\ \text{kg}\ \ \text{K}/94\ \text{kg}\ \ \text{K}_2\text{O} = 12.45\%$

The factor of conversion is calculated as the ratio of the element mass to the molecule mass.

The content of secondary nutrients or micronutrients in a complex or compound fertilizer is expressed by another number with the percentage of the nutrient and indication of the nutrient. For example if the ternary mentioned above has 2 % of MgO, this should be indicated in the following way: 15-15-15-2 MgO.

The nutrient concentrations of different fertilizers are presented in Table 23.2.

Table 23.2 Most relevant mineral fertilizers and their macronutrients content

	N (%)	P_2O_5 (%)	P (%)	K_2O (%)	K (%)
Straight nitrogen fertilizers					
Sodium nitrate	15.5				
Calcium nitrate	16				
Magnesium nitrate	10.5				
Ammonium sulphate	21				
Urea	46				
Calcium cyanamide	16–20				
Anhydrous ammonia	82				
Pressured ammonia solutions	41 %				
Ammonium sulfate	21				
Ammonium nitrate	32				
Calcium ammonium nitrate	20.5–30				
Ammonium nitrosulphate	26				
Nitrogen solutions	20–32				
Slow release fertilizers					
Urea formaldehyde (UF)	38				
Isobutylidene diurea (IBDU)	32				
Crotonylidene diurea (CDU)	31				
Straight phosphorus fertilizers					
Superphosphate		18–21	8–9		
Triple superphosphate (TSP)		45	20		
Phosphoric acid		54	24		
Sperphosphoric acid		76	33		
Dycalcium phosphate		40	17		
Calcium metaphosphate		64	28		
Calcined phosphate		18–28	8–12		
Basic slags		15	7		
Ground phosphate rock		25–40	11–17		
Straight potassium fertilizers					
Potassium chloride				60	50
Potassium sulphate				50	41.5
Complex fertilizers					
Binary N-P					
Mono-ammonium phosphate (MAP)	10–12	48–60	21–26		
Di-ammonium phosphate (DAP)	18	46	20		
Ammonium polyphosphates (APP)	10–11	34–37	15–16		
Nitrophosphates	20	20	9		
Binary P-K					
Potassium phosphates		52	23	34	28
Binary N-K					
Potassium nitrate	13			44	36.5

23.4 Straight N Fertilizers

23.4.1 Fertilizers with Nitrate

The nitrate fertilizers are very soluble in water and the nitrate ion, a N form in which plants readily absorbs this nutrient, is not fixed by soil particles when applied to the soil so it remains in the soil solution. Therefore, N applied in this form is easily absorbed by plants, but may be leached and lost from the soil. It can be considered a fast-action N fertilizer but should therefore be applied when it can be used by the crop to avoid losses (typically as side-dressing). These fertilizers show high hygroscopicity and a slightly basic reaction. Beside this reaction of nitrate fertilizers, nitrate can have an effect of increasing pH of plant apoplast or rhizosphere due to its absorption into cells which is coupled with H^+ which decreases the acidity of these media.

The main fertilizers in this group are calcium nitrate (16 % N) and sodium nitrate (Chilean nitrate) (15.5 % N). This group also includes magnesium nitrate (10.5 % N), very soluble and used in fertigation, sometimes as solution fertilizer.

23.4.2 Fertilizers with Ammonium

Ammonium supplied with these fertilizers is a cation which is readily adsorbed by the soil exchange complex and is therefore not leached when percolation occurs. Thus, this type of fertilizers is recommended for basal applications in winter crops when high risk of leaching and low extraction by crops occurs at the beginning of the growing season. Although ammonium can be absorbed by plants, the progressive nitrification of ammonium (microbial transformation to nitrate) enhances its use by plants. At high rates, ammonium can be toxic for crops. At basic pH there is an increased risk of losses to the atmosphere by volatilization. This risk is increased if fertilizer is not mixed with the soil, thus making it less suitable for topdressing applications. In hydroponics, a portion of N should be applied in ammonium form (10–20 %) to avoid pH rising in the solution due to nitrate absorption which can result in decreased availability of other nutrients such as Fe.

This group includes ammonium sulfate (21 % N, 24 % S), anhydrous ammonia (gas, 82 % N) and pressured solutions of ammonia (41 %) which have to be injected into the soil at 15–20 cm depth, with moderately wet conditions. Anhydrous ammonia is the cheapest N fertilizer but requires special machinery for its application and is difficult to store and handle. Another problem in the US has been the theft of anhydrous ammonia fertilizer from storage tanks on farms for production of the illegal drug methamphetamine.

23.4.3 Fertilizers with Nitrate and Ammonium

These fertilizers combine the advantages of both forms of N: rapid availability of nitrate and longer availability of ammonium. They do not depend entirely on nitrification to provide nitrate so they can be used in low temperature periods when nitrification rate is low. They are used primarily in winter and in spring for topdressing.

This group includes ammonium nitrate (32 % N) and ammonium nitrosulfate (26 % N). One of the main concerns in the use of ammonium nitrate is its application for producing explosives like ANFO which is used in mining and may be home made by mixing ammonium nitrate (AN) with fuel in the right proportions. It has been thus the choice for terrorists which has led to strict regulations in many countries regarding the purchase of AN or its commercial formulation. For instance in Ireland and Northern Ireland AN fertilizer is marketed as a mixture of ammonium nitrate and calcium carbonate.

23.4.4 Urea and Related Products

Urea (46 % N) and calcium cyanamide (around 20 % N in commercial products) are included in this group. Urea has N in ureic form and cyanamide is transformed to urea in the soil. It has acidic reaction, and it is very soluble and hygroscopic. Urea is a white crystalline solid that can be purchased as prills or as a granulated material. The importance of granules is increasing as they are larger, harder, and more resistant to moisture. Urea is rapidly hydrolyzed to ammonium through the activity of urease enzyme, present in soils. This requires a certain temperature and humidity. Urea is highly soluble so it may be leached before hydrolysis. Application to the soil surface may involve volatilization losses of ammonia formed during hydrolysis so it is advisable to incorporate urea by tillage or irrigation. Urea is widely used both for basal applications and topdressing because of its low cost per unit of N applied. It can also be applied as solutions which may also contain ammonium nitrate. Its high solubility makes feasible its use in fertigation and foliar sprays, which are recommended in tree orchards when soil conditions are not appropriate for N absorption by roots (e.g. dry soil). The content of biuret (condensation product) in urea fertilizers must be controlled since it is phytotoxic, particularly for foliar sprays with maximum recommended contents of 0.25 %. To reduce leaching, slow release fertilizers based on urea have been developed. These are based on either reducing the solubility (larger granules, special coatings as paraffin or sulfur) or by adding nitrification inhibitors.

Calcium cyanamide reactions in soil release urea and calcium hydroxide, which explain its strong basic reaction. It is expensive, can be phytotoxic, and release slowly available N, thus it is only recommended as basal fertilizer.

23.5 Straight P Fertilizers

Phosphate fertilizers are produced by physical (grounding, calcination) or chemical (acid attack) of phosphate rock which is a natural non-renewable resource. The most important feature of straight phosphate fertilizers is the reduced solubility in water of many of them. This low solubility in water does not necessarily imply that plants cannot use them as P source. Organic acids exuded by roots, such as citrate, contribute to the mobilization of P by solubilizing many of the precipitates of this nutrient in the soil. This is why the solubility of P fertilizers is also measured with ammonium citrate. The sum of the water-soluble and citrate-soluble phosphorus in the fertilizer is considered to be the amount available to plants so it is given on the fertilizer label. Usually, the citrate-soluble component is less than the water-soluble component. According to solubility, three main groups of phosphate fertilizers can be distinguished:

(a) Mostly soluble in water, including single superphosphates (18–21 % P_2O_5, 8–9 % P, 85 % soluble in water), triple superphosphate (45 % P_2O_5, 20 % P, 85 % soluble in water), phosphoric acid (54 % P_2O_5, 24 % P) and superphosphoric acid (76 % P_2O_5, 33 % P). The two acids are only used in fertigation (see Chap. 26)

(b) Mostly soluble in ammonium citrate, such as dicalcium phosphate (40 % P_2O_5, 17 % P) and calcium metaphosphate (64 % P_2O_5, 28 % P).

(c) Insoluble, including calcined phosphate (18–28 % P_2O_5, 8–12 % P), basic slags (or Thomas slags, byproduct of iron and steel industry) (15 % P_2O_5, 7 % P) and ground phosphate rock (25–40 % P_2O_5, 11–17 % P, from mining without chemical treatment in the industry).

The more soluble fertilizers are to be incorporated in granular form and localized when possible to enhance its efficiency, particularly in P-poor soils or in soils with a high P-fixing capacity. The less soluble forms are available as powder or fine granules which should be mixed with the soil to enhance its dissolution.

23.6 Straight K Fertilizers

Potassic fertilizers also come from mining resources, which are not so limited as phosphate rock. Although potassic fertilizers are very soluble in water, potassium ions are usually adsorbed to the soil exchange complex, which reduces the risk of losses. As with phosphatic fertilizers, localization in bands of potassic fertilizers is recommended in K-deficient soils with high cation exchange capacity to saturate it and maintain a high availability of K in the soil solution.

The two fertilizers with only K as primary nutrient are potassium chloride (60 % K_2O, 50 % K) and potassium sulfate (50 % K_2O, 41.5 % K). The former is cheaper and more soluble but should be avoided under saline conditions to avoid negative effects of chloride.

23.7 Compound and Complex Fertilizers

This group includes binary and ternary fertilizers. Binary are usually complex forms, and ternary are compound fertilizers, usually obtained by mixture of straight and complex fertilizers. Complex and compound fertilizers facilitate the simultaneous application of several nutrients, avoiding self-made mixtures of fertilizer by farmers which can be less effective and adequate for a homogeneous distribution and can have problems of compatibility between blended products. The selection of compound or complex fertilizers must be based on the relative proportion of N, P, and K needed by the crop, and on the price per nutrient unit applied. Blending of fertilizers to produce compound fertilizers must consider basic rules of incompatibility: avoiding mixtures of P fertilizer with products with Ca to avoid P precipitation, and the mixtures of ammonium fertilizers with basic reaction products to avoid volatilization of ammonia.

(a) Binary NP fertilizers include ammonium phosphates, mono- (MAP) or di-ammonium phosphate (DAP), ammonium poliphosphates and nitrophosphates. DAP (18-46-0) is the most widely P fertilizer used in the World. It is highly soluble and promotes a basic reaction around the granule in the soil. MAP (10/12-48/60-0) is less soluble than DAP but its reaction is acidic, which makes it a better choice in fertigation. Ammonium polyphosphates (APP, 10/11-34/37-0) have part of the P as polyphosphates which must be hydrolyzed by the action of enzymes in the soil to pass to the available orthophosphate form which takes a few weeks with adequate temperature and water content. APP is frequently used in fluid fertilizers among other reasons by its acidic reaction. Nitrophosphates (20-20-0) have only a portion of water soluble P and N in nitric and ammonium form. Ammonium phosphates are typical fertilizers used in basal applications, particularly if no K is necessary. Combination of ammonium and phosphate seems to enhance P uptake by plants compared with other P sources.

(b) Binary PK fertilizers are mixtures of phosphates and potassium chloride or potassium sulfate, or potassium phosphates and polyphosphates. Potassium phosphate (0-52-34) is soluble and has a slight acid reaction. It can be used in fertigation and foliar sprays. It is more expensive than other binary fertilizers with P.

(c) Binary NK fertilizers include blends of straights N and K products and only one complex fertilizer, potassium nitrate (13-0-44). This is a very soluble product recommended for fertigation and foliar sprays. It can be applied as topdressing if additional K (beside the basal application) is required.

(d) Ternary NPK fertilizers are solid or liquid mixtures of straight and compound fertilizers with a wide range in grades and presentations. They are used for basal broadcast applications. Although the amount of N applied as ternary products is really modest, they can represent a large fraction of the total consumption of P and K applied to the soil. Depending on each particular product, the nutrients can be present in different chemical forms.

23.8 Fertilizers and Products with Secondary Nutrients

Although crops can take up large amounts of secondary nutrients, its application is not frequent because available pools in the soil can cover plants extractions. Its application usually follows a “sufficiency” strategy, which means that nutrient is applied only if an increased yield can be expected from its application.

Calcium can be extracted in high amounts by crops, its concentration in leaves being sometimes higher than that of N (e.g. in citrus). The need to apply Ca as a fertilizer is rare; its deficiency is typical in acidic soils with low base saturation of the exchange complex. Seldom, antagonistic problems with Mg make its application advisable. Fertilizers with significant amounts of Ca are:

(a) Nitrogenous fertilizers: calcium ammonium nitrate (10–20 % CaO, 7–14 % Ca), calcium cyanamide (54 % CaO, 39 % Ca), and calcium nitrate (28 % CaO, 20 % Ca)

(b) Phosphate fertilizers: superphosphate (17–28 % CaO, 12–20 % Ca, mostly present as gypsum), slags (45–50 % CaO, 32–36 % Ca), and dicalcium phosphate (32 % CaO, 23 % Ca)

Ca is usually added in the amendments used for the reclamation of sodic or acid soils, which implies a nutrient supply that can overcome Ca deficiency in crops. As amendments to correct soil acidity, products containing Ca and/or Mg carbonate or Ca oxide or hydroxide are used. The most common products are: limestone (45–55 % CaO, 32–39 % Ca), lime (100 % CaO, 71 % Ca), and dolomite (30 % CaO, 21 % Ca). These products are efficient in increasing the base (mainly Ca) saturation of the soil and soil pH.

For the correction of sodic soils gypsum (33 % CaO, 24 % Ca) or phosphogypsum (a byproduct of the P fertilizer industry which is mostly gypsum) are the best choice in efficiency and price.

Magnesium is required in lower amounts than Ca. Its deficiency is frequently due to an antagonism with Ca, and sometimes with K when potassic fertilizers are applied in high amounts, particularly in K-rich soils. Its concentration is low in most fertilizers. When needed it may be added as dolomite (20 % MgO, 12 % Mg), magnesium oxide (90 % MgO, 54 % Mg), magnesium chelates (foliar application), and magnesium sulfate (16 % MgO, 10 % Mg). The latter can be applied by foliar sprays.

Sulphur extraction by crops can be as high as that of P, being particularly high in legumes (e.g. more than 45 kg/ha in alfalfa) and cruciferous crops. It is present in many fertilizers, such as ammonium sulfate (24 % S), ammonium nitrosulfate (12 % S), and superphosphates (12 % S in single superphosphate), which has been a traditional source of S for crops. However, the decreasing trend in the use of ammonium sulfate, superphosphates, and elemental S as fungicide could lead to S deficiencies in the next future. The need for adding S is not common, but if necessary it can be applied as sulfuric acid (30 % S), elemental sulfur (30–99 % S), potassium sulfate (17 % S) and urea-sulfur (19 % S).

23.9 Fertilizers and Products with Micronutrients

Micronutrients are usually applied following a "sufficiency strategy", which means that their application is done if a deficiency is expected. Frequently, micronutrients deficiency is the consequence of soil conditions promoting a failure in the mobilization, absorption or transport mechanisms of plants, not the result of a lack of nutrient in soil. The paradigmatic case is the iron deficiency chlorosis, related to alkaline and calcareous conditions, not to the lack of iron in soil. The most common fertilizers in the market do not contain significant amounts of trace elements with the exception of Chilean nitrate and slags. Micronutrients are not added to other fertilizers because of the risk of toxicity. The deficiencies, when detected, are treated with specific products.

Iron deficiency is called "iron deficiency chlorosis" and is related typically to calcareous soil and sensitive plants. The application of inorganic Fe salts (sulfates and carbonates) to the soil is usually not effective due to the rapid oxidation of Fe in the soil which results in the precipitation of insoluble Fe(III) oxides. These products are more effective by foliar sprays or injections to the trunk. The only inorganic salt effective in overcoming the problem (during several years) is vivianite (ferrous phosphate). Siderite (Fe carbonate) with colloidal size can also be effective. The easiest to use and most effective products are Fe-chelates, although they have the problems of high price and low residual effect (3-4 applications per growing season are usually needed). Fe-chelates are Fe complexed by organic compounds (usually synthetic amino carboxylic acids) which provide a supply of Fe that is maintained available in the soil, and also a positive effect on Fe transport mechanism through plasmamembranes. Accurate selection of Fe-chelate is necessary depending on soil conditions, e.g. chelates applied to calcareous soils may be stable in condition of high Ca concentration and pH in the soil solution. In calcareous soils, the most used Fe-chelate is EDDHA-Fe. Fe-chelates can be applied directly to the soil or by fertigation; care should be taken with foliar sprays since the chelates are not always photo-stable. Other type of Fe-complexes can be obtained using natural organic matter as complexing substances (e.g. lignosulphonates); in this case, the definition of the product is “Fe-complexes”.

The deficiency of zinc is, beside that of Fe, mostly contributing to decrease agricultural yields in calcareous soils. The stability of Zn-chelates is high but in a very narrow pH range (typically 6.5–7.5 for many commercial products). Furthermore, Zn is strongly bound to complexing agents when low free Zn is present in the soil, limiting its use by plants. This is the reason why joint applications of chelates and inorganic salts (sulfates, nitrates, chlorides, oxides) are usually done. The application of inorganic sources alone could be more effective that in the case of Fe. Lignosulphonates of Zn are also commercially available as Zn source for crops.

Manganese and copper can be applied if necessary as inorganic products (chlorides, sulfates, nitrates, or oxides, which however are less soluble) or chelates. There are not specific chelating compounds for Cu or Mn, which explains why its application as chelates is not always successful.

The deficiency of molybdenum is usual in strongly acid soils, where its solubility is significantly decreased. If needed it is applied as inorganic salts such as ammonium or sodium molybdate. Amendments to increase soil pH in acidic soils can contribute to an increased availability of this nutrient.

The deficiency of boron occurs often in the most demanding crops (alfalfa, beet, cauliflower, sunflower, olive, etc.). Sandy soils poor in organic matter and soils with very high pH can promote B deficiency. The main products are Borax (11 % B) and sodium borate in foliar or soil application. B bound to etanolamine or trietanolamine can be also used.

23.10 Slow Release Fertilizers

Slow release fertilizers were firstly focused on N supply since the progressive solubilization of N decreases the risk of leaching, particularly in sandy soils. Recently, there are available slow release products which supply different combinations of nutrients, including also those considered non-mobile in the soil such as P and K. Nowadays, a new line of products, particularly phosphatic fertilizers based on organometallic compounds, whose solubilisation is enhanced under rhyzosphere conditions (e.g. increased organic acid concentration) is being developed thinking in a progressive and highly efficient use of nutrients.

Slow N release fertilizers can be classified into different categories:

(a) Natural organic sources such as manures, which contain part of the N in organic form which must be mineralized to be used by plants. This category will be studied in Sect. 23.11.

(b) Products formulated from urea that have been chemically reacted, slowing down the urea release into the soil solution since these compounds must be hydrolyzed; the release speed depends on environmental conditions such as temperature and humidity and also on the microbial activity in the soil because this activity breaks the link between urea and other organic molecules. The main groups in this category are: urea-formaldehyde reaction products (UF, commercial products can have 38 % N and maximum decomposition speed at pH 6.1–6.5), isobutylidene diurea (IBDU, typically 31 % N, maximum decomposition speed at pH 4), crotonylidene diurea (CDU, usually 31 % N, maximum decomposition speed at basic pH), and triazone (cyclic compounds with ammonium).

(c) Products with slow release of N achieved by physical coating of urea prills. Coatings are usually composed of sulfur, wax or resins, which form a semipermeable membrane which allows a slow dissolution of covered fertilizers. Release is enhanced with the progressive decomposition of membranes. Some commercial products have different contents of primary and secondary elements and micronutrients covered plastic polymers with pores which allow a slow release. In some cases, this type of products is commercialized with a wide range of release times.

(d) Some authors also consider slow release N fertilizers those based on urea or ammonia mixed with inhibitors of the nitrification such as nitrapyrin. This allows ammonium to remain retained in the exchange complex during several weeks, decreasing the risk of losses through leaching or denitrification.

23.11 Organic Fertilizers

Organic fertilizers are products consisting of animal or plant material or obtained by transformation (e.g. composting) of these type of material which contains enough plant nutrients to be useful as fertilizer. Nutrients in the organic fertilizer, such as N, P and S, can be at least partly in organic form. To be available for plants they should be previously mineralized by the action of microorganisms. Other nutrients, such as K, are in cationic form and can be considered readily available in these products.

If these products contain significant amounts of organic matter, they can be used as organic matter source for soils, thus contributing to improve soil structure, or can increase biological activity in soils. Then, they can be also considered as organic amendments.

The most commonly used organic fertilizers can be classified into the following three groups:

- Animal wastes: slurry, dung, farmyard manure and poultry litter.
- Within farm: crop residues, pruning residues, green manure and garbage.
- External: peat, compost from different origin (e.g. organic urban residues), byproducts or wastes of food industry (blood, bones, etc.).

It should be noted here that only plant residues generate humus. Thus, only this type of residue contributes to increasing the soil organic matter content and is advisable as organic amendment for soils. On the other side, animal residues only contribute with nutrients that can be used by the crop or by microorganisms. Manures are composed of animal excreta mixed with straw "beds" of livestock, which contribute to generate soil humus. The yield in humus increases with increasing C to N ratio in the residue; e.g. fresh manures (mixed with livestock beds) or plants residues rich in lignin such as cereal straw or sawdust. On the other hand, fresh plant residues with low C to N ratio do not provide much humus but are efficient in increasing the microbiological activity in the soil which is important in many relevant processes affecting the good functioning of soil such as those involved in the N cycle.

The direct application of animal waste or its direct deposition in the field by the animals has several drawbacks:

- High water content and low nutrient concentration which increases the application cost per unit of nutrient applied when compared with mineral fertilizers (with high nutrient concentration)
- Uneven distribution
- High losses of N by volatilization of ammonia, particularly if they are not incorporated.
- Bad smells and potential chemical and microbial contamination of water courses if the product is eroded, e.g. after an intense rainfall following application
- Addition of weed seeds, pathogenic microorganisms and insect larvae (e.g. flies).
- Fermentation in the field of fresh organic residues can reduce seed germination and seedling growth due to the production of phytotoxic compounds or to decreased oxygen partial pressure around the seedlings.
- Some residues with high C to N ratio, such as fresh manure or cereal straw, can promote an initial N immobilization which may decrease N availability to plants. Later on, after humification of residues, N remaining in them increases the total N content of the soil.

Many of these problems are greatly reduced if the residues are subjected to composting (aerobic decomposition in the temperature range of 40–65 °C). Composting implies a decrease in C to N ratio of the residue (typically, in the case of manure from >50 to <20) and an increase in the density. To avoid problems it is also advisable to apply some time before sowing (2–3 months at least in the case of fresh manures or residues). It is also advisable to incorporate the residues or compost into the soil and avoid their application along with basic reaction products such as lime as that could promote ammonia volatilization.

The main limitations in the use of organic fertilizers are the following:

- Nutrient concentration in organic fertilizers is highly variable depending on the nature and processing of the product. In the case of manures the composition is affected by animal species (Table 23.3), age, proportion of bed, diet and composting time. Usually the ranges in N, P and K concentrations in manure are 0.3–0.8, 0.07–0.13 and 0.33–0.58 kg/t, respectively.

Table 23.3 Total manure produced per year and per animal for several species and average macronutrient concentration on fresh weight basis (compiled from various sources)

		Manure (fresh)	N	P	K	Total N	Total P	Total K
		kg/animal/year	%			kg/animal/year		
Dairy	Cow	17,883	0.48	0.11	0.40	85.8	19.5	71.2
	Heifer	10,367	0.53	0.17	0.51	54.9	17.7	53.3
Beef	Cow	9,925	0.6	0.16	0.33	59.6	16.0	32.9
	Feeder	8,275	0.55	0.19	0.45	45.5	15.5	37.1
	Stocker	2,867	0.51	0.14	0.41	14.6	3.9	11.9
Swine	Finishing	2,350	0.76	0.31	0.46	17.9	7.4	10.7
	Growing	3,317	0.55	0.18	0.35	18.2	5.9	11.6
	Nursery	495	0.55	0.20	0.32	2.7	1.0	1.6
	Gestating sow	2,110	0.78	0.37	0.43	16.5	7.7	9.1
	Sow and litter	4,963	0.45	0.20	0.32	22.3	9.8	15.6
Poultry	Layer	46.2	1.32	0.47	0.53	0.6	0.2	0.2
	Broiler	24.4	1.98	0.66	0.87	0.5	0.2	0.2
	Turkey	112	1.89	0.78	0.91	2.1	0.9	1.0
	Duck	50	1.01	0.45	0.56	0.5	0.2	0.3
	Goose	100	1.1	0.26	0.41	1.1	0.3	0.4
Other	Horse	8,600	0.57	0.11	0.45	49.0	9.4	38.5
	Sheep	610	0.94	0.17	0.65	5.7	1.0	3.9
	Goat	1,100	0.99	0.24	0.89	10.9	2.6	9.8
	Rabbit	56	1.56	0.53	0.71	0.9	0.3	0.4

In poultry litter, nutrient concentrations are usually larger, with N and P concentrations above 2 %. Thus, it is difficult to know the amounts of nutrient applied with a given rate of organic fertilizer if specific analysis of each batch applied is not performed.

- Organic fertilizers have low nutrients concentration thus making difficult to meet crop demand. This forces to apply high rates of organic fertilizers or to an additional supply of mineral fertilizers. For example, the application of 20 t/ha of cow manure may provide 60 kg N/ha, 30 kg P/ha and 80 kg K/ha.
- Part of the nutrients in these products are in organic form, particularly N and P. Thus their release is not immediate, since it requires the mineralization of organic matter which may take several years to be completed. It is assumed that N in manures is released in 3–5 years; in slurries, a greater portion of N is readily available in the first season after application (60–70 %). This slow release of nutrients presents the advantage that the mobile elements as nitrogen are retained by the soil, so leaching losses are reduced. Beside this, the application of P as organic forms or with organic matrix is more efficient in increasing available pool in the soil than mineral fertilizers. On the other hand, the slow release of nutrients through mineralization implies that the whole amount of applied nutrient is not readily available to plants, thus they should be complemented with mineral fertilizers.

- The nutrient equilibrium in organic fertilizers does not match the equilibrium required by crops. For instance, cereals usually have a N:P:K requirement around 7:1:4.8, so meeting the crop N requirement with the cow manure described above implies an excess application of P. Thus, for an adequate nutrient supply to the crop a combination of organic and mineral fertilizers is required.

Animal wastes and plant residues or green manure with legumes produced within farms must be integrated in a nutrient balance at the farm scale for a sustainable fertilizer management which must consider that external mineral or organic fertilizers must complete the availability of nutrient in farm soils plus the potential internal supply with residues or green manure. In organic or ecological farming systems only organic or natural fertilizers are allowed. This often leads to reduced yields which can partially be explained by the limited supply of nutrients, although this may be compensated by the higher prices of organic crops.

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Chapter 24
Nitrogen Fertilization I: The Nitrogen Balance

Miguel Quemada, Antonio Delgado, Luciano Mateos, and Francisco J. Villalobos

Abstract Nitrogen is the most important nutrient in agricultural production. The natural input of N is due to N fixation, especially by *Rhizobium* bacteria that infect the roots of legumes. Organic N becomes inorganic through mineralization, and then inorganic N is absorbed by plants. Often soil microorganisms "capture" temporarily inorganic N when residue with high C/N ratio decompose (immobilization process). The ammonium in the soil is converted to NO_3^- through nitrification which is greatly reduced in waterlogged soils. In the latter denitrification generates gaseous N forms that are lost (oxides of N and N_2). Major losses of N may occur by nitrate leaching which is proportional to deep percolation and to nitrate concentration in the soil solution. A Leaching Index may be calculated as a function of rainfall and soil type to quantify the risk of leaching.

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24.1 Introduction

The original source of nitrogen for terrestrial plants is the N_2 gas which constitutes 78 % of the atmosphere. As plants cannot convert N_2 to protein, first it has to be transformed following one of the following paths:

1. Fixation by microorganisms living in symbiosis with the roots of legumes.
2. Fixation by free living soil microorganisms.
3. Fixation as oxides by electrical discharges in the atmosphere.
4. Fixation as NH_3, NO_3^- or CN_2^{2-} by N fertilizer manufacturers.

The contribution of atmospheric N_2 is in dynamic equilibrium with the forms fixed in the soil. While N_2 is fixed according to various processes, other chemical and microbiological processes release N_2 to the atmosphere (Fig. 24.1). Except for industrial fixation or combustion, all other processes are natural, but can be altered by soil and crop management.

Understanding the N cycle in the soil-crop system is the key to optimizing nitrogen fertilizer management, maximizing yields and minimizing negative environmental impacts on water (nitrate pollution) and atmosphere (emission of greenhouse effect gases). The sources of N for crops are inorganic and organic N fertilizers and symbiotic N_2 fixation.

Although N_2 in the atmosphere can be considered an infinite source of N for fertilizer production, this industrial process requires huge amounts of energy. Thus, N for industrial production of mineral fertilizers cannot be considered a renewable resource since it depends on a very high consumption of energy which is mostly obtained from non-renewable resources.

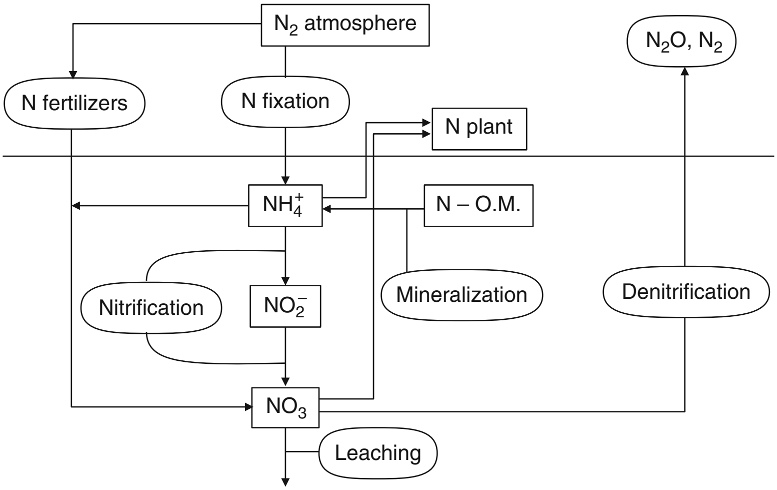


Fig. 24.1 Nitrogen cycle

24.2 N Forms in the Soil

The soil N concentration ranges from 0.02 % (subsoil) to 2.5 % (peat) with a typical range 0.03–0.4 %. This N can be inorganic or organic, with the latter being the predominant form.

Organic N appears as proteins, amino acids, amino sugars and other N compounds. Inorganic forms include ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO) and N_2. The first three are important from the fertility point of view and are derived from fertilizers or come from the organic matter mineralization. The other three forms are gases that are lost as a result of the denitrification.

24.3 N Forms Absorbed by Plants

Plants absorb NH_4^+ and NO_3^- although often the presence of both improves plant nutrition. The nitrate concentration is generally higher than that of ammonium and NO_3^- in the soil solution, so it reaches the roots with the water flow (mass transport flow). Plant preference for one or another form of inorganic N depends on the species, plant age, environmental conditions and other factors. For instance, cereals and beets absorb either NO_3^- or NH_4^+. The *Solanaceae* (potato, tobacco, tomato), benefit from a high NO_3^-/ NH_4^+ ratio in the soil solution. Species adapted to acid soils are used to low NO_3^-/NH_4^+ ratio, as NH_4^+ tends to accumulate due to nitrification slowdown in acid environments.

In terms of energy, NO_3^- uptake is less efficient than that of NH_4^+, as the nitrate has to be reduced to ammonium before the N becomes part of the organic compounds. However, NH_4^+ absorption leads to acidification of the rhizosphere and decreases the absorption of Ca^{2+}, Mg^{2+} and K^+ while it increases the absorption of $H_2PO_4^-$, SO_4^{2-} and Cl^-. On the other hand, NO_3^- uptake is co-transported with H^+ thus contributing to rizhosphere and apoplast alkalinization which can decrease Fe uptake by plants. Small amounts of organic N are absorbed by plants mainly in the form of amino acids, however, evidence that organic N contributes significantly to plant N nutrition is still lacking.

24.4 Symbiotic N_2 Fixation

Symbiotic N fixation involves the reduction of atmospheric N_2 to NH_3 by an enzyme (nitrogenase) in aerobic microorganisms (mainly *Rhizobium* bacteria) that form nodules on the legumes roots. For centuries this was the major N source in agriculture, but the increasing availability and better prices of synthetic N fertilizer reduced the importance of this source.

The Rhizobium-legume symbiosis is characterized by its specificity, i.e. specific *Rhizobium* species will only infect a specific type of legume. Therefore, it is often necessary to inoculate the seeds with the adequate species or strain of *Rhizobium*.

The mere presence of nodules on the roots does not imply fixation activity. For example, in alfalfa active nodules are enlarged (2–4 × 4–8 mm) and are grouped in the primary roots. The red color inside the nodules denotes the presence of leghemoglobin, a N and O carrier required for the activity of the *Rhizobium*.

The factors that affect the rate of N fixation by *Rhizobium* are pH, concentration of nutrients in the soil, photosynthetic activity, climate and overall crop management. Soil acidity restricts the presence and activity of Rhizobium, although major differences in the sensitivity to acidity of different species and even races, of *Rhizobium* exist. For example, a pH below 6 drastically reduces the number of nodules of *Rhizobium meliloti* in alfalfa roots while pH between 5 and 7 hardly affects nodulation of *R. trifoli* in clover.

An excess of NO_3^- in the soil reduces the nitrogenase activity and thus N fixation. The maximum fixation occurs when there is little inorganic N available in the soil. However, small doses of N fertilizer are often recommended to ensure good seedling establishment of legumes while the *Rhizobium* nodulation is completed. Applications of N may also be necessary at the beginning of spring, when the demand for N by the plant exceeds the supply by *Rhizobium* due, for example, to low temperatures. In some legumes (i.e. beans), fixation is so poor that it is necessary to apply N fertilizer systematically.

In general, a high photosynthetic activity is related to high N_2 fixation, and therefore water stress, low temperature or any other stress that reduces photosynthetic activity will also decrease N_2 symbiotic fixation.

24.5 Quantifying N_2 Fixation

Perennial crops fix between 110 and 225 kg N/ha/year, although the values may be above or below that range depending on environmental conditions. Annual legumes fix between 50 and 110 kg N/ha/year.

As a first approximation, the amount of N fixed by a legume crop, can be estimated as:

$$N_{fixed} = (1 + f_{NR})\, Y \left(NC_h + \frac{1 - HI}{HI} NC_r \right) F_{NBF} \tag{24.1}$$

where f_{NR} is the ratio of N in roots and N in shoots, Y is yield, NC_h and NC_r are the N concentrations in the harvested product and the residues, respectively, HI is harvest index and F_{NBF} is the fraction of N resulting from biological fixation. The value of f_{NR} lies between 0.05 and 0.25. F_{NBF} depends greatly on the availability of soil N, which in turn is related to fertilizer application rate and the type of legume.

Table 24.1 Nitrogen concentration in different crop species

Crop species	DM %	N min	N max	N typical		DM %	N min	N max	N typical
Alfalfa (hay)	85.0	2.80	3.80	3.30					
Apple	18	0.25	0.45	0.35					
Barley	88.5	1.50	1.80	1.60	Straw	90	0.58	0.88	0.70
Bean (Phaseolus) (dry seed)	89	3.50	4.50	4.00	Straw	89	1.10	1.40	1.20
Cotton	91	2.32	2.75	2.53	Residues	92.5	0.90	1.00	0.98
Grapes (wine)	19	0.50	0.60	0.57					
Lettuce	6	4.00	4.40	4.27					
Maize (grain)	30	1.10	1.45	1.25					
Millet	89.5			2.00	Stover	91.5			0.80
Olives (60 % canopy cover)	50	0.20	0.40	0.30	Vegetative	70	1.00	2.00	1.50
Orange	18	1.00	1.40	1.20					
Palm trees	79			1.25					
Peach	12	0.80	1.20	1.00					
Peas (dry harv.)	90	4.00	4.30	4.20	Straw	88.5	1.20	1.40	1.30
Potato	23.5	1.20	1.90	1.60	Residues	51	2.00	2.40	2.20
Rapeseed, Canola	91	3.40	4.30	3.90	Residues	82.5	0.55	0.90	0.80
Rice	94			1.33					
Sorghum (grain)	87.5	1.45	2.00	1.90	Stover	92	0.60	0.80	0.70
Soybeans	87.5	6.10	6.90	6.50	Residues	89	1.00	1.00	0.85
Sugar beet	21	0.90	1.10	1.05	Residues	18	1.80	2.80	2.30
Sugar cane (virgin)	25			0.13		26			0.41
Sunflower	91.5	2.20	3.20	2.95	Residues	87	0.40	1.10	0.80
Tomato	6	2.30	3.10	2.60		20			1.80
Winter wheat	87.5	1.85	2.30	2.10	Straw	90.5	0.40	0.85	0.65

Maximum and minimum values are shown when available. Also the dry matter content (% over fresh mass) is indicated

When soil N availability is low, most of the crop N comes from fixation (Table 24.2). If the organic matter content is high the lower values of the proposed intervals should be used. On the other hand the N concentrations in the harvested product and the residues may be measured or taken from Table 24.1.

Example 24.1 The expected yield of an alfalfa crop is 8 t/ha (15 % moisture) on a soil with 1 % organic matter. Initial inorganic N in the soil is 40 kg/ha and expected N mineralization is 35 kg N/ha. We assume that HI is 0.9 and that residues have the same N concentration as the harvested part.

(continued)

Example 24.1 (continued)

In Table 24.1 we find that N concentration of alfalfa is 3.3 kg N/100 kg dry matter. As water content is 15 %, harvested dry matter biomass is 6800 kg dry matter/ha.

Available N in the soil will be the sum of initial inorganic N and expected mineralized N:

$$40\,\mathrm{kg\,N/ha} + 35\,\mathrm{kg\,N/ha} = 75\,\mathrm{kg\,N/ha}$$

So we are in the 55–110 kg/ha interval of Table 24.2, implying that 60–90 % of N comes from fixation. As organic matter content is low (1 %) we use the upper limit (0.90). We also take $f_{NR} = 0.2$, which means that total fixed N is:

$$\begin{aligned} N_{fixed} &= (1 + f_{NR})Y\left(NC_h + \frac{1 - HI}{HI}NC_r\right)F_{NBF} \\ &= (1 + 0.2)6800\left(0.033 + \frac{0.1}{0.9}0.033\right)0.9 = 270\ \mathrm{kgN/ha} \end{aligned}$$

Table 24.2 Percent of crop N obtained from symbiotic fixation in legumes as a function of legume type, % organic matter and inorganic N in the soil

		Available inorganic N (kg/ha)			
% OM	Type	55	55–110	110–225	>225
>3	Annuals	70	50	30	5
	Perennials	80	60	50	10
<3	Annuals	95	80	60	40
	Perennials	95	90	80	50

Adapted from Meisinger and Randall (1991)

24.6 Transformations of N in the Soil

24.6.1 Mineralization and Immobilizacion

Dead plant materials (senesced leaves, residues left after harvest) suffer a process called decomposition, which is the breaking down of the structure into unrecognizable organic matter. This process is performed by bacteria and fungi which get energy from the respiration of carbon compounds of the residue. Decomposition rate increases with temperature up to 32–35 °C and with water content up to Field Capacity, so faster decomposition is expected if the residue is buried into the soil. In general decomposition rate is proportional to N concentration in the

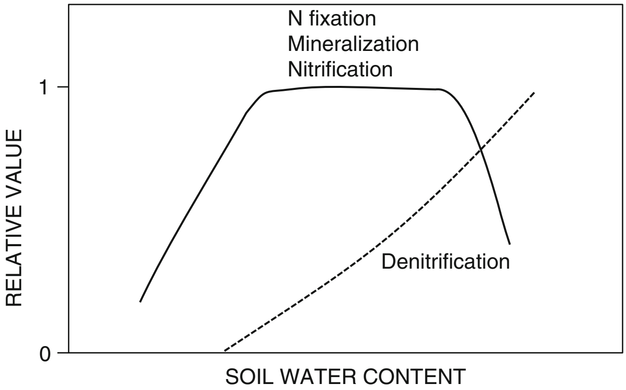
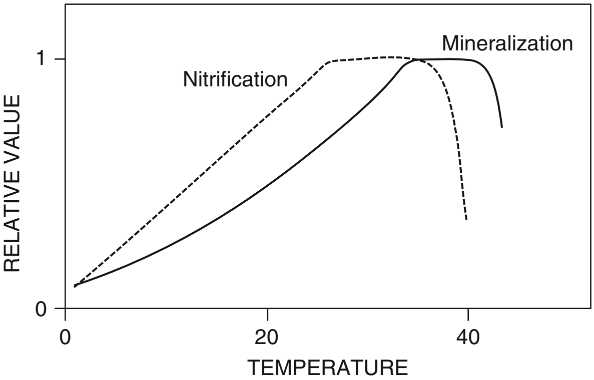


Fig. 24.2 Response of N fixation, N mineralization and nitrification to soil water content

Fig. 24.3 Response of N mineralization and nitrification to soil temperature



residue, which explains the faster breakdown of legume residues as compared to those of cereals.

Nitrogen mineralization is the conversion of organic N to NH_4^+. After decomposition of plant residues, N mineralization occurs in two stages, aminization (breaking up of proteins to amino acids, amines and urea, with release of CO_2) and ammonization (conversion of amines and amino acids to NH_4^+). This transformation is performed by heterotrophic microorganisms (fungi and bacteria), and is based on aerobic and to a lesser extent, anaerobic respiration.

Mineralization is favored by high soil water content, without reaching saturation to ensure oxygen supply (Fig. 24.2). The decomposition does occur in waterlogged conditions but at a lower rate. As most biological processes, mineralization is affected by temperature. The temperature coefficient, Q_{10} for mineralization is 2 in the range of 5–35 °C, i.e. mineralization rate is doubled by raising the temperature 10 °C. The optimum temperature is around 35 °C (Fig. 24.3).

Immobilization is the conversion of inorganic N (NH_4^+ and NO_3^-) to organic N being basically the reverse of mineralization. If decaying organic matter contains little N relative to C, the microorganisms use (immobilize) soil mineral N. Microorganisms require a C/N ratio of about 8:1, therefore the soil inorganic N may decrease rapidly during waste decomposition and the crop may experience N deficiency. When the residue with low N content is finally decomposed, C availability as energy source for microbes is decreased and microbial activity decreases, thus finishing N immobilization.

The predominant process (mineralization or immobilization) depends on the C/N ratio of decomposing organic matter. At the start of the decomposition of organic residues, there is a rapidly growing population of heterotrophic microorganisms which is detected in the increased release of CO_2. If the C/N is greater than 30/1, immobilization occurs. As decomposition proceeds, the C source decreases, and so does the C/N ratio, until the microorganisms begin to die. Finally a new equilibrium is reached that starts with mineralization of N and ends with a higher inorganic N level and C/N ratio of around 10/1. The time required depends on the amount of added organic residue, the availability of inorganic N, the resistance of the residue to be decomposed (i.e. its lignin content), the temperature and soil water content.

Example 24.2 After harvest of a cereal we incorporate 3000 kg/ha of straw with 45 % C and 0.75 % N (C/N = 60/1) to the soil. The total amounts of C and N are:

$$3000\,\mathrm{kg/ha} \times 0.45 = 1350\mathrm{kg\ C/ha}$$
$$3000\mathrm{kg/ha} \times 0.0075 = 22.5\mathrm{kg\ N/ha}$$

We assume that 35 % of C will be used in growth of microorganisms while 65 % of C is lost as respired CO_2. The amount of C accumulated in the microbial biomass will be:

$$1350\,\mathrm{kg\ C/ha} \times 0.35 = 472.5\mathrm{kg\ C/ha}$$

The C/N ratio of the microorganisms is 8/1 so N accumulated will be:

$$472.5\mathrm{kg/ha}/8 = 59\,\mathrm{kg\,N/ha}$$

And the amount of immobilized N is:

$$59\mathrm{kg\ N/ha} - 22.5\,\mathrm{kg\,N/ha} = 36.5\,\mathrm{kg\,N/ha}$$

The C/N in the surface layer of a natural soil is between 8 and 12, being 10 the most common value. These soils have a relatively stable microorganism population and deposition of organic residues (and thus mineralization) is also constant. If this soil is cultivated a rapid increase in decomposition and mineralization will occur which will decrease the organic matter content.

Example 24.3 A soil has 2.0 % organic matter in its surface layer (0.20 m) and bulk density of 1.3 t/m^3. The N concentration in organic matter is 5 %. Therefore the total amount of organic N in this layer is:

$$\begin{aligned}&1.310^3\text{kg soil/m}^3\text{soil} \times 0.20\text{m} \times 10^4\text{m}^2/\text{ha} \times 0.02\text{kg O.M./kg soil}\\&\quad \times 0.05\text{kg N/kg O.M.}\\&\quad = 2600\text{kg organicN/ha}\end{aligned}$$

If mineralization rate is 1 %/year, the amount of inorganic N released will be:

$$2600\text{kg organic N/ha} \times 0.01\,\text{kgN/kgorganic N/year} = 26\text{kg N/ha/year}$$

24.6.2 Nitrification

The NH_4^+ transformation to NO_3^-, called nitrification, is performed by bacteria (*Nitrosomonas* and *Nitrobacter*) in two stages:

$NH_4^+ + O_2 > NO_2^- + H_2O + H^+ \quad (\textit{Nitrosomonas})$
$NO_2^- + O_2 > NO_3^- \quad (\textit{Nitrobacter})$

Both *Nitrosomonas* and *Nitrobacter* are autotrophic bacteria, although in both processes some heterotrophic organisms are also involved. The second stage is faster than the first, which prevents the accumulation of NO_2^-, which is toxic to plants.

Among the factors affecting the nitrification rate, the first is the substrate concentration (NH_4^+) that depends on fertilization and mineralization. The need for oxygen in the reactions indicated above, means that a good aeration is required (optimum oxygen concentration is 20 %), so waterlogging is undesirable. However, nitrification is high with relatively high water content, and is maximized when 80–90 % of the soil pores are filled with water. The optimum temperature for nitrification is between 25 and 35 °C. It is generally accepted that nitrification is optimal at neutral to slightly alkaline soil pH, but nitrification can occur in the range of 4.5–10 (Fig. 24.4). A secondary effect of lime application to acid soils is enhancing nitrification and mineralization contributing to an increase in N supply to crops.

The product of nitrification (NO_3^-) is very soluble in water and is hardly adsorbed by soil colloids so it may be lost by leaching.

Nitrogen fertilizer management has to take into account the facts stated above. In regions with low soil temperatures and/or low winter rainfall, NH_4^+ applications in the fall, before planting, save time and money. If air temperatures are below 4–5 °C or mean soil temperature is below 10 °C, the preplant applications of ammonium in the autumn are efficient since nitrification rates are low.

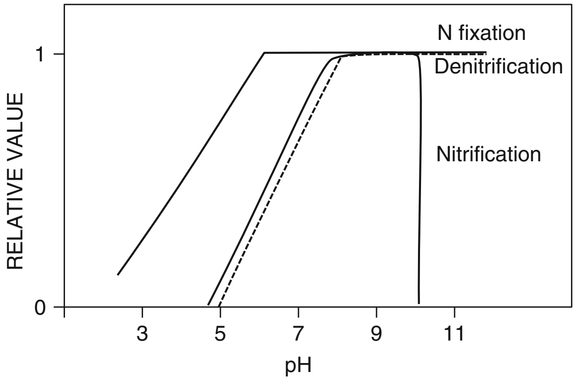


Fig. 24.4 Response of N fixation, nitrification and denitrification to soil pH

Nitrosomonas activity is very sensitive to the presence of a large number of compounds. Because of that, the fertilizer industry has developed substances called ‘nitrification inhibitors’ that are blended to the fertilizer granules or added to manures and slurries. The inhibitors slow down the nitrification process, controlling nitrate accumulation in the soil and thus nitrate losses. These compounds need to be biodegradable and in many countries they can be only commercialized when blended to the fertilizers.

24.6.3 Denitrification

Denitrification is not the opposite of nitrification but the reduction of nitrate into volatile N compounds. When soil oxygen availability is reduced because of high water content, soil compaction or the application of easily decomposable organic matter, the rate of denitrification increases. Anaerobic micro-zones containing still a source of labile C appear and a broad number of microorganisms (mainly bacteria as *Pseudomonas*, *Bacillus* and *Paracoccus*, but also some fungi) are able to use NO_3^- or NO_2^- as oxidizing agents releasing gaseous N forms to the atmosphere:

$$NO_3^- > NO_2^- > N_2O > NO > N_2$$

The incomplete reduction promotes the emission of N_2O, a very reactive gas that enhance the ozone destruction and the atmosphere warming capacity. The reaction is very fast and peaks of N_2O emission are observed after application of organic or synthetic fertilizers. It was previously thought that denitrification required water logging conditions, but nowadays it is recognized as a main pathway of N losses to the atmosphere under a broad range of environmental conditions.

Among the factors affecting denitrification, the soil water content is one of the most important. Water logging prevents the diffusion of oxygen and thus enhances denitrification (Table 24.3). Because of that, the highest denitrification N losses from agricultural fields have being reported in rice paddy fields, were potential losses of up to 16 kg N/ ha in the day after soil saturation have been found. A strategy to control losses in paddy fields is application of urea or ammonium based fertilizers. The N will remain in the soil as NH_4^+ and only small amounts transformed to NO_3^- in the proximity of roots were oxygen is available, therefore, denitrification will be slow due to a lack of substrate. In well-aerated soils, however, nitrification rate is high and denitrification will only occur in anaerobic micro-zones of the soil (e.g. cattle dung). Care should be taken when combining inorganic N fertilizers with manure application as denitrification may be greatly enhanced and fertilizer efficiency drastically reduced. Recently, a leak on the first stage of the nitrification has been identified as a source of N_2O, adding uncertainty to gaseous emissions in well-aerated soil. Quantification of denitrification is complicated as it is hard to tell apart from the atmospheric N_2, so we use Table 24.3 that shows the effect of organic matter on denitrification rate for different soil types.

Many of the bacteria responsible for denitrification are very sensitive to acidity (Fig. 24.4). Thus, in soils with pH below 5, denitrification is negligible while it can be high in basic soils. However, in soils with $pH > 7$ the N tend to be reduced to N_2 whereas in acid soils most of the emission gases are as N_2O. Moreover, the denitrification is very sensitive to temperature and increases rapidly as soil temperature goes from 2 to 60 °C, above which it is inhibited.

24.6.4 Ammonia Volatilization

The ammonium ion in solution is in equilibrium with ammonia (NH_3), which is volatile. Ammonia volatilization occurs naturally in soils but at slow rate. However, volatilization losses of N fertilizer can be very important, depending on the type of fertilizer, application form, the cation exchange capacity and climatic factors (Table 24.4). The set of conditions with higher ammonia losses would be the surface application of urea on a soil with basic pH and low CEC under dry conditions. Volatilization risk can also be high with surface application of manures since a relevant fraction of N can be ammonium. To reduce ammonia volatilization, incorporation of ammonium fertilizers/urea/manure is recommended by tillage or irrigation within 2 days of fertilization.

The general ranges of loss by volatilization of ammonia fertilizer are 2–50 % ($pH > 7$) and 0–25 % ($pH < 7$). The NH_3/NH_4^+ equilibrium is pH dependent. In acidic and neutral conditions the equilibrium is shifted to NH_4^+ which explains the lower losses.

Table 24.3 Denitrification losses (% of inorganic N) for different cases and soil types as a function of organic matter content

		Arid and semiarid rainfed crops					Irrigated crops or humid areas				
		Rate of drainage									
Case	% O.M	Very high	High	Medium	Low	Very low	Very high	High	Medium	Low	Very low
N from fertilizer. Tilled	<2	2	3	4	6	10	4	9	14	20	30
	2–5	3	4	6	10	15	9	16	20	25	45
	>5	4	6	10	15	25	12	20	25	35	55
N from fertilizer. No tillage	<2	3	4	6	10	10	9	14	20	30	30
	2–5	4	6	10	15	15	16	20	25	45	45
	>5	6	10	15	25	25	20	25	35	55	55
N from manure. Tilled[a]	<2	4	6	8	12	20	8	18	28	40	60
	2–5	6	8	12	20	30	18	32	40	50	90
	>5	8	12	20	30	50	24	40	50	70	95

[a] The same values apply to N from fertilizer in tilled soils when a compacted impervious layer is present below the plow depth (Adapted from Meisinger and Randall (1991))

Table 24.4 Ammonia volatilization loss (% of N applied) for soils as a function of soil pH, CEC and climatic conditions

			High CEC>250 meq/kg			Low CEC <100 meq/kg[a]		
			Rainfall after application and climate type					
			>12 mm in 2 days	<6 mm in 7 days	No rain in 7 days	>12 mm in 2 days	<6 mm in 7 days	No rain in 7 days
	N source	Application method	Humid	Sub-humid	Dry	Humid	Sub-humid	Dry
pH>7	Urea	Surface broadcast	0	2	2	20	30	40
		Surface localized	0	2	2	15	20	30
		Incorporated	0	0	0	10	10	10
	Ammonium sulphate	Surface broadcast	0	2	5	40	50	60
		Incorporated	0	0	0	10	20	30
	Ammonium nitrate	Surface broadcast	0	2	5	20	25	30
		Incorporated	0	0	0	10	15	20
	Anhydrous ammonia	Injected	0	0	0	2	3	5
ph <7	Urea	Surface broadcast	0	5	5	5	30	40
		Surface localized	0	2	2	5	20	30
		Incorporated	0	0	0	0	2	2

(continued)

Table 24.4 (continued)

			High CEC>250 meq/kg			Low CEC <100 meq/kg[a]		
			Rainfall after application and climate type					
			>12 mm in 2 days	<6 mm in 7 days	No rain in 7 days	>12 mm in 2 days	<6 mm in 7 days	No rain in 7 days
	N source	Application method	Humid	Sub-humid	Dry	Humid	Sub-humid	Dry
	Ammonium sulphate	Surface broadcast	0	0	0	0	2	2
		Incorporated	0	0	0	0	2	2
	Ammonium nitrate	Surface broadcast	0	0	0	0	2	2
		Incorporated	0	0	0	0	2	2
	Anhydrous ammonia	Injected	0	0	0	0	2	2

[a] The same values applied in no tilled soils covered with more than 50 % surface residue cover (Adapted from Meisinger and Randall (1991))

24.7 Crop N Uptake

Nitrogen is an essential nutrient for crops. It is a constituent of proteins, nucleic acids, and other intermediate metabolites. If the N supply is limiting, crop growth is reduced and so is intercepted radiation. A more severe N deficiency leads to lower Radiation-Use Efficiency. Therefore N availability will limit biomass accumulation and yield. There is an optimum N concentration range, above which excess N can cause decreased yield. For instance, in indeterminate crops, high N concentration promotes vegetative growth at the expense of reproductive growth which results in lower harvest index. At a global level, N is the second limiting factor (after water) in crop production.

Nitrogen uptake is parallel to biomass accumulation so it shows a typical sigmoid curve with an initial exponential increase followed by a fast linear accumulation phase. In this rapid phase, accumulation may be up to 3–5 kg N/ha/day. The concentrations of N in the different organs are high when the plants are young and decrease with age. Therefore, the crop response to N depends not only on the amount absorbed but also on the translocation capacity to the growing organs (and finally to the grain or harvestable part).

In most crops, N concentration decreases with increasing aboveground biomass and the decline is described by a negative power function called the nitrogen dilution curve. The critical nitrogen dilution curve has been developed for many species ($\mathrm{NC_{crit}} = a\ \mathrm{Biomass}^{-b}$) based on datasets of N concentration and biomass under different fertilization regimes. The critical N concentration of a crop ($\mathrm{NC_{crit}}$) is defined as the minimum crop N concentration (%) allowing maximum biomass production. The coefficient a is crop N concentration when biomass equals 1 t/ha, and b is a dimensionless parameter governing the slope of the relationship. The critical nitrogen dilution curve (Fig. 24.5) can be used to determine the crop N status: if crop N concentration is close to the $\mathrm{NC_{crit}}$ corresponding to the current biomass, it indicates that N is not limiting crop growth, while when it is below it indicates a N deficiency. The ratio between the actual crop N concentration and the $\mathrm{NC_{crit}}$ for a given biomass is known as the N nutrition index (NNI):

$$NNI = \frac{NC_{actual}}{NC_{crit}} = \frac{NC_{actual}}{a\,B^{-b}} \tag{24.2}$$

where B is crop biomass (t/ha). In general, C4 species have a lower $\mathrm{NC_{crit}}$ for a given biomass than C3 species, presumably related to a lower content of photosynthetic proteins. The dilution curves are generally accepted because of its simplicity for modeling crop growth during vegetative stages, however, when other factor different from N limits growth (i.e. severe drought, disease) the curve may depart greatly from the model. The requirement of destructive samples for measuring biomass and the need to fit the dilution curve to local conditions or cultivar specific characteristics, make difficult the adoption of dilution curves as a management tool.

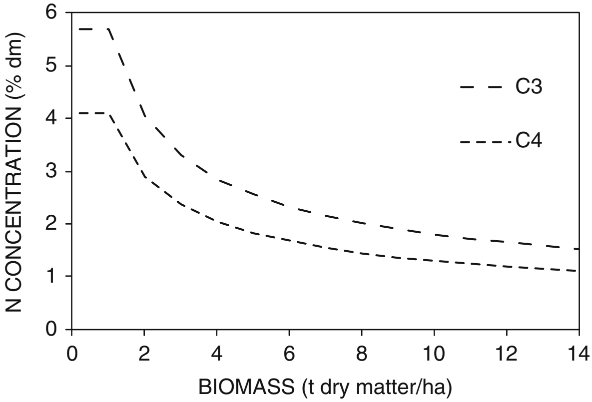


Fig. 24.5 Critical nitrogen concentration curve for various crops (Adapted from Gastal F. and Lemaire G. (2002). J Exper Bot 53: 789–799)

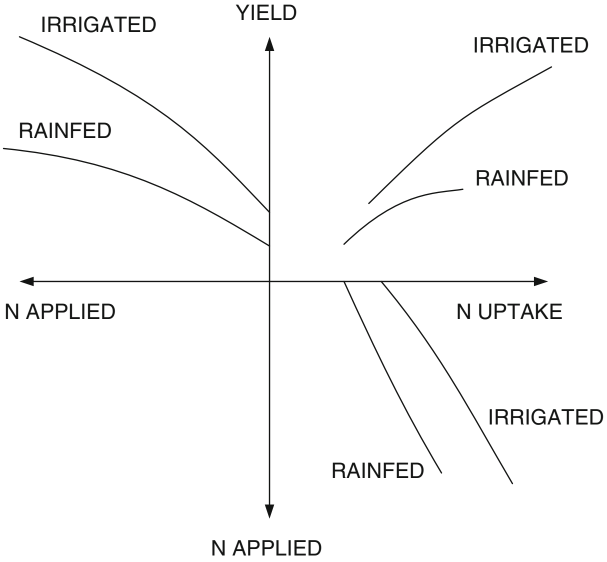


Fig. 24.6 Response of sunflower yield to N applied and N uptake

Other techniques based on crop N status have been developed for fertilizer recommendation and will be discussed in Chap. 25 (Fig. 24.5).

The relationship between yield and N uptake is generally linear until the maximum yield is reached. From that point, if there is N available in the soil, absorption continues, but it does not result in higher yield. This limit depends on environmental conditions and crop management. Figure 24.6 shows a linear relationship between yield and N uptake for an experiment conducted with sunflower in Cordoba with different levels of irrigation and N fertilizer. The maximum yields, where the yield-N uptake relation saturates, increased with irrigation levels. Therefore, despite the linear relationship between yield and N uptake when no other factor is limiting, it is important to set the objective yield to define the maximum level of N uptake.

For a set of environmental conditions, the relationship between yield and applied N is curvilinear (Fig. 24.6). Therefore, the apparent efficiency of the N fertilizer decreases with increasing the dose. When this dose reaches a certain value, an increase of fertilizer does not result in a yield increase, and in some cases it may even be detrimental. Furthermore, the amount of residual soil N will be greater, which increases the risk of nitrate leaching.

The yield response to N applied, depends on the initial availability of soil N and the mineralization potential during the season, besides the production potential of the crop. Thus, in very fertile soils, the crop may not respond to the application of N or the response may be negative. If another factor (i.e. water) is limiting, the high N input will not bring yield increases. Figure 24.6 illustrates this behavior in the sunflower experiment mentioned earlier. As the irrigation amount was higher, so were yields for any dose of N. The response to applied N was also higher under irrigation, at least for low N doses.

As a framework for understanding the responses to fertilization, de Wit proposed to represent in different quadrants the curves of N uptake and yield in response to the N application (Fig. 24.6). In quadrant (a) yield is plotted as a function of N applied for different irrigation regimes of the sunflower experiment This yield corresponds to an amount of N absorbed (quadrant b), which in turn corresponds to a rate of N application (quadrant c). Each line of the lower quadrant is characterized by its slope and its intercept. We see that both the intercept and the slope of the N uptake-N applied lines increased with applied irrigation. This means that irrigation increased N availability, because either NO_3^- was applied in irrigation water, the mineralization rate was enhanced by irrigation or N uptake was facilitated in a wetter soil. Furthermore, as the level of irrigation increased, the curves of N uptake did not show saturation, i.e. a ceiling of N absorption was not reached. Water and N are the main limiting factors in many irrigated systems and a combined management should be followed for a successful crop performance.

In any case the criterion for choosing the amount of N fertilizer should be economical, i.e. the optimum amount will be that that results in maximum profit. This amount will be lower than that required for maximum yield and may be calculated as the point where the marginal profit is zero.

The results of the sunflower experiment mentioned above contrast with other previous experiments on sunflower fertilization in Cordoba, which did not show response to N fertilization. It should be noted that in the experiment mentioned the soil had been “cleaned” of N with a previous unfertilized cereal crop. Obviously initial fertility conditions and other environmental factors (i.e. water supply) greatly affect crop responses to N application. This is why production functions of yield versus N applied cannot be extrapolated to other situations. To emphasize this concept, results from a rainfed experiment conducted in three adjacent fields in Navarra (Spain) where the response of wheat to increasing rates of N fertilizer application are presented in Fig. 24.7. No yield response was observed when high initial inorganic N (>140 kg N/ha) was present in the soil (top 0.9 m) before

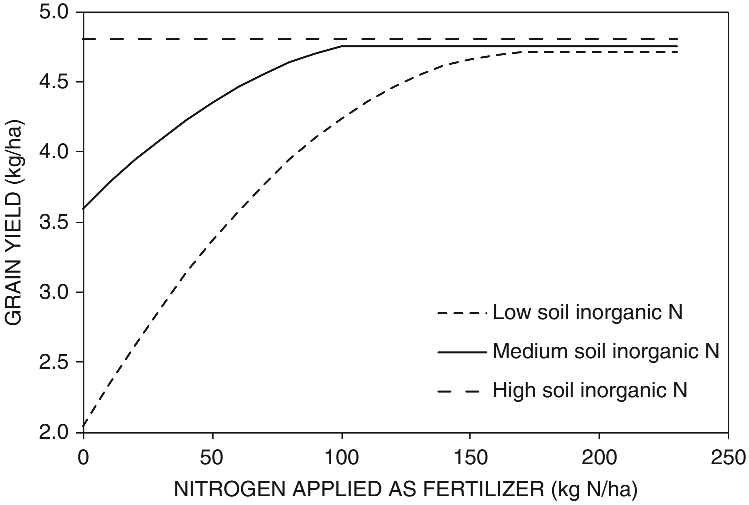


Fig. 24.7 Wheat response to N fertilizer application based on the soil inorganic N content determined in the upper 0.9 m of soil

planting, whereas yield response increased for the medium (90 kg N/ha) and low (30 kg N/ha) inorganic N fields. Because of that, determination of available N in soil samples taken before planting or before side-dress applications is a recommended practice to avoid over-fertilization in many regions.

24.8 Nitrate Leaching

The consequences of N losses from agricultural systems to water bodies is a major social concern in developed countries, with special attention to aquifer contamination by nitrate and excessive N availability in lakes and estuaries. Potential harmful effects of nitrate on human health (cyanosis, risk of cancer) had led to the establishment of maximum allowable concentrations of nitrate in drinking water of 50 g NO_3^- m^{-3} (World Health Organization). The EU and the USA have identified regions affected by excessive nitrate contamination and passed legislation to prevent it (i.e. Directives 2000/60/EC; USA Congress, 1978). As the main contributor to nitrate pollution is agriculture, restrictions to the use of N fertilizers and to agricultural practices that may enhance nitrate leaching have been implemented in many countries.

Nitrate leaching occurs as soil water containing dissolved nitrate drains below the root zone. Therefore leaching will be proportional to deep percolation and to nitrate concentration in the soil solution. Deep percolation will depend on the components of the water balance (rain and irrigation), on the water retention of the soil and on its hydraulic conductivity. Soils with high water retention capacity and low conductivity (e.g. fine-textured) will have therefore a lower percolation and leaching potential. Apart from soil characteristics and climatic conditions, fallow periods between successive crops in the rotation are the most dangerous for leaching. Nitrate left in the soil at harvest plus that originated from mineralization and nitrification during the fallow period is left available for leaching during drainage episodes after heavy rains. The absence of a crop extracting water and nitrate is ideal for keeping a high risk of leaching (high water content, high nitrate concentration). This has led to the introduction of "catch" crops to fill the gap of fallow periods as they reduce water content and absorb inorganic N which is thus fixed in organic form. Other possible measures for reducing leaching would be earlier plantings (to reduce fallow periods), reduce basal N applications in the autumn or use slow-release fertilizers (Chap. 23). In irrigated systems it is extremely important to follow irrigation schedules based on the water balance with corrections at the end of the season to deplete soil water as much as possible.

To evaluate the risk of leaching we may use the Leaching Index (LI, mm) which is an estimate of the amount of percolation below a soil depth of 1 m and was proposed by the USDA (Williams and Kissel 1991). The LI is calculated as the product of a Percolation Index (PI) and a Seasonal Index (SI):

$$LI = PI \cdot SI \tag{24.3}$$

The Percolation Index is calculated as:

$$PI = \frac{(P - 10160/CN' + 101.6)^2}{P + 15240/CN' - 152.4} \quad if\ P - 10160/CN' + 101.6 > 0 \tag{24.4}$$

where P is annual rainfall (mm) and CN′ is a modified curve number with values 28, 21, 17 and 15 for hydrologic groups A, B, C and D, respectively (Chap. 8). If the condition stated in Eq. 24.4 is not met then PI=0.

The Seasonal Index represents the concentration of rainfall during the winter period:

$$SI = \left(\frac{2P_w}{P}\right)^{1/3} \tag{24.5}$$

where P_w is total rainfall (mm) during autumn and winter (1 October–31 March in N latitudes, 1 April–30 September in S latitudes).

The Leaching Index is only indicative of potential losses by leaching but not of actual losses. If the LI is high, adequate crop and soil management may lead to low actual leaching. On the contrary with low LI we may expect low actual leaching independently of actual management. In other words, measures to reduce the concentration of nitrate will be very effective in reducing leaching in locations with high LI.

Example 24.4 Let's calculate the LI for two locations, Adelaide (Australia) and Dublin (Ireland) for a soil of hydrologic class A ($CN' = 28$) using the monthly rainfall shown below:

Month	1	2	3	4	5	6	7	8	9	10	11	12	Year
Adelaide, Australia	19	20	22	38	57	50	67	51	40	37	23	24	448
Dublin, Ireland	69	50	54	51	55	56	50	71	66	70	64	76	732

Applying Eq. 24.4 to Adelaide ($P = 448$ mm, $P_w = 303$) we obtain PI=41.5 mm and SI = 1.1 (Eq. 24.5) so LI=45.9 mm.

For Dublin ($P = 732$ mm, $P_w = 383$ mm) the PI=197 mm and SI = 1.02 so LI=200 mm. The risk of leaching is much higher in Dublin than in Adelaide.

We will now illustrate how we can convert LI values to approximate leaching values. Let's assume that the soil has water contents at Field Capacity and saturation, $\theta_{FC} = 0.25$ m^3m^{-3} and $\theta_{SAT} = 0.45$ m^3m^{-3}. We also assume that during percolation the soil water content is the average of those values, i.e. 0.35 m^3m^{-3}. We can compare situations of low and high nitrate content at the start of the winter period (e.g. 25 versus 100 kg N/ha in 1 m depth) by assuming that all percolation occurs during winter. The N loss by leaching can be calculated as:

$$N_{leached} = N_{init}\left[1 - \exp\left(-\frac{LI}{Z\,\theta_{mean}}\right)\right] \tag{24.6}$$

where N_{init} is the initial N content (kg N/ha), Z is soil depth (mm) and θ_{mean} is the average water content during percolation (0.35 m^3m^{-3} in this soil). Applying this equation we deduce that leaching could be between 3 and 12 kg N/ha in Adelaide and between 11 and 44 kg N/ha in Dublin. In the latter the reduction in leaching by reducing soil N would be 33 kg N/ha, while in the former the reduction would only be 9 kg N/ha.

Appendix 24.1: Nitrogen concentration in different crop species. Maximum and minimum values are shown when available. Also the dry matter content (% over fresh mass) is indicated

Cereals & pseudocereals		**DM %**	**N min**	**N max**	**N typical**		**DM %**	**N min**	**N max**	**N typical**
Barley 2 row	Grain	86.5	2.20	2.40	2.30	Straw	90.5	0.58	0.88	0.70
Barley 6 row	Grain	88.5	1.50	1.80	1.60	Straw	90	0.58	0.88	0.70
Buckwheat	Seed	94.85			2.96					
Corn	Grain	86	1.35	1.75	1.60	Stover	87	0.90	1.10	0.97
Maize	Silage	30	1.10	1.45	1.25					
Millet (finger)	Grain	90			2.20	Stover	92			0.67
Millet (pearl)	Grain	89.5			2.00	Stover	91.5			0.80
Millet (proso)	Grain	90.5			2.30		92			0.80
Oat	Grain	91	1.50	1.80	1.60	Straw	89.5	0.60	0.80	0.70
Quinoa	Seed	94.5			2.43					
Rice	Grain	94			1.33					
Rice (milled)	Grain	87.5	1.05	1.65	1.40	Straw	90	0.50	0.80	0.70
Rye	Grain	87	2.00	2.40	2.20	Straw	90.5	0.35	0.65	0.50
Sorghum	Grain	87.5	1.45	2.00	1.90	Stover	92	0.60	0.80	0.70
Sorghum	Silage	26	0.70	1.30	1.00					
Sorghum	Green	20	1.30	1.40	1.37					
Triticale	Grain	89	2.20	2.50	2.45	Straw	90	0.60	0.90	0.70
Wheat (bread)	Grain	87.5	1.85	2.30	2.10	Straw	90.5	0.40	0.85	0.65
Wheat (durum)	Grain	87.5	2.05	2.70	2.40	Straw	90.5	0.40	0.85	0.65

(continued)

Sugar, oil & fiber crops		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Castor bean	Seed	95			2.70					
Cotton	Seed	91	2.32	2.75	2.53	Residues	92.5	0.90	1.00	0.98
Flax	Seed	93.5	3.30	4.30	3.80	Straw	93	1.00	1.20	1.06
Opium poppy	Capsule	87.5	2.30	3.10	2.60	Straw	90	0.80	1.20	1.00
Rapeseed	Grain	91	3.40	4.30	3.90	Residues	82.5	0.55	0.90	0.80
Safflower	Seed	92	2.60	2.80	2.70	Residues	90			0.60
Sugar beet	Root with crown	20	1.20	1.40	1.30	Residues	18	1.80	2.80	2.30
Sugar beet	Root w/o crown	21	0.90	1.10	1.05	Residues	18	1.80	2.80	2.30
Sugarcane	Tops	25			0.13		26			0.41
Sunflower (oil)	Seed	91.5	2.20	3.20	2.95	Residues	87	0.40	1.10	0.80
Sunflower (seed)	Seed	91.5	2.80	3.60	3.20	Residues	87	0.40	1.10	0.80
Tobacco Burley	Leaf + stem	75	3.80	4.20	4.00					
Tobacco Flue	Leaves	8	2.00	2.30	2.10	Stalk	9	0.75	1.00	0.80
Legumes		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Bean (dry)	Seed	89	3.50	4.50	4.00	Straw	89	1.10	1.40	1.20
Black eyed pea	Seed	90	4.00	4.20	4.10	Straw	90			1.25
Chickpea (desi)	Seeds	89.5			3.50	Straw	89.5			0.85
Chickpea (desi)	Seeds	89.5			3.60	Straw	89.5			0.85
Faba bean dry	Grain	90	3.00	4.90	3.70	Straw	85	0.80	2.50	1.60
Groundnut	Fruits	93	4.10	4.30	4.25	Residues	90.5	1.50	1.70	1.65
Groundnut	Seeds	92	4.70	4.90	4.85	Residues	90.5	1.50	1.70	1.65
Lentil	Grain	89	4.20	4.40	4.30	Straw	91			1.10

Pea	Seed	90	4.00	4.30	4.20	Straw	88.5	1.20	1.40	1.30
Soybean	Grain	87.5	6.10	6.90	6.50	Residues	89	1.00	1.00	0.85
Forages		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Alfalfa (green, vegetative) Medicago	Biomass	25.0	3.05	4.05	3.55					
Alfalfa (green, flowering) Medicago	Biomass	25.0	2.10	3.10	2.60					
Alfalfa (hay, vegetative) Medicago	Biomass	85.0	2.80	3.80	3.30					
Alfalfa (hay, flowering) Medicago	Biomass	85.0	2.00	3.00	2.50					
Bluegrass-Kentucky (hay) Poa pratensis	Biomass	89.1			1.60					
Bromegrass (hay) Bromus sp.	Biomass	91.1			1.53					
Canarygrass-Reed (hay) Phalaris arundinacea	Biomass	89.0			1.70					
Clover-Alsike (hay) Trifolium hybridum	Biomass	87.4			2.27					
Clover-Crimson (hay) Trifolium incarnatum	Biomass	88.3			2.65					
Clover-Red (hay) Trifolium pratense	Biomass	86.1			2.51					
Clover-White (hay) Trifolium repens	Biomass	90.3			3.09					
Clover-White-Ladino (hay) Trofolium repens	Biomass	89.2			3.32					
Fescue (hay) Festuca or Lolium sp.	Biomass	90.0			1.51					
Fescue-Meadow (hay) Lolium pratense	Biomass	88.4			1.19					
Fescue-Tall (hay) Lolium arundinaceum	Biomass	91.6			2.31					
Grass (hay) Poaceae	Biomass	89.1			1.52					
Grass (silage) Poaceae	Biomass	24.9			1.84					
Millet-Foxtail (silage) Setaria italica	Biomass	27.6			1.59					
Millet-Pearl (silage) Pennisetum glaucum	Biomass	21.6			1.54					
Oat (hay) Avena sativa	Biomass	89.8			1.37					
Orchardgrass (green chop) Dactylis glomerata	Biomass	25.9			2.37					
Orchardgrass (hay) Dactylis glomerata	Biomass	89.2			1.71					
Rye (hay) Secale cereale	Biomass	92.6			1.21					

(continued)

Ryegrass-Perennial (hay) Lolium perenne ssp. perenne	Biomass	87.3			1.49					
Sweetclover (hay) Melilotus sp.	Biomass	89.6			2.65					
Timothy (hay) Phleum pratense	Biomass	90.5			1.20					
Trefoil-Birdsfoot (hay) Lotus corniculatus	Biomass	90.0			2.52					
Turnip (green chop) Brassica rapa var. rapa	Root	13.5			3.30					
Vetch (green) flowering	Biomass	25.0	2.60	3.40	3.00					
Vetch (hay) Vicia sativa	Biomass	87.8			2.60					
Vetch (hay) flowering	Biomass	85.0	2.50	3.30	2.90					
Vetch-Hairy (hay) Vicia villosa	Biomass	87.9			3.68					
Wheatgrass (hay) Poaceae	Biomass	91.6			1.34					
Horticultural crops		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Artichoke	Fruit	17	2.40	2.60	2.50					
Asparagus (green)	Stems	8	5.40	5.60	5.50					
Asparagus (white)	Stems	7	4.20	4.40	4.30					
Bean (green)	Pods	30	3.00	3.70	3.30	Straw	89	1.10	1.40	1.20
Beet	Root	12	2.10	2.20	2.15	Residues	12	3.60	3.80	3.70
Broccoli	Stems	45	3.30	3.40	3.35					
Brussels sprouts		13	4.90	5.10	5.00					
Cabbage	Cabagge	9	3.00	3.50	3.30	Residues	14	2.60	2.80	2.70
Carrot	Root	12	1.40	1.60	1.50	Leaves	16	2.30	2.40	2.35
Cauliflower		9	4.30	4.50	4.40					
Celery	Leaves	5	2.30	2.50	2.40					
Chicory	Leaves	6	3.10	3.30	3.20					
Cucumber	Fruit	4	2.40	2.60	2.50					
Eggplant	Fruits	7	2.40	2.60	2.50					

Endive	Leaves	5	4.10	4.20	4.15					
Faba bean green	Fruits	19	4.60	4.80	4.70	Straw	25			2.20
Garlic	Heads	39	2.50	2.80	2.60					1.50
Leek	Bulb	17	1.30	1.50	1.40	Leaves	20			0.90
Lettuce Iceberg	Leaves	5	2.40	2.70	2.55					
Lettuce Roman	Leaves	6	4.00	4.40	4.27					
Melon	Fruit	12	0.80	1.00	0.90					
Musk melon	Fruit	10	1.40	1.60	1.50					
Onion	Bulb	10	1.90	2.50	2.20	Leaves	8	3.80	4.10	4.00
Parsley	Leaves	10	3.30	3.60	3.50					
Pea (green)	Fruits	12.5	2.20	3.70	3.00	Straw	25	1.90	2.10	2.00
Pea (green)	Seeds	21	4.30	4.50	4.40	Straw	25	1.90	2.10	2.00
Pepper green	Fruit	10.5	2.10	2.40	2.30					
Pepper red	Fruit	12.5	1.40	2.00	1.90					
Pumpkin	Fruit	9	2.50	2.70	2.60					
Radish	Root	6	1.50	1.70	1.60					
Spinach	Leaves	9	5.10	5.30	5.20					
Squash (immature)	Fruit	5.5	2.70	3.84	3.20					
Squash (mature)	Fruit	14	0.90	1.00	0.91					
Strawberry	Fruit	9	1.10	1.60	1.35					
Sweet corn dry	Grain	90.5	1.90	2.10	2.00	Stover	91	0.90	1.10	1.05
Sweet corn fresh	Grain	35	1.50	1.70	1.60	Stover	23	1.10	1.30	1.20
Tomato	Fruit	6	2.30	3.10	2.60		20			1.80
Fruit trees, vines and shrubs		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Watermelon	Fruit	9	1.00	1.50	1.25					
Almond	With hull	85	3.00	3.60	3.30					

(continued)

Apple	Fruit	18	0.25	0.45	0.35					
Apricot	Fruit	14	1.50	1.70	1.65					
Avocado	Fruit	27	1.10	1.30	1.20					
Banana	Fruit	26	0.60	0.70	0.65					
Cherimoya	Fruit	26	0.70	0.90	0.78					
Cherry	Fruit	19	1.00	1.20	1.07					
Date palm	Fruit	77	0.35	0.45	0.40					
Fig	Fruit	21	0.50	0.60	0.57					
Grape	Fruit	19	0.50	0.60	0.57					
Grapefruit	Fruit	11	0.70	0.80	0.75					
Hazel nut	Fruit	94.5	2.10	2.30	2.20					
Kiwi	Fruit	17			0.80					
Lemon	Fruit	13	1.30	1.70	1.50					
Mango	Fruit	18			0.50					
Oil palm	Kernel	79			1.25					
Olive	Fruit	50	0.20	0.40	0.30	Vegetative	70	1.00	2.00	1.50
Orange	Fruit	18	1.00	1.40	1.20					
Peach	Fruit	12	0.80	1.20	1.00					
Pear	Fruit	18	0.30	0.50	0.40					
Persimmon	Fruit	20			0.55					
Plum	Fruit	15	0.80	0.90	0.85					
Pomegranate	Fruit	25			0.60					
Quince	Fruit	16			0.54					
Walnut	Fruit	93			0.20					

Roots, tubers & bulbs		**DM** %	**N min**	**N max**	**N typical**		**DM** %	**N min**	**N max**	**N typical**
Cassava	Root	68.8			0.42					
Chinese yam	Tuber	59.3			1.39					
Potato	Tuber	23.5	1.20	1.90	1.60	Residues	51	2.00	2.40	2.20
Sweet potato	Tuber	65			0.88					
White yam	Tuber	63.1			0.94					
Yellow yam	Tuber	58.3			0.99					

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Chapter 25
Nitrogen Fertilization II: Fertilizer Requirements

Miguel Quemada, Antonio Delgado, Luciano Mateos, and Francisco J. Villalobos

Abstract The N balance allows the calculation of the fertilizer requirement which depends on the amount of N absorbed by the crop, the amount of inorganic N in the soil or produced by mineralization and N losses of the system, which are quantified by the Recovery Efficiency. A fertilization plan should take into account the variability of environmental factors, especially rain, to distribute the N with flexibility to match the specific conditions of each year. Doing so we will avoid yield reductions due to N deficiency and the negative environmental impacts by excess application. Fertilization of trees should be based on the nutrient balance (mature trees) or the growth rate expected from actual transpiration.

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25.1 Calculation of N Fertilizer Doses Using the Nmin Method

As stated in Chap. 24, crop response to N fertilization is very dependent on the amount of available N (essentially inorganic N) present in soil before fertilization. Thus, it can be expected low N fertilizer needs when a large amount of available N is present in the soil. Nmin methods are based on the amount of mineral N present in the soil at the end of winter, recommending decreased N rates with increasing levels of available N in the soil. To implement this method, it is necessary to establish a relationship between the economic optimum N rate for a crop and the amount of mineral N in the soil at a given depth at the beginning of the crop cycle in a given geographical area with similar environment (soil + climate) and crop management. To establish this relationship it is necessary to conduct a network of trials in various locations including different levels of mineral N in the soil. The model fitted is:

$$N_f = A_f - B_f N_{min} \tag{25.1}$$

where N_f is the optimum economic dose of N, the parameter A_f represents the total N needed by the crop for these given environmental and management conditions, and B_f is the amount of N provided by the soil per unit N content in the sampled soil depth (N_{min}). Thus, this model for estimating N rates represents the difference between the required mineral N by the crop and the amount actually delivered by the soil.

Sometimes, the method is simplified by only determining soil nitrate, since most of inorganic nitrogen is in nitric form at the end of the winter, but care should be taken as ammonium may be relevant after cold winters or in acid soils. Another common simplification is taking soil samples for inorganic N analysis only in the top layer (i.e. 30 cm depth) and use it as a surrogate of the N supply potential of the whole soil. However, it is recommended to sample the depth of the effective nutrient uptake by the crop. These methods have being applied with success in Europe (N_{min} method) and also in the USA, where it is known as “preplant nitrate test” (PPNT).

Some additional factors have to be considered when this method is used to estimate the requirement of N fertilizer:

- Winter crops: at the end of winter (before applying topdressing) the soil is analyzed to determine N_{min} and adjust the N rate. If the expected crop growth during winter is small, basal N fertilizer application is not recommended to avoid nitrate losses by leaching or denitrification. In warm areas where crop growth and N uptake are important before topdressing, a small fraction of fertilizer (15–30 %) might be applied before planting.
- Spring crops: analysis and estimation of the dose is based on N_{min} determination before planting and the fertilizer is split in a pre-planting application and

topdressings during the growth cycle, as performed for sugar beet in several Northern European countries or for maize in South Europe.

- The method is only valid for environmental and management conditions for which it has been developed. Changes in management, such as adding manure amendments or incorporation of crop residues may require adapting the recommendation.

25.2 Calculation of N Fertilizer Doses Using the N Balance

The estimation based on nutrient mass-balance can be the recommended strategy for mobile nutrients, such as N, which are not efficiently retained in soils and can be lost through leaching or gaseous emissions. It should be remarked that the mass-balance approach is targeted to preplant estimates of N needs. For N, the increase in soil inorganic N, i.e. the difference between final (N_{end}) and initial (N_i) soil N content, for a non-leguminous crop cycle may be written as:

$$N_{end} - N_i = N_f + N_m + N_{irr} + N_{dep} - N_c - N_l - N_d - N_v \tag{25.2}$$

where N_f, N_m,N_{irr} and N_{dep} are N inputs as fertilizer applied, mineralized, and N in irrigation water and atmospheric deposition, respectively. The outputs are N absorbed by the crop, N lost by leaching, N lost by denitrification and N lost by ammonia volatilization. The N balance equation can be simplified to:

$$N_{end} - N_i = N_f + N_m + N_{other} - (N_{biom} + N_{root}) - N_{loss} \tag{25.3}$$

where N_{loss} includes all losses of N, and N_{other} includes other minor inputs (irrigation, deposition). The equation now shows the two components of crop N: that accumulated in aboveground biomass (N_{biom}) and that accumulated in roots (N_{root}).

25.2.1 Crop N Uptake (N_c)

Crop N content of the aboveground biomass (N_{biom}, kg N/ha) is calculated as a function of expected aerial biomass production (yield and residues) and N concentration of biomass components:

$$N_{biom} = Y \cdot NC_{yield} + (B - Y)NC_{res} = Y\left(NC_{yield} + \frac{1 - HI}{HI} NC_{res}\right) \tag{25.4}$$

where Y is yield (kg/ha), B is aerial biomass (kg/ha), HI is harvest index and NC_{yield} and NC_{res} are N concentrations in the harvested organ and the residues, respectively. To calculate total N accumulated by the crop (N_c) we need to add the N accumulated in roots as follows:

$$N_c = N_{biom}\,(1 + f_{NR}) = \left(N_{yield} + N_{res}\right)(1 + f_{NR}) \tag{25.5}$$

where f_{NR} is the ratio of N in roots and N in shoots and N_{yield} and N_{res} are the amounts of N in yield and residues, respectively.

If biomass is overestimated, the same will happen with N applied and N losses will occur. On the other hand, under predicting biomass will lead to insufficient N and thus, N will become the limiting factor for yield. Usually, N in roots accounts for 5–25 % of N in aboveground biomass, so values of 15–20 % can be considered acceptable for field crops, and up to 25 % for horticulture crops.

The estimated yield (also called target yield) should be based on previous years' yields with inputs similar to those the farmer intends to use. If this species has not been previously cultivated, the yield should be estimated based on yields from neighboring farms, always making sure that there were no limiting production factors unrelated to those in our crop. Additionally, for N it is always useful to set the maximum and minimum expected yields to establish maximum and minimum values of N_c and so decide the most appropriate strategy, which we will discuss later.

The crop N concentration can be determined *a posteriori* by analyzing the biomass produced. However, to design the fertilization program it is necessary to have estimates of N concentration a priori. Table 24.1 lists the N concentrations referred to dry matter for different crop species. In years when we plan to apply less N than needed or when other factors are not limiting (rainy year or under irrigation), we must choose the lower values of the ranges given in Table 24.1. In all cases it should be noted that the values refer to dry matter, so estimated yields should be corrected according to the expected moisture content (Table 24.1).

25.2.2 Initial and Final Soil N and Mineralization

The initial soil inorganic N content can vary greatly and values between 30 and 500 kg N/ha in the upper 1 m soil have been reported. The common strategy will seek to deplete soil N during the crop cycle, i.e. try to make the final soil inorganic N (N_{end}) as low as possible. The N_{end} is also called the residual N and below a threshold value (between 10 and 70 kg N/ha depending on soil texture and depth) it cannot be recovered by the crop. Determinations of inorganic N in the soil should include both NO_3^- and NH_4^+. However, the concentration of NO_3^- is usually high relative to that of NH_4^+ so we may analyze only NO_3^- concentration to determine N_i.

Mineralization of soil organic matter may be an important source of N. The N mineralized during the crop campaign is the net result of the mineralization of the stable organic matter and the residues and roots from the previous crops. This contribution is hard to estimate, so a common approach is assuming that the soil is in steady state and to calculate the soil N supply as the addition of the N in the residues and the roots of the previous crop. Management factors such as tillage, irrigation or application of manure, can greatly modify the steady state and produce pulses of N mineralization that should be taken into account to profit from the N supply and avoid pollution problems. For calculation purposes we can group initial N and N mineralized during the current season into a single component (N_{i+m}) which should be proportional to the amount of N in residues from the previous crop (N'_{res} in shoots and N'_{root} in roots):

$$N_{i+m} = k_{im} F_{res} N'_{res} + N'_{root} = k_{im} F_{res} N'_{res} + f_{NR} \left(N'_{yield} + N'_{res} \right) \tag{25.6}$$

where F_{res} is the fraction of residues that are left in the field, and N'_{yield} and N'_{res} refer to N accumulated in the harvest organ and residues of the previous crop, respectively. The coefficient k_{im} has a maximum value of 1, if all the aboveground residues are mineralized with no loss. Lower values are expected if the residues are not incorporated by tillage or when the N concentration in residues is low. We propose $k_{im} = 0.9$ for legumes with tillage, 0.7 for legumes left on the ground and for non-legumes with tillage and 0.5 for non-legumes left on the ground. Note that N in roots is assumed to be fully available and can be calculated as a function of N in aboveground biomass of the previous crop.

25.2.3 Fertilizer Requirement Calculation According to N Balance

From Eqs. 25.5 to 25.6 we may deduce the following formula for calculating N fertilizer requirements:

$$N_f = \frac{N_{end} + (1 + f_{NR})\left(N_{yield} + N_{res}\right) - k_{im} F_{res} N'_{res} - f_{NR}\left(N'_{yield} + N'_{res}\right) - N_{other}}{(1 - n)} \tag{25.7}$$

N_{other} is the total N received by atmospheric deposition (5–10 kg N/ha, as a conservative value) and irrigation water. The coefficient *n* is the fraction of applied N lost (leaching, volatilization, denitrification) and f_{NR} is the ratio N in roots/N in shoots.

This model assumes that most of soil N supply (N_m and N_i) and N in irrigation water and atmospheric deposition are taken up by crops with no losses. There are several ways to calculate the efficiency of fertilization. The most commonly used, which we may call E_f, is the fraction of applied N that is finally accumulated in the aerial part of the crop, and is equal to the slope of the relationship between N uptake and N applied (Chap. 24, Fig. 24.6). However, this definition does not take into account N in roots and the fact that a fraction of the N left in the soil at the end of the growing cycle may be available for the next crop in the rotation. This explains why measured values of E_f are typically in the range 0.4–0.75, and values between 0.5 and 0.7 are usually acceptable. A second definition of efficiency (E_{fR}) would include roots, so it would be the fraction of total N applied that is accumulated in the crop shoots and roots. In mathematical terms:

$$E_{fR} = E_f(1 + f_{NR}) = 1 - n \tag{25.8}$$

With $f_{NR} = 0.2$, this equation implies that the normal range of E_{fR} is 0.5–0.9. So if we aim at $E_f = 0.6$–0.7, then our aim is $E_{fR} = 0.7$–0.85.

Besides agronomic considerations in some cases we will have to take into account other environmental constraints. In several countries, the amounts and types of N fertilizer have been restricted by law to prevent nitrate pollution.

The N balance and other methods to estimate crop N requirement are intended to achieve an optimal N supply for optimal yields, which depends on environmental conditions. However, depending on the ratio of fertilization cost to crop value, estimated requirements can be modified. When fertilizer prices rise, maximum profit is obtained with fertilization rates lower than those estimated as optimal. Estimated high N rates expecting high yields can lead to increased N losses or high amounts of residual N remaining in the soil after crop harvest if conditions are not suitable for optimal crop performance.

Example 25.1 A cereal crop is grown as monoculture on an acid soil with the following distribution of yields:

2000–3000 kg/ha in 40 % of the years
3000–4000 kg/ha in 30 % of the years
4000–5000 kg/ha in 20 % of the years
5000–6000 kg/ha in 10 % of the years

The average yield is therefore 3500 kg/ha.

We assume that all the residues of the previous crop stay in the field ($F_{RES} = 1$) and are incorporated by tillage. So $k_{im} = 0.7$.

The concentration of N is 1.5 % in grain and 0.5 % in straw. The Harvest Index is 0.5. The water content of grains is 10 %. We assume $f_{NR} = 0.2$, $N_{other} = 5$ kg N/ha. Our aim is $E_{fR} = 0.85$ (losses of denitrification and volatilization are very low in acid soils) and $N_{end} = 25$ kg N/ha.

How would we modify the cereal N fertilizer strategies if faba bean (dry yield 1500 kg/ha, HI = 0.3) is introduced as a preceding cash crop?

(continued)

Example 25.1 (continued)

(a) For each interval of yield (taking the midpoint) we calculate the N fertilizer requirement. For instance for yield 2500 kg/ha:
N_c (N uptake):

$$\begin{aligned}&\text{Yield (dry matter)} = 2500(1-0.1) = 2250\,\text{kg/ha}\\&\text{Residues} = \text{Y}\cdot(1-\text{HI})/\text{HI} = 2250\,\text{kg/ha}\\&\text{N}_{\text{yield}} = \text{Y}\cdot\text{NC}_{\text{y}} = 2250\cdot 0.015 = 33.75\,\text{kg N/ha}\\&\text{N}_{\text{res}} = 2250\cdot 0.005 = 11.25\,\text{kg N/ha}\end{aligned}$$

We asume that the previous wheat crop had an average yield (3500 kg/ha)

$$\begin{aligned}&\text{Yield (dry matter)} = 3500(1-0.1) = 3150\,\text{kg/ha}\\&\text{Residues} = \text{Y}\cdot(1-\text{HI})/\text{HI} = 3150\,\text{kg/ha}\\&\text{N}'_{\text{yield}} = \text{Y}'\cdot\text{NC}_{\text{y}} = 3150\cdot 0.015 = 47.25\,\text{kg N/ha}\\&\text{N}'_{\text{res}} = 3150\cdot 0.005 = 15.75\,\text{kg N/ha}\end{aligned}$$

$$N_f = \frac{25+(1+0.2)(33.75+11.25)-0.7\cdot 1\cdot 15.75-0.2(47.25+15.75)-5}{0.85}$$

$$= 59\,\text{kg N/ha}$$

For the other yield values we will have:

For $\text{Y} = 3500$ kg/ha: $\text{N}_\text{f} = 85$ kg N/ha
For $\text{Y} = 4500$ kg/ha: $\text{N}_\text{f} = 110$ kg N/ha
For $\text{Y} = 5500$ kg/ha: $\text{N}_\text{f} = 135.5$ kg N/ha

(b) Possible strategies:

- Apply 59 kg N/ha every year. The crop would always be limited by N and we would have an average yield of 2500 kg/ha so the average exported N would be $2500 \times 0.015 = 37.5$ kg N/ha. The ratio N exported/N applied would be 0.64.
- Apply 85 kg N/ha every year. In the best case yield would be 3500 kg/ha. The average yield is then:

$$0.4\cdot 2500 + 0.6\cdot 3500 = 3100\,\text{kg/ha}$$

  So the average exported N would be 46.5 kg N/ha and the ratio N exported/N applied would be 0.55.
- Apply 110 kg N/ha every year. The average yield is then:

$$0.4\cdot 2500 + 0.3\cdot 3500 + 0.3\cdot 4500 = 3400\,\text{kg/ha}$$

  So the average exported N would be 51 kg N/ha and the ratio N exported/N applied would be 0.46.

(continued)

Example 25.1 (continued)

– Apply 135.5 kg N/ha every year. The average yield is then:

$$0.4 \cdot 2500 + 0.3 \cdot 3500 + 0.2 \cdot 4500 + 0.1 \cdot 5500 = 3500\,\mathrm{kg/ha}$$

The average exported N would be 52.5 kg N/ha and the ratio N exported/N applied would be 0.39.

The best strategy would depend on the price of the grain and the cost of fertilizer. In any case it is always better to follow a flexible strategy, i.e. basal application lower than 59 kg N/ha and then apply a top dressing 2 months later. The latter would be omitted if the year came bad, and would be between 26 and 76 kg N/ha depending on the actual conditions of the year. By following a flexible strategy, if we can exactly match the N requirements of each type of year we would apply an average amount of N:

$$0.4 \cdot 59 + 0.3 \cdot 85 + 0.2 \cdot 110 + 0.1 \cdot 135.5 = 84.7\,\mathrm{kg\ N/ha}$$

While the average exported N is 3500·0.015 = 52.5 kg N/ha and the ratio N exported/N applied would be 0.62.

(c) After the faba bean crop, the available N at wheat sowing will increase. Measurement of soil N before sowing would allow quantification of this N supply. If the measurement is not available, we can calculate the fertilizer requirement after faba bean. First we calculate N in yield and residues of the faba bean:

$$\mathrm{N}'_{\mathrm{yield}} = \mathrm{Y\ NC_y} = 1500 \cdot 0.037 = 55.5\,\mathrm{kg\ N/ha}$$
$$\mathrm{N}'_{\mathrm{res}} = \mathrm{Y} \cdot (1 - \mathrm{HI})/\mathrm{HI} \cdot \mathrm{NC_r} = 1500 \cdot 0.7/0.3 \cdot 0.016 = 56\,\mathrm{kg\,N/ha}$$

$$N_f = \frac{25 + (1 + 0.2)(33.75 + 11.25) - 0.9 \cdot 1 \cdot 56 - \ 0.2(55.5 + 56) - 5}{0.85}$$
$$= 1.5\,\mathrm{kg\,N/ha}$$

Which is almost zero, i.e. no fertilizer should be applied. The amount of N to apply for the other yield classes will be 27, 52 and 78 kg N/ha. Therefore, the basal N application to wheat could be avoided and the topdressing between 27 and 78 kg N/ha would be applied 2 months later.

The N fertilizer savings provided by the introduction of the faba bean would be added to other agronomic advantages of a crop rotation. The faba bean income will probably be lower than that of the cereal, but the introduction of the legume crop every 2 or 3 years may increase the sustainability of the cropping system in the midterm.

25.3 Within-Season Methods for Improved Nitrogen Management

The well-known spatial and temporal variability of processes affecting soil N represents a relevant limitation on the accuracy of approaches based on the N-balance, which is a preplant estimation of N needs for the whole crop cycle. To overcome this limitation, within-season monitoring approaches have been proposed based on the improvements of tools and methods for improving N requirements estimation. These strategies measure the N status of the soil or the crop during the season, assessing the need for additional N, or recommending specific rates of supplemental N. They usually involve multiple N applications and allow the change of fertilizer rates depending on actual measurements of soil or crop N status. Thus, these methods involve a dynamic strategy able to adapt to environmental conditions during the crop season.

The most classical method is the pre-sidedress nitrate test (PSNT), performed for corn in the USA. It is a type of N_{min} method based on a soil nitrate analysis (30 cm depth) when plants are 20–30 cm tall. It represents a point-in-time assessment of the spring accumulation of NO_3^- before the crop begins the rapid growth phase. The PSNT method takes into account the remaining residual N from the previous crops, N mineralization and N losses before the date of sampling, just before large amounts of N are required by the crop.

In addition to the methods based on soil available N, there has been a major development in sensors to determine crop nutritional N status to adjust fertilizer rates during growing season. The sensors are based on the determination of transmittance or reflectance of a leaf or the crop canopy at various wave-lengths and can be hand-held or tractor mounted. If other growth factors are known, readings can be related with chlorophyll activity and therefore with crop N status. Comparing with a well fertilized band a sufficiency index (ratio of crop reading/ well fertilized crop reading) can be developed and used to apply variable rates.

25.4 Fertilization of Fruit Trees

25.4.1 Mature Orchards

Mature trees are very efficient in translocating N to reserves (e.g. before leaf fall in deciduous species) which will be later made available for new growth. Therefore in mature orchards the calculation of crop N should only consider the amounts of N exported in yield, or lost by pruning and leaf fall:

$$N_c = Y\, C_{N\,fruit} + B_{pruning} C_{N\,shoots} + B_{leaf\,fall} C_{N\ senesced} \tag{25.9}$$

Values of N concentration in fruits are presented in Table 24.1. The concentrations for shoots and senesced leaves may be taken as 1 %. The amount of leaf fall will be equal to total leaf biomass for deciduous trees and around 50 % of leaf biomass for evergreens with leaf life span around 2 years. Note that this is a conservative estimate of crop N uptake as N in pruning residues is only lost when they are burned. The total vegetative biomass production in the growing season (B_v) is the sum of those in pruning, senesced leaves and growth of permanent structures (trunk, main branches). Then, using the definition of harvest index we may write:

$$B_{pruning} + B_{leaf\ fall} = \beta_{pl} \frac{1 - HI}{HI} Y \tag{25.10}$$

where β_{pl} is the fraction of B_v not used in permanent structures. This parameter is very high (0.8–0.9) for most deciduous species and for evergreens under intensive management. Therefore, now we can simplify Eq. 25.6 to:

$$N_c = Y \left[C_{N\ fruit} + \beta_{pl} \frac{1 - HI}{HI} C_{N\ pl} \right] \tag{25.11}$$

where $C_{N\ pl}$ is the average concentration of N in pruning residues and senesced leaves, that may be taken as 1 %. Data on HI of fruit crops indicate that it is usually above 0.5, so if no information is available for a given species we may take a value of 0.6.

To calculate the amount of fertilizer to apply we need to consider the fate of the pruning residues. If they are burned or exported only leaf fall remains on the soil which will give back mineral N after mineralization some time later. In the best case, with zero losses of N from the system, we will recover all N from senesced leaves. Therefore, the minimum amount of fertilizer to apply if residues are burned or exported will be:

$$N_f = \frac{1}{E_{fR}} \left[N_c - 0.5 Y \beta_{pl} \frac{1 - HI}{HI} C_{N\ pl} \right] = \frac{Y}{E_f} \left[C_{N\ fruit} + 0.5 \beta_{pl} \frac{1 - HI}{HI} C_{N\ pl} \right] \tag{25.12}$$

If residues are incorporated then the minimum amount to apply reduces to Y $C_{N\ fruit}/E_{fR}$.

Example 25.2 An irrigated vineyard yields 25 t/ha of table grape. Water content is 80 % (Table 24.1) so yield is 5 t dry matter/ha. N concentration in fruits is 0.6 % (dry matter basis). Now, using Eq. 25.9:

$$N_c = 5000 \left[0.006 + 0.9 \frac{0.4}{0.6} 0.01 \right] = 60\,\mathrm{kg} \frac{\mathrm{N}}{\mathrm{ha}}$$

Assuming $E_f = 0.8$, if pruning residues are incorporated then the minimum fertilizer amount would be 37.5 kg N/ha. If residues are exported we should

(continued)

Example 25.2 (continued)

apply at least 56 kg N/ha. In any case fertilizer amounts should not exceed 60/0.8 = 75 kg N/ha. A well established cover crop (e.g. legume or legume/grass mixture) could fix enough N to supply or reduce vineyard requirements. A fraction of the N content in the residues would be available for the vineyard during the growing season after the cover crop is mowed (50 %) or soil incorporated (70 %).

25.4.2 Young Trees

For young orchards we have also to include the demand of vegetative growth, which depends on age, species and environmental conditions. It is not easy to calculate the increase in standing biomass of young trees. For some species empirical relations have been established between tree biomass and trunk diameter. A more general and simple approach is to relate canopy growth to transpiration using the Water Use Efficiency, extending Eq. 14.8 to the whole growing season:

$$\Delta B = \sum_0^T E_{p\ tree} \frac{\alpha_w}{VPD} \tag{25.13}$$

where T is the duration of growth, while transpiration is proportional to ET_0, the relative intercepted radiation (f_{IR}) and the transpiration coefficient for full ground cover (K_{tf}) (see Eq. 9.20). Therefore:

$$\Delta B = \sum_0^T \frac{\alpha_w}{VPD} ET_0\ RR_i\ K_{tf} \tag{25.14}$$

Finally we calculate the N uptake (N_c, g N/tree) required for that increase in biomass assuming a high N concentration (2 %) which is an upper boundary for biomass of young trees:

$$N_c = 0.02 \sum_0^T \frac{\alpha_w}{VPD} ET_0\ RR_i\ K_{tf} \tag{25.15}$$

For young trees the amount of fertilizer to apply should match the expected uptake, using a proper value of efficiency.

Example 25.3 In example 3.5 we calculated the relative interception of an olive tree with radius 0.5 m in Cordoba, Spain on 21 March as $RR_i = 0.69\ m^2$. If ET_0 is 3 mm day^{-1}, taking a value of $\alpha_w = 7.5$ g kPa L^{-1} (Chap. 14) and $K_{tf} = 1$, with VPD=1.5 kPa:

$$N_c = 0.02 \sum_0^T \frac{\alpha_w}{VPD} ET_0\ RR_i\ K_{tf} = 0.02\,\frac{6.5}{1.5}\ 3 \cdot 0.69 \cdot 1 = 0.18\ \frac{g\ N}{tree}$$

Assuming E = 0.8, the amount of N fertilizer should be 0.18/0.8 = 0.23 g N/day/tree.

A similar approach for fertilizing young trees with N may be taken for P and K by applying the proper concentrations. For deciduous trees we may use 0.2 % of P and 0.9 % of K. For evergreen trees the values are 0.12 % P and 0.9 %K.

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Chapter 26
Fertilization with Phosphorus, Potassium and Other Nutrients

Antonio Delgado, Miguel Quemada, Francisco J. Villalobos, and Luciano Mateos

Abstract Phosphorus and potassium are important nutrients whose management has some common characteristics since both are non-mobile nutrients in the soil. Most of P and K in the soil is not available to plants. Reactions involved in their cycle in the soil imply that only part of applied nutrients remain available for plants (retrogradation). Adequate fertilizer management must be designed for maximum recovery of applied P and K, which means that retrogradation is not favored. To this end, alternatives to basal broadcast application should be taken into account, such as banding or fertigation applications. Since both nutrients are non-mobile the risk of leaching is very low. Therefore, management strategies for both nutrients may be designed at medium- and long-term periods, contrasting with N, whose management strategies were designed for short-term periods for each crop. The achievement of high efficiencies in P and K fertilization is gaining interest since both nutrients are considered non-renewable resources. An example of what could happen with the progressive depletion of reserves was the "P crisis" in 2008, when the price of phosphate rock was multiplied by three due to the shortage of exportations from China.

Other nutrients are usually applied when deficiency is expected (sufficiency strategy). Deficiencies in Ca and Mg can be expected in acidic soils; Mg

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deficiencies can be also promoted by high Ca saturation in the exchange complex or by excessive K fertilization. Micronutrient availability is not only limited by the amounts in the soil, but also by soil properties affecting plant root functioning in acquiring and absorbing these nutrients.

26.1 Introduction: Phosphorus and Potassium as Essential Nutrients

Phosphorus and potassium are the two primary nutrients which are considered non-mobile in the soil (see Chap. 2). Both nutrients applied as fertilizer are quickly fixed in the soil through different process. This means that, in contrast to N, leaching risk is not significant in most soils, except in those with very low fixing capacity (e.g. very sandy soils). On the other hand, retention reactions in soils imply that only a fraction of applied fertilizer remains available for plants. As for N, fertilizer management must be focused on achieving the maximum efficiency in applied fertilizer. To this end, in the case of N it was very relevant to reduce the risk of loses, mainly through leaching; in the case of P and K, fertilizer management must be focused on minimizing the fraction of applied nutrient that is finally fixed in the soil as non-available forms.

Under a non-limiting N supply, in terrestrial and aquatic systems, P is usually the limiting nutrient for plant growth. Phosphorus is involved in many biological processes, including relevant structural functions as part of nucleic acids or phospholipids in membranes. It has also a key role in metabolic reactions, particularly those involved in energy transfer (phosphorilation reactions). Plants absorb phosphorus actively and only in the forms $H_2PO_4^-$ and HPO_4^{2-}, with the second showing much slower absorption rates.

Phosphorus deficiency has a significant impact on crop growth. Given the high mobility of P within the plant, deficiency symptoms are first detected in older leaves that senesce prematurely. In P-deficient plants, purple color in leaves due to the accumulation of anthocyanic pigments is usual. Normal concentrations in leaves vary greatly among species in the range of 0.05–0.3 % P (dry matter basis) (Table 26.1).

High P fertilizer rates can lead to an enrichment of the soil in this nutrient. This can have adverse consequences not only for crops, such as the increased risk of Zn and Fe deficiencies, but also on the neighbor ecosystems. Excessive enrichment in P of agricultural soils may promote high loses of this nutrients to water bodies mainly bound to eroded particles. High P concentration in surface water triggers the growth of algae and weeds which results in the eutrophication of surface waters. Therefore soil erosion may have a large effect on P losses from the soil and pollution of surface water by the transported sediment.

Table 26.1 Critical concentration and sufficiency range for P, K, Ca and Mg in leaves or shoots of crops

		Nutrient concentration (% over dry mass)					
		P		K		Ca	Mg
Crop	Stage	Critical	Adequate	Critical	Adequate	Adequate	Adequate
Cotton	45 DAS		>0.4		>3.2		0.65–0.8
Faba	Flowering	0.19–0.24	0.3–0.55	1.8–2	2.2–4	0.6–1.2	0.24–0.5
Linseed[a]	53 DAS		0.37–0.69		2.5–3.5	0.96–1.7	0.36–0.65
Oat	Tillering	0.24–0.29	0.3–0.5	4.3–4.9	5–5.7	0.21–0.4	0.13–0.3
Rice[a]	Tillering		0.37–0.55	1.6	1.6–3	0.1–0.30	0.14–0.21
Sugar beet	50–80 DAS	<0.45	0.45–1.1	2	2.0–6.0	0.5–1.5	0.25–1
Wheat	Tillering	<0.35	0.35–0.49	<2.3	2.4–4	0.21–0.4	0.13–0.3
Apple	Summer	0.10–0.14	0.15–0.2	0.8–1.1	1.2–1.5	1.1–2.0	0.21–0.25
Apricot	Summer	0.09–0.13	0.14–0.25	1.0–1.9	2.0–3.5	2.0–4.0	0.30–0.85
Citrus spp.		0.09–0.11	0.12–0.16	0.4–0.69	0.7–1.5	3.0–6.0	0.26–0.60
Olive	Summer		0.1–0.3	0.4–0.8	>0.8	>1.0	>0.1
Peach	Summer	0.09–0.13	0.14–0.25	1.0–1.9	2.0–3.0	1.8–2.7	0.30–0.80
Pear	Summer	0.10–0.13	0.14–0.20	0.7–1.1	1.2–2.0	1.5–2.2	0.3–0.5

DAS days after sowing

[a] Whole shoot

Potassium is absorbed actively as an ion. The absorption is controlled by the internal concentration. Once absorbed it is transported mainly to young growing tissues. Potassium has a role as osmoregulator and is involved in stomatal control. It indirectly promotes photosynthesis and transport of assimilates, and has a direct action on the activity of some important enzymes. Potassium is also involved in plant tolerance to cold and water stress.

Symptoms of potassium deficiency are unclear and when they appear, the crop has already suffered a negative effect. Being mobile, the deficiency symptoms appear first on older leaves. Table 26.1 provides guidance on the usual and threshold concentrations of K in leaves of different crops.

Phosphorus and potassium are considered as non-renewable resources because their fertilizer production comes ultimately from mining. This contrasts with the case of N because the atmosphere is a near-infinite source of this nutrient for fertilizer production. Phosphorus and potassium reserves are finite and their demand will increase in the next decades due to the need of increasing agricultural production to meet the requirements of an increasing population in the World. Under this perspective, prices of P and K fertilizers are expected to increase sharply in the next future. Beside this, P can be considered a strategic resource since most of the known reserves are in only three countries (USA, Morocco and China). Thus, the need of a rational management of P and K is a basic requirement to ensure sustainability of agricultural production in the next decades.

26.2 P in the Soil

Phosphorus is not a major element present in soil since it is not part of commonly abundant soil minerals, its total concentration in the soil being usually less than 1 g/kg. It is mainly present as phosphate, which can be found in organic (basically esters) or mineral forms. Both mineral and organic forms can be found in the soil solution or bound to the solid fraction. As indicated above, inorganic phosphate (dissociate forms of orthophosphoric acid) is the form in which plants take up P; in the soil solution it is in equilibrium in a more or less reversible way with specifically adsorbed forms (see Sect. 2.4.3) on hydroxylated surfaces (Fe and Al oxides and, to a lesser extent, borders of clay minerals and carbonates) and with precipitated metal phosphates (mainly Fe, Al, and Ca phosphates, depending on soil pH). Thermodynamically stable metal phosphates, such as apatite type in soils with high pH and high Ca saturation, are insoluble thus contributing little to P in the soil solution; other less stable precipitates can be present in a lesser extend which can contribute more to P in solution (Fig. 26.1). Precipitation as insoluble metal phosphates and adsorption reactions explain that a minor part of applied P as fertilizers remains available to plants. Organic forms are mainly phosphate-monoesters and phosphate-diesters, and they may be also adsorbed, sometimes more strongly than inorganic phosphate, and they can precipitate as well. As in the case of N and other elements, phosphorus can be used by soil microorganisms and be immobilized, at

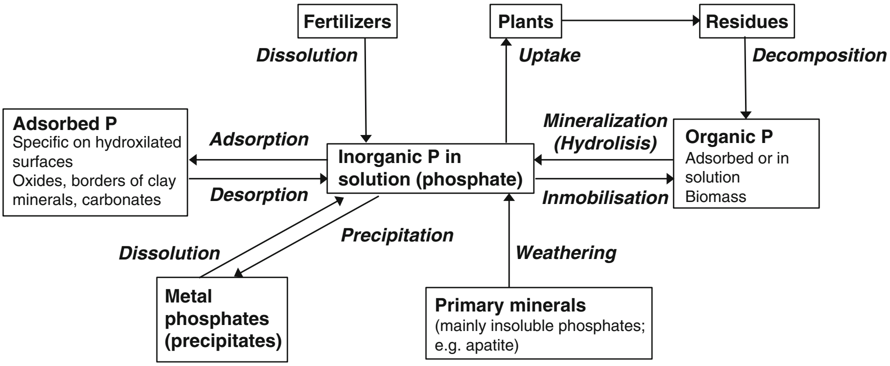


Fig. 26.1 P cycle in the soil. In italics: physical, chemical or biological processes involved in nutrients cycle

least temporarily. The reverse process, mineralization, requires the hydrolysis of ester bounds which is catalyzed by different types of phosphatases, which can be produced by plant roots and some soil microorganisms. Organic P may account for a significant fraction of the total P in the soil (usually between 20 and 80 % in agricultural soils) even in Mediterranean soils with low organic matter concentration.

Phosphorus concentration in the soil solution is usually very low, typically less than 1 mg/L in agricultural soils, forcing its replenishment from adsorbed or precipitated forms as plants absorbs it. The relationship between adsorbed P and P in the soil solution is determined by the P buffer capacity of soil, which depends, among other factors, on the adsorption capacity of the soil (Fig. 26.2). A high buffer capacity indicates a good ability of the soil to replenish P of the solution as it is absorbed by the crop. If the buffer capacity is low, the concentration of P in the solution may be high, but the soil's ability to replenish that used by the crop is limited. On the other hand, the P supplied as fertilizer initially passes to the soil solution, but will shift to fixed forms more the higher the buffer capacity. This means that for restoring a deficiency of P in the solution we need to provide higher doses of fertilizer the higher the soil buffer capacity.

The degree of ionization of phosphates depends on the pH (Fig. 26.3). In acid soils monovalent ions predominate while in neutral soil the ratio between monovalent and divalent forms is about 1:1. Plants absorb only $H_2PO_4^-$ and HPO_4^{2-}, and the latter much more slowly. Therefore, the absorption of P is faster in acid soils. Plants can secrete organic acids to the rhizosphere which release adsorbed P and dissolve precipitated P, and phosphatases that contribute to mineralize organic P. Besides this, the interaction between plants roots and microorganisms in the rhizosphere is very relevant in P uptake by plants because microorganisms can release organic acids and phosphatases. Symbiotic mycorrhizae can also enhance P uptake by plants by increasing the absorption surface for P.

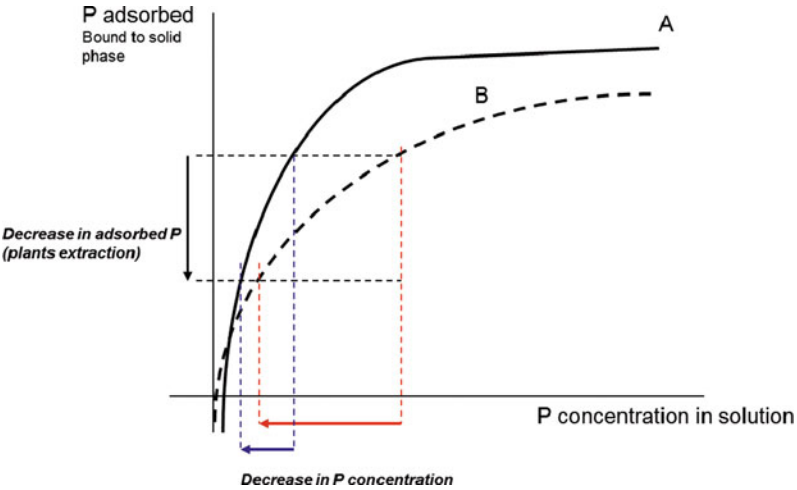
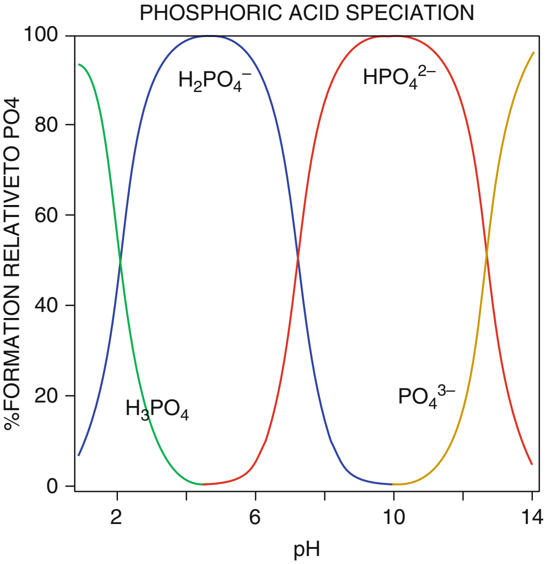


Fig. 26.2 Consequences of P buffering capacity in soils: A soil with high buffering capacity; B (*dotted line*) with low buffering capacity; *red arrow* represents the decrease in P concentration in solution for soil B, and *blue arrow* the decrease in soil A for the same decrease in adsorbed P

Fig. 26.3 Phosphoric acid speciation



26.2.1 *Available P to Plants in the Soil: The Soil P Test*

Labile phosphorus in the soil is that in the solid phase that may be easily released to the soil solution. It is generally accepted that available phosphorus is the sum of P in the soil solution and P in labile forms (see Sect. 2.6). Available P in a soil usually accounts for a minor fraction of total P (frequently less than 10 %). Accurate determination of available P can be done only by biological methods measuring the amount extracted by successive crops until evident deficiency in plants appears (P starvation assays). This is not practical for estimating fertilizer requirements. However, chemical or biological methods can provide results which are well correlated with those obtained with P starvation assays. The methods can be considered as P availability indexes or soil P tests, the most usual being those involving chemical extraction of P from soil (Table 26.2).

The soil P test is not a real measure of the amount of available P but can provide information about if the available pool in the soil is enough to cover crop needs. Soil P tests are crucial for P fertilizer management, but for practical use, *critical values or threshold values* for each soil P test should be defined, which is the value above which no response in crop yield can be expected if P fertilizer is applied. Thus, below this value, the soil can be considered deficient in P. Critical values can vary between soil types and crops. Besides this, there is not a universal soil P test since its efficiency for fertilizer requirement estimation is very affected by soil properties. This explains why only in Europe more than 6 official P indexes are used depending on the country: Olsen and lactate (ammonium or Ca) extractions are the soil P tests more widely used in Europe, while in North America, Olsen, Mehlich (I and III) and Bray tests are the more usual.

26.3 Potassium in the Soil

Most of the potassium in soils is found as a component of feldspar and mica minerals, common primary minerals in soils which explain that potassium is an abundant element in soils (frequently 0.3–3 % in mass). Potassium in primary minerals is slowly released by weathering. After this release, potassium is found in soluble, exchangeable, and non-exchangeable forms. Potassium in the soil solution is in rapid equilibrium with exchangeable K that is retained by electrostatic attraction to the negatively charged sites located on clays and soil organic matter. Non-exchangeable K, also defined as “fixed” K, is found within the interlayers and on the edges of 2:1 clay minerals and cannot be considered readily available to plants (Fig. 26.4). A part of K supplied as fertilizer is fixed in this form explaining that not all the applied K remains available to plants; the fraction of applied K that is fixed is greater with increasing fertilizer rates and increased 2:1 clay content of the soil. Adsorption as exchangeable or non-exchangeable forms explains why K moves so little in the soil.

The available K to plants is basically that in the soil solution plus the exchangeable pool. The potassium concentration in the solution is typically between 0.2 and 10 meq/L, which usually accounts for less than 1 % of exchangeable K and can be quickly depleted by plant uptake. Potassium in cationic form in the solution is the unique form that plants are able to absorb. As defined for P, soil buffering capacity for K is the ability to replenish K in the soil solution from that bound to soil

Table 26.2 Different soil P tests

Method	Extractant	Conditions to be applied	Countries	Specific conditions	Threshold levels mg P/kg
Olsen	0.5 M $NaHCO_3$ pH 8.5	Slightly acidic to basic soils	UK, part of USA, Mediterranean EU countries	Rainfed crops in semi-arid areas on clay soils	4–12 (mean 8)
				Rainfed crops in Mediterranean areas	8–10
				Rainfed crops in humid areas and medium texture soils	4–5
				Spring cereals in humid areas in medium texture soils (moderate yield)	8–10
				Winter cereals in humid areas in medium texture soils (high yield)	15–20
				Sugar beet	15–20
				Corn and wheat in sandy loamy soils (China)	8–16
				General recommendation clay soils[a]	8–10
				General recommendation loamy soils[a]	10–12
				General recommendation sandy soils[a]	12–20
Mehlich I	0.05 M HCl + 0.0125 M H_2SO_4	Multinutrient extraction for soils with low CEC	Part of USA	General	25

Mehlich III	0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 NH_4F + 0.013 M HNO_3 + 0.001 M EDTA – pH 2.5	Multinutrient extraction for wide range of soils; well correlated with Bray I, Mechlich I and Olsen	Part of USA	General	50
Bray I (Bray-Kurtz)	0.03 N NHF4 + 0.025 N HCl	Soils with acidic and neutral pH	Acidic soils in some countries (e.g. USA)	General	30
Bray II	0.03 N NH4F and 0.01 N HCl	Soils with acidic and neutral pH		General	10–20
Egnér et al.	0.1 M ammonium lactate + 0.2 M acetic, pH 3.75	Multinutrient extraction	Scandinavia, Central and East Europe, Portugal	General	70–80
Egnér -Riehm	0.01 M Ca lactate + 0.02 M HCl	Multinutrient extraction	Germany	General	100
Morgan	0.7 M $NaC_2H_3O_2$ + 0.54 M CH_3COOH – PH 4.8.	Multinutrient extraction for acidic soils with low cation exchange capacity		General	4–6
Morgan modified	0.62 M NH_4OH + 1.25 M CH_3COOH – PH 4.8	Multinutrient extraction for acidic soils with low cation exchange capacity		General	4–6
Soltanpour (AB-DTPA)	1 M NH_4HCO_3 + 0.005 M DTPA – pH 7.5	Multinutrient extraction for P, cations and micronutrients; mainly for calcareous soils		General	10 (similar to Olsen)
Dyer-Demolon	2 % Citric acid	Acidic soils		General	90–180
Schüller	0.05 N Ca lactate + 0.05 M Ca acetate + 0.3 M acetic	Acidic soils		General	80–140
Truog	0.2 N H_2SO_4	Non-calcareous soils		General	20

[a] Multiply by 1.5–2 for high yield crops

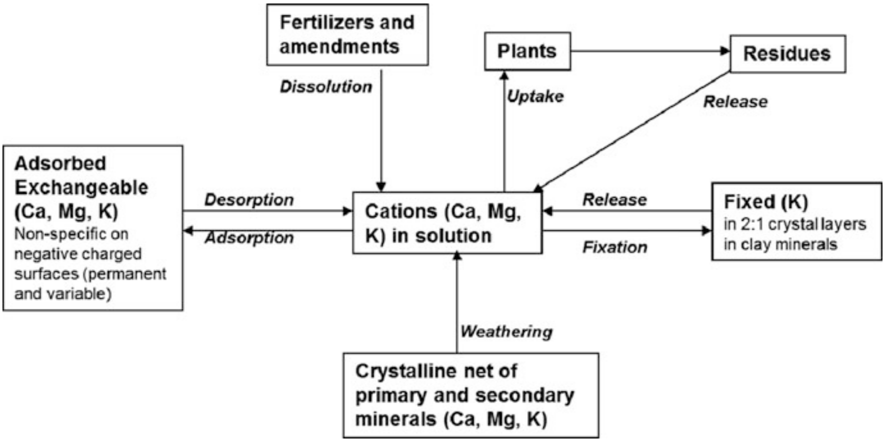


Fig. 26.4 K, Ca, and Mg cycle in soil. In italics: physical, chemical or biological processes involved in nutrients cycle

Table 26.3 Treshold levels (STL_t) for ammonium acetate extractable K in soils depending on the cation exchange capacity (cmol(+)/kg) and on the texture

Cation exchange capacity (CEC)	Threshold levels	Texture	Treshold levels
cmol(+)/kg	mg K/kg soil		mg K/kg soil
10	150	Sandy	100
20	180	Loamy	150–175
30	210	Clay	200–300
40	240		

The thresholds can be also calculated using $STL_t = 75 + 2.5$ CEC (Tri-state recommendation for corn, wheat, soybean and alfalfa) or $STL_t = 110 + 2.5$ CEC (general recommendation)

particles, and it is critical to maintain K concentration in the solution in appropriate ranges for plants. Potassium buffer capacity mainly depends on clay content and mineralogy, being the highest in clay soils with 2:1 as major clay minerals.

26.3.1 Plant Available Potassium in the Soil

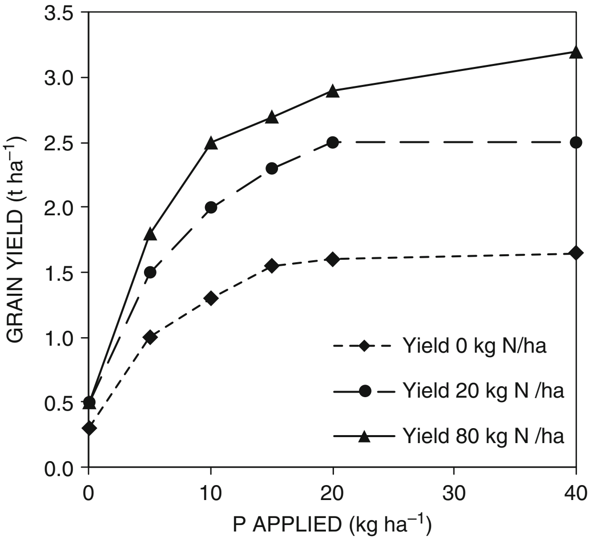
As for P, K fertilizer management must be based on availability indexes. Although several indexes have been proposed, the most common are those based on the estimation of exchangeable K. The most widespread method is extraction with ammonium acetate solution at pH 7 (Table 26.3). This method has generally shown a good correlation of crop response with soil potassium content. Other methods to determine exchangeable K, such as buffered $BaCl_2$ or unbuffered NH_4Cl provide similar results. For acidic soils, methods based on extraction with acids (e.g. Mehlich or Morgan) have been proposed, generally with good correlations with amounts extracted with ammonium acetate.

26.4 Response of Crops to P or K Fertilizer

The production functions of yield versus applied nutrient (P or K) show similar responses with decreasing slope (Figs. 26.5 and 26.6). The relationship between yield and P uptake is similar to that described for N, i.e. more or less straight initially and then it may reach a ceiling (Fig. 26.7). The relationship between dose of fertilizer and P uptake is initially linear and can also reach a ceiling where the absorption is saturated (Fig. 26.7). The intercept with the Y axis of the linear portion indicates the amount of P the crop may absorb from sources other than fertilizer (P previously present in soil) and the slope is the recovery efficiency (or fertilizer efficiency) in the straight section of the relationship.

The relationship between yield and applied K is of the same type as those described for N and P (Fig. 26.6). The examples shown in Figs. 26.5 and 26.6 indicate that these relations described for P and K may vary with N fertilizer applications or soil management system. This reveals that nutrition and fertilization for a given nutrient cannot be considered isolated. Synergistic effects with other nutrients, such as N, explains that accumulation of P and K can be faster if an appropriate N supply is performed; this also implies better response in yield to P or K supply. Adequate water supply also implies better responses of crops to P and K supply in terms of uptake and yield since a more efficient uptake of nutrients is achieved. Soil water content is critical in explaining nutrient flux to the roots,

Fig. 26.5 Wheat grain yield response to P fertilizer application with increasing rates of N fertilizer in Australia (Adapted from Brennan and Bolland (2009) Crop pasture sci 60:566–577)



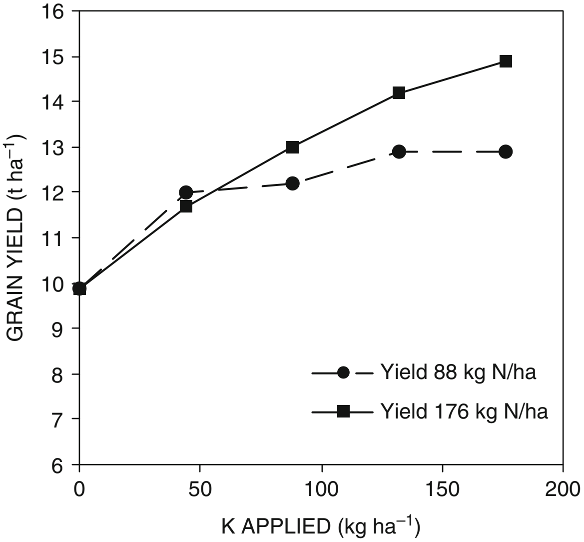


Fig. 26.6 Rice grain yield response to K fertilizer application with increasing rates of N fertilizer in Arkansas (Adapted from Slaton et al. (2010) Rice Response to Nitrogen and Potassium Fertilization Rate. Arkansas Agric Extension Service Res 591. available at http://arkansasagnews.uark.edu/591–38.pdf)

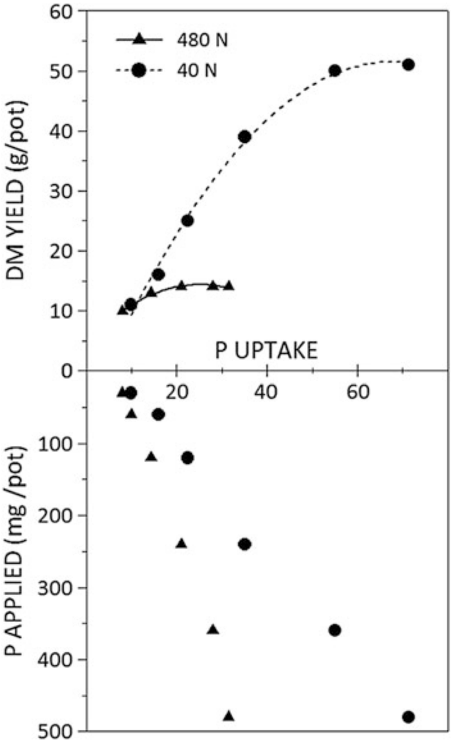


Fig. 26.7 Response of maize biomass production to P uptake and of P uptake to P applied for different levels of N supply

particularly in those that basically move through diffusion mechanisms due to their low concentration in the solution, such as P and K. The key role of water content explaining nutrient uptake by plants explains that in Mediterranean dryland areas (annual rainfall 300–500 mm) threshold Olsen values can vary from 4–5 in rainy years to 8–9 mg/kg in dry years, reflecting the need of more P present in the soil for optimal supply to plants in dry years. These examples justify the need of adequate and integrated management practices to achieve the better crop response to inputs supplied.

26.5 Phosphorus and Potassium Fertilization Strategies

The principles for establishing the P and K fertilization plan based on soil-test interpretations vary across countries. In the cases of the *sufficiency approach*, the main objective is maximum short-term profitability from applied fertilizer and minimum risk of environmental impact related to excess fertilizer by accepting some risk of yield loss. On the other hand, *the buildup and maintenance approach* seeks long-term profitability from fertilization, long term maximum returns, and reduced risk of yield loss due to low fertility.

Due to complex reactions of P and K fertilizers in soils, soil test above threshold values is the only guarantee of optimal P or K supply to plants since available reserve of nutrient in the soil is enough for an optimal supply (no fertilizer response). Below threshold values, there is not guarantee of optimal P or K supply to crops due to the uncertainty on the fraction of applied fertilizer that can finally remain available to plants. Thus, according to both strategies of fertilization, an optimal condition of soil from a point of view of nutrient supply is to stay above threshold values (or critical values) defined for the recommended soil test. Soil tests and threshold values can vary widely for P depending on the region/country and depending on soil properties. In general, the threshold value will depend on the particular requirement of each crop (high or low P or K extractions), on the clay content of the soil for P and K, and on carbonate content for P.

26.5.1 Buildup and Maintenance Approach

According to this strategy, if the soil test level (STL) is below the threshold value (STL_t), the fertility level of the soil should be corrected to bring it up to slightly above this value, according to the references shown in Tables 26.2 and 26.3 for P and K, respectively. The increase in P or K availability till optimal levels takes usually several years, being clearly slower if soils have a high fixation and buffering capacity. It should be remarked that the buildup rate for a given supply strategy could vary from soil to soil since P and K reactions in the soil cannot be predicted accurately.

After reaching an adequate level of fertility above the threshold value, fertilizer applications should compensate removal of nutrients by the previous crop. Nutrient exports are calculated as the product of the quantity of biomass going out of the field and its nutrient concentration (Table 26.4). Soil analysis should be performed every 3-4 years to check the evolution of the level of fertility and varying the fertilizer rates according to the evolution of soil test levels.

A single formulation of the buildup and maintenance strategy could be:

$STL < STL_t$	Add crop exportation + more (according to models)
$STL_t < STL < 2\ STL_t$	Add only exported nutrient (or slightly above exportations)
$STL > 2\ STL_t$ (*Maintenance limit*)	Add less P than crop export (e.g. 50 %) or do not fertilize

Table 26.4 Average phosphorus and potassium concentration (% dry weight) in different harvested organs and residues for different species

	Concentration (% dry matter)			Concentration (% dry matter)		
Crop species	Part harvested	P	K	Part not harvested	P	K
Alfalfa (hay)	Biomass	0.26	2.10			
Apple	Fruit	0.05	0.75			
Barley	Grain	0.42	0.54	Straw	0.1	1.8
Bean (Phaseolus) (dry seed)	Seed (dry)	0.54	2.7	Straw	0.14	1.3
Cotton	Fiber+seed	0.41	0.49	Residues	0.1	1.6
Lettuce	Leaves	0.75	6.67			
Maize (grain)	Grain	0.32	0.34	Stover	0.1	1.5
Millet	Grain	0.38	0.39	Stover	0.04	1.6
Olives (60 % canopy cover)*	Fruit	0.14	1.25			
Orange	Fruit	0.14	1.35			
Palm Trees	fruit bunch	0.09	0.75			
Peach	Fruit	0.12	1.55			
Peas (dry harv.)	Seed (dry)	0.48	1.3	Straw	0.3	1.2
Potato	Tuber	0.25	2	shoot	0.2	3.95
Rapeseed, Canola	Grain	0.62	0.98	residues	0.1	0.8
Rice	Grain	0.29	0.28	Straw	0.09	1.5
Sorghum (grain)	Grain	0.33	0.39	Stover	0.13	0.73
Soybeans	Seed	0.66	1.5	Stover	0.06	0.57
Sugar Beet	Root without crown	0.25	1.54	shoot	0.22	5.8
Sugar Cane (virgin)	Stalks	0.01	0.2	Leaves + stems	0.07	0.12
Sunflower	Grain	0.63	0.72	residues	0.14	2.52
Tomato	Fruit	0.47	4.28	residues	0.1	1.9
Winter Wheat	Grain	0.37	0.46	Straw	0.06	1.2

A more complete list is provided in Appendix 26.1

*This canopy cover is assumed to be that of fully developed trees

Table 26.5 Correction factor f for buildup strategy in K fertilization

Soil texture	f range
Sandy and sandy-loam	1.1–1.2
Loam and silty-loam	1.5–1.7
Clay-loam	2
Clay	2.5–5

For the case of P, buildup models to estimate P fertilizer rate for soil test values below threshold values could be based on the Tri States fertilizer recommendation:

$$P\ rate\left(kg\frac{P}{ha}\right) = Exported\ P + \frac{10\rho_b\, Z}{N_{year}}\left(STL_t - STL\right) \qquad (26.1)$$

STL and STLt are given in mg/kg; ρ_b is bulk density (t/m^3), Z is soil depth to correct (m). P rate should be less than 100 kg P ha^{-1}. $N_{year} = 1$ if P rate <100 kg P ha^{-1}; N_{year} should be considered >1 to achieve a final P rates always lower than 100.

In soils with a high P fixation capacity, the application of crop exportations in the case of $STL_t < STL < 2\ STL_t$ could lead to a decrease in STL in the long-term. In this case, P applications above crop exportations could be recommended, e.g. between 10 and 30 % more than exportations depending on the capacity of soil to fix P.

In the case of K, a buildup equation will be based on the desired increase in soil K (STL_t – STL) which is corrected by a factor f_K that depends on the K interlayer fixing capacity of soils (Table 26.5).

$$K\ rate\left(kg\frac{K}{ha}\right) = Exported\ K + \frac{10\rho_b Z f_K}{N_{year}}\left(STL_t - STL\right) \qquad (26.2)$$

where ρ_b is bulk density (t/m^3), Z is soil depth to correct (m) and N_{year} is the number of years to reach STL_t. $N_{year} = 1$ if K rate <275 kgK/ha; N year should be considered >1 to achieve final K rates always lower than 275 kgK/ha

Buildup for P and K is usually achieved in several years and periodic control of soil levels (at least every 3 years) are necessary to check when the critical values are achieved. Massive applications of P and K are less effective, in terms of the ratio nutrient available to total amount applied. Thus, massive applications allow to achieve STL_t in shorter times, but with a total consumption of fertilizers (and subsequent cost) greater than with more fractionated applications. This is the reason why in some areas (e.g. some states in the USA) less than 100 kg P/ha and less than 275 kgK/ha are usually recommended as total rates in a buildup and maintenance strategy. This is the limit stablished to recommend 1 or more years in the Eqs. 26.1 and 26.2.

Above a certain level, which can be defined as "maintenance limit", rates lower than crop exportation (e.g. 50 %) or no fertilizer are applied. The maintenance limit can vary depending on the recommendation, but in general a reasonable recommendation could be to consider it as twice the threshold value.

Example 26.1 The P concentration in a soil determined by the method of Olsen in the top 25 cm is 7 ppm while the K concentration is 100 ppm (ammonium acetate method). In this soil, maize is going to be grown with an expected yield of 15 t/ha (14 % moisture). Threshold values for P and K are 15 ppm and 250 ppm, respectively. Soil bulk density is 1.4 t/m^3. Texture is clay (45 % clay) and carbonate content 30 %. Calculate P and K fertilizer rates for these conditions. Calculate also if Olsen P is 27 ppm and acetate extractable K is 300 ppm.

Fertilization based on Buildup and Maintenance strategy

Crop extraction and exportation; the amount of dry matter exported is:

$$15000\ \mathrm{kg/ha} \cdot (1 - 0.14) = 12900\ \mathrm{kg\ grain\ dry\ matter/ha}$$

Now, according to Table 26.4, P and K concentrations in maize grain are 0.32 % and 0.34 %, thus, the amount of P and K removed in grain are:

$$\begin{aligned} 12900\ \mathrm{kg/ha} \cdot 0.0032\ \mathrm{kg\ P/kg} &= 41.25\ \mathrm{kg\ P/ha} \\ 12900\ \mathrm{kg/ha} \cdot 0.0034\ \mathrm{kg\,K/kg} &= 43.8\ \mathrm{kg\ K/ha} \end{aligned}$$

Now we use Eq. 26.1:

$$\begin{aligned} \mathrm{P\ rate} &= 41.25 + 10 \cdot 1.4 \cdot 0.25 \cdot (15 - 7) = 69.3 \\ &\approx 69\ \mathrm{kg\ P/ha}\ (340\ \mathrm{kg\ triple\ super\ phosphate/ha}) \end{aligned}$$

If Olsen P is 27 ppm, as it is below the maintenance limit (30 ppm), we may apply only the exported nutrient:

$$\mathrm{P\ rate} = 41.25 \approx 41\mathrm{kg\ P/ha}\ (\mathrm{e.g.}\ 205\ \mathrm{kg\ TS/ha})$$

For potassium:

Increase in K = 250 − 150 = 100 ppm(mg/kg)

From Table 26.5 for clay soil we have a range of f_K between 2.5 and 5, and we choose $f_K = 3$.

$$\begin{aligned} \mathrm{K\ rate(kg\ K/ha)} &= 43.8 + 10 \cdot 1.4 \cdot 0.25 \cdot 3 \cdot (250 - 150) = 1050 + 43.8 \\ &= 1093.8\ \mathrm{kg\ K/ha} \end{aligned}$$

much higher than 275 kg/ha, then $N_{year} > 1$. It is easy to check that to avoid exceeding 275 kg K/ha in this case we need to assume $N_{year} = 5$, so:

$$\mathrm{K\ rate(kg/ha)} = 48.3 + (10 \cdot 1.4 \cdot 0.25 \cdot 3)/5(250 - 150) = 258.3\mathrm{kg\ K/ha}$$

which may be supplied with 258.3/0.5=516.6 kg potassium chloride

(continued)

Example 26.1 (continued)

In any case, as commented above, this is not a precise estimate and periodic checks of K status of the soil are recommended to know when the threshold level in soil has been reached.

If acetate extractable K is 300 ppm, as it is above the threshold and below the maintenance limit, then we should compensate only the exported nutrient:

$$\text{K rate} = 43.8 \text{ kg K/ha} (\text{e.g. } 87.6 \text{ kg Cl K/ha})$$

26.5.2 Sufficiency Approach

If initial fertility is below the threshold value, this strategy would begin by buildup applications which may be applied in several years as in the case of the build up and maintenance strategy. Once the soil test is above threshold values, it is tested every year, and fertilizer is only applied when the nutrient level is below this value. The sufficiency approach was initially recommended to avoid environmental problems derived from an excessive P enrichment of soil which leads to high P concentration in water bodies triggering eutrophication effects. Beside this, it has another advantage: it promotes an increased use of residual P and K in the soil, i.e. a progressive starvation of P and K levels in soils may enhance the transformation of non-available forms to available forms and thus an enhanced use by plants of non-available forms. In any case, this can be understood as a depletion of soil nutrient reserves which in the long-term may imply the application of increased rates of fertilizer.

26.6 Other Nutrients

The application of other nutrients different from N, P and K is usually done following a sufficiency strategy: they are applied if their deficiency is expected. Calcium and Mg have a similar cycle to that described for K (Fig. 26.4). Available amounts are also equivalent to nutrient in solution plus exchangeable pool. All extraction methods used as soil test for K can also be useful as Ca and Mg availability indexes. Threshold values for Ca and Mg according to the ammonium acetate extraction are 250–500, and 30–60 mg/kg, respectively. The threshold values increase in proportion to cation exchange capacity of the soil. In general terms, low availability levels of Ca are usually found found in acidic sandy soils with low base saturation.

Fertilization with K, Ca or Mg must take into account the available levels of the other alkaline or alkaline-terreous nutrient levels since antagonistic effects can be

Table 26.6 Availability index (soil test) for micronutrients and threshold values

Micronutrient	Method	Threshold values (mg/kg)	Conditions of use
Boron	Hot water	0.1–2	
Copper	Ammonium Bicarbonate-DTPA (AB-DTPA Sultanpour)	0.5–2.5	AB-DTPA y DPTA recommended in soils with basic pH
	DTPA	0.1–2.5	
Iron	AB-DTPA	4.0–5.0	Soils with basic pH
	DTPA	2.5–5.0	
	"Fast ammonium oxalate"	350–900	Basic soils; threshold values depend on crop sensivity to Fe chlorosis (e.g. 350 olive and grapevine)
	Non-buffered hydroxylammonium	10	Soils with basic pH; threshold value defined for sensitive crops to Fe deficiency chlorosis
Manganese	AB-DTPA	0.5–5.0	Soils with basic pH
	DTPA	1.0–5.0	
Molybdenum	Oxalato amónico pH 3.3	0.1–0.3	
Zinc	AB-DTPA	0.5–1.0	Soils with basic pH
	DTPA	0.2–2.0	

promoted. Exchangeable K/Mg ratios above 0.5 can induce Mg deficiency, and values lower than 0.1 promote K deficiency; on the other hand Ca/Mg ratios above 10 may promote Mg deficiency, while when they are lower than 2, Ca deficiency may appear.

Micronutrient availability to plants is not only determined by its amount in the soil. In the case of metals (Fe, Cu, Mn and Zn), it is clearly affected by soil conditions affecting their solubility and the ability of plants to mobilize, absorb and transport them. The paradigmatic case is Fe, a fairly abundant element in soils whose availability is clearly decreased in calcareous soils. Iron deficiency, known as Fe deficiency chlorosis, is the consequence of insolubility of Fe compounds at basic pH and the failure of plant mechanisms to mobilize Fe from soil, to absorb, or to transport it across cell membranes. Iron chlorosis is a relevant agronomic problem in agriculture production on calcareous soils.

The most usual soil test for micronutrients is the extraction with the chelating agent DTPA (Table 26.6.). For Fe, extraction based on ammonium oxalate usually provides better results than DTPA extractions. In the case of Fe, active calcium carbonate has been also usually used as an index to predict its deficiency.

26.7 Timing and Fractioning of P and K Fertilizer Applications

Phosphates have traditionally been used as basal fertilizers before sowing, but can also be applied at planting which is recommended under no-till by using proper machinery for sowing and fertilizer application. Under no-till, incorporation contributes to decrease the risk of incidental P losses (e.g. by unexpected rain after fertilization) and to avoid enriching only the surface layer which would facilitate losses by runoff or erosion. The application should be performed with more anticipation the lower the solubility of fertilizer (not less than three months before planting for poorly soluble such as rock phosphate).

Fractionation of P fertilizer is an uncommon practice. It can be justified in very sandy soils saturated with P to avoid leaching. It can be also recommended because it has been found that massive contributions favor retrogradation (conversion to non-available forms) and decrease the recovery efficiency. Therefore, in soils very low in phosphorus, or high in calcium or for crops with high P demand, fractionation with soluble P fertilizer can be considered. The main limitation for P fertilizer fractionation, as it is done with N, comes from its low mobility in the soil; topdress broadcast P fertilization would lead to an enrichment in P of the soil surface, increasing P loss risk and constraining root growth in depth. Thus, it seems more feasible the fractionation of P fertilization when fertilizer can be incorporated into the soil, particularly close to the root system. Fertigation can meet these requirements; this application method not only involves a high fractionation of P fertilizer, but also location near the roots and watering conditions that favor P movement to roots. All this results in a much higher efficiency of applied P with fertigation than with traditional basal applications.

As P shows low mobility in the soil, it can be recommended to locate it close to the roots by band application at sowing, particularly in low-P soils, to enhance its use by plants. Localized application can help in reducing retrogradation by saturating the fixation capacity of a more reduced volume of soil, puts the fertilizer closer to the roots, and usually promotes an early growth of crops (“starting” effect). The amount of P that can be banded is not limiting except if P is applied as ammonium phosphate since ammonium can be phytotoxic at high rates; in this case, less than 40 kg N/ha as ammonium should be applied. Banded fertilizer at sowing must be located in bands 5 cm to the side and 5 cm below the seed to avoid germination problems of seeds due to high salt concentration.

Application of P as organic amendments/fertilizer or with organic matter should be also considered for improved efficiency. Organic matter competes with P for adsorption sites and decreases the precipitation as insoluble metal phosphates thus clearly enhancing the recovery of applied P. This explains why greater improvements of soil P test have been found with manure applications when compared with soluble inorganic fertilizers applications. The application of P as organic by-products is also gaining interest nowadays as a P recycling strategy to make agriculture less dependent on a non-renewable resource.

Strategies considered for P can be also practical for K fertilizer which is also usually applied before or at sowing. Fractionation and located application in bands are good choices since they contribute to saturating the soil and keeping high concentration in the soil solution. However, no improvement in recovery efficiency can be expected with the joint application with organic matter, except in very sandy soils, since the only contribution of organic matter to the soil K cycle is to provide more charged surface and thus more retention capacity if clay content is very low.

Appendix 26.1. Average phosphorus and potassium concentration (% dry weight) in different harvested organs and residues for different species

			% dry matter			% dry matter	
Cereals & Pseudocereals		Part harvested	P	K	Not harvested	P	K
Barley (2 row)	Hordeum vulgare	Grain	0.35	0.49	Straw	0.08	2.1
Barley (6 row)	Hordeum vulgare	Grain	0.42	0.54	Straw	0.1	1.8
Buckwheat	Fagopyrum esculentum	Seed	0.35	0.46			
Maize	Zea mays	Grain	0.32	0.34	Stover	0.1	1.5
Millet-Foxtail	Setaria italica	Grain	0.34	0.35	Stover		1.6
Millet-Pearl	Pennisetum glaucum	Grain	0.38	0.39	Stover	0.04	1.6
Millet-Proso	Panicum miliaceum	Grain	0.34	0.48	Stover		1.6
Oats	Avena sativa	Grain	0.36	0.44	Straw	0.1	2.3
Quinoa	Chenopodium quinoa	Seed	0.41	1.12			
Rice	Oryza sativa	Grain	0.29	0.28	Straw	0.09	1.5
Rice (milled)	Oryza sativa	Grain	0.3	0.45	Straw	0.09	1.5
Rye	Secale cereale	Grain	0.38	0.52	Straw	0.09	0.97
Sorghum	Sorghum bicolor	Grain	0.33	0.39	Stover	0.13	0.73
Triticale	X Triticosecale rimpaui	Grain	0.34	0.57	Straw	0.03	1.2
Wheat- Spelt	Triticum spelta	Grain	0.42	0.44	Straw	0.13	1.4
Wheat-Bread-Hard type	Triticum aestivum	Grain	0.43	0.45	Straw	0.06	1.2
Wheat-Bread-Soft type	Triticum aestivum	Grain	0.37	0.46	Straw	0.06	1.2
Wheat-durum	Triticum durum	Grain	0.42	0.5	Straw	0.06	1.2
Grain Legumes		Part harvested	P	K	Not harvested	P	K

(continued)

			% dry matter			% dry matter	
Bean	Phaseolus spp.	Seed (dry)	0.54	2.7	Straw	0.14	1.3
Chickpea (desi)	Cicer arietinum	Seeds	0.4	1.2	Straw	0.16	2.3
Chickpea (kabuli)	Cicer arietinum	Seeds	0.4	1.2	Straw	0.16	2.3
Cowpea	Vigna unguiculata	Seed	0.52	1.5	Straw	0.28	1.55
Faba bean	Vicia faba	Seed	0.47	1.2	Straw	0.2	1.6
Lentil	Lens culinaris	Seed	0.43	0.86	Straw	0.14	1.15
Pea	Pisum sativum	Seed (dry)	0.48	1.3	Straw	0.3	1.2
Peanut	Arachis hypogaea	Pods	0.35	0.56	Straw	0.14	1.38
Soybean	Glycine max	Seed	0.66	1.5	Stover	0.06	0.57
Forages		Part harvested	P	K	Not harvested	P	K
Alfalfa (hay)	Medicago sativa	Biomass	0.26	2.10			
Bluegrass-Kentucky (hay)	Poa pratensis	Biomass	0.28	1.92			
Bromegrass (hay)	Bromus sp.	Biomass	0.16	1.64			
Canarygrass-Reed (hay)	Phalaris arundinacea	Biomass	0.28	2.99			
Clover (white) (hay)	Trifolium repens	Biomass	0.35	2.30			
Clover-Alsike (hay)	Trifolium hybridum	Biomass	0.25	2.48			
Clover-Crimson (hay)	Trifolium incarnatum	Biomass	0.22	2.76			
Clover-Red (hay)	Trifolium pratense	Biomass	0.26	1.89			
Clover-White (hay)	Trifolium repens	Biomass	0.35	2.25			
Clover-White-Ladino (hay)	Trofolium repens	Biomass	0.32	2.43			
Fescue-Tall (hay)	Lolium arundinaceum	Biomass	0.32	2.36			
Grass (hay)	Poaceae	Biomass	0.22	1.45			
Grass (silage)	Poaceae	Biomass	0.32	1.88			
Maize (silage)	Zea mays	Biomass	0.20	1.00			
Millet-Foxtail (silage)	Setaria italica	Biomass	0.18	1.94			
Millet-Pearl (silage)	Pennisetum glaucum	Biomass	0.26	1.63			
Oat (hay)	Avena sativa	Biomass	0.24	1.26			
Orchardgrass (green chop)	Dactylis glomerata	Biomass	0.18	2.64			
Orchardgrass (hay)	Dactylis glomerata	Biomass	0.25	2.80			

(continued)

			% dry matter			% dry matter	
Rye (hay)	Secale cereale	Biomass	0.22	1.24			
Ryegrass-Perennial (hay)	Lolium perenne	Biomass	0.20	1.42			
Sorghum	Sorghum bicolor	Biomass	0.21	1.10			
Sweetclover (hay)	Melilotus sp.	Biomass	0.24	1.65			
Timothy (hay)	Phleum pratense	Biomass	0.17	1.63			
Trefoil-Birdsfoot (hay)	Lotus corniculatus	Biomass	0.23	1.89			
Turnip (green chop)	Brassica rapa var. rapa	Biomass	0.42	3.02			
Vetch (hay)	Vicia sativa	Biomass	0.36	2.24			
Vetch-Hairy (hay)	Vicia villosa	Biomass	0.36	2.23			
Wheatgrass (hay)	Poaceae	Biomass	0.07	2.70			
Sugar, oil & fiber crops		Part harvested	P	K	Not harvested	P	K
Cotton	Gossypium hirsutum	fiber+seed	0.41	0.49	residues	0.1	1.6
Flax	Linum ussitatisimum	Seed	0.57	0.84	residues	0.08	1.74
Opium poppy	Papaver somniferum	Capsules	0.6	2.4	Leaves +stems	0.3	3.1
Rapeseed	Brassica spp	Grain	0.62	0.98	residues	0.1	0.8
Safflower	Carthamus tinctorius	Grain	0.6	0.75	residues	–	–
Sugar beet	Beta vulgaris	Root without crown	0.25	1.54	shoot	0.22	5.8
Sugarcane	Saccharum spp.	Stalks	0.01	0.2	Leaves +stems	0.07	0.12
Sunflower	Helieanthus annuus	Grain	0.63	0.72	residues	0.14	2.52
Tobacco Burley	Nicotiana tabacum	Leaf+stem	0.31	3.86	stalks	0.31	3.86
Tobacco Virginia	Nicotiana tabacum	Leaves	0.27	2	stalks	0.27	2
Horticultural crops		Part harvested	P	K	Not harvested	P	K
Artichoke	Cynara scolimus		0.51	2	residues	–	–
Asparagus (green)	Asparagus officinalis	Stem	0.69	3.4			
Asparagus (white)	Asparagus officinalis	Stem	0.74	4			
Beet	Beta vulgaris	Root	0.32	2.46	shoot	0.44	6.26
Brussels sprout	Brassica oleracea	Leaves	0.51	3.25			
Cabbage	Brassica oleracea	Leaves	0.35	2.73			

(continued)

			% dry matter			% dry matter	
Carrot	Daucus carota	Root	0.33	2.43	shoot	0.19	1.88
Cauliflower	Brassica oleracea	Head	0.66	3.22			
Celery	Apium graveolens	Leaves	0.66	4.8		0.66	4.8
Chicory	Cichorium intybus	Leaves	0.23	4			
Cucumber	Cucumis sativus	Fruit	0.53	4.25	residues	–	–
Eggplant	Solanum melongena	Fruit	0.31	3	residues	–	–
Endive	Cichorium endivia	Leaves	0.45	5.6			
Faba bean (green)	Vicia faba	Fruits	0.5	1.32	residues	–	–
Leak	Allium porrum	Bulb	0.21	1.06	residues	–	–
Lettuce Iceberg	Lactuca sativa	Leaves	0.5	2			
Lettuce Roman	Lactuca sativa	Leaves	0.75	6.67			
Melon	Cucumis melo	Fruit	0.16	2.58	residues	–	–
Muskmelon	Cucumis melo	Fruit	0.36	3.16	residues	–	–
Parsley	Petroselinum crispum	Leaves	0.4	2.7			
Pepper (green)	Capsicum annuum	Fruits	0.35	2	residues	–	–
Pepper (red)	Capsicum annuum	Fruits	0.3	2.4	residues	–	–
Pumpkin	Cucurbita spp.	Fruit	0.39	2.78	residues	–	–
Radish	Raphanus sativus	Root	0.4	3.17	residues	–	–
Spinach	Spinacia oleracea	Leaves	0.56	5.66			
Squash	Cucurbita pepo	Fruit	0.4	3.5	residues	–	–
Tomato	Lycopersicon esculentum	Fruit	0.47	4.28	residues	0.1	1.9
Watermelon	Citrullus lanatus	Fruit	0.11	1.33	residues	–	–
Fruit trees, vines and shrubs		Part harvested	P	K	Not harvested	P	K
Almond	Prunus amygdalus	Fruit	0.37	0.75			
Apple	Malus sylvestris	Fruit	0.05	0.75			
Apricot	Prunus armeniaca	Fruit	0.14	2.17			
Avocado	Persea americana	Fruit	0.15	2.31			
Banana	Musa paradisiaca	Fruit	0.08	1.54			
Cherimoya	Annona cherimola	Fruit	0.15	1.17			

(continued)

			% dry matter			% dry matter	
Cherry	Prunus avium	Fruit	0.01	1.16			
Coconut	Cocos nucifera	copra	0.3	5			
Date palm	Phoenix dactylifera	Fruit	0.05	0.84			
Fig	Ficus carica	Fruit	0.07	1.11			
Grape (table)	Vitis vinifera	Fruit	0.05	1.02			
Grape (wine)	Vitis vinifera	Fruit	0.07	0.95			
Grapefruit	Citrus paradisi	Fruit	0.11	1.38			
Hazelnut	Corylus avellana	Fruit	0.33	0.47			
Kiwi	Actinidia spp	Fruit	0.18	1.43			
Lemon	Citrus limon	Fruit	0.12	1.15			
Mango	Mangifera indica	Fruit	0.11	0.95			
Oil palm	Elaeis guineensis	fruit bunch	0.09	0.75			
Olive	Olea europaea	Fruit	0.14	1.25			
Orange	Citrus sinensis	Fruit	0.14	1.35			
Peach	Prunus persica	Fruit	0.12	1.55			
Pear	Pyrus communis	Fruit	0.07	0.77			
Persimmon	Dyospiros kaki	Fruit	0.07	1.01			
Plum	Prunus domestica	Fruit	0.07	1.16			
Pomegranate	Punica granatum	Fruit	0.1	1.04			
Quince	Cydonia oblonga	Fruit	0.1	0.95			
Walnut	Juglans regia	Fruit	0.22	0.41			
Roots, tubers & bulbs		Part harvested	P	K	Not harvested	P	K
Cassava	Manihot esculenta	Root	0.12	0.77			
Garlic	Allium sativum	Bulb	0.44	1.38	residues	0.2	1.3
Onion	Allium cepa	Bulb	0.35	1.2	shoot	0.38	2.75
Potato	Solanum tuberosum	Tuber	0.25	2	shoot	0.2	3.95
Sweet potato	Ipomoea batatas	Tuber	0.15	1.22			
Yam (chinese)	Dioscorea opposita	Tuber	0.15				
Yam (white)	Dioscorea rotundata	Tuber	0.25	2.3			
Yam (yellow)	Dioscorea cayenensis	Tuber					

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Chapter 27
Fertigation

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Abstract Fertigation is the joint application of nutrients along with irrigation water. It is best suited for high frequency drip irrigation although it may be adapted to other irrigation methods. Fertigation requires a dosing system and tanks for the stock solution where nutrients are incorporated. The main characteristics to consider for the fertilizers used in fertigation are concentration, purity, solubility and pH reaction. The quality of irrigation water has also to be considered in special the concentration of bicarbonates and calcium. The calculation of stock solutions is based on the total requirements for N, P and K and total irrigation to be applied. Specific recipes of fertigation solutions have been developed for several species. Complete nutrient solutions (e.g. Hoagland-Arnon) are easy to calculate taking into account the actual concentration of salts in irrigation water.

27.1 Introduction

Fertigation is the joint application of water and nutrients, which requires the connection of a dosing system of nutrients to the irrigation system. Although this technique can be applied in principle to all types of irrigation systems, it is generally used in drip irrigation systems and to a lesser extent in full coverage sprinkler systems and irrigation machines.

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If handled correctly, a very high efficiency in nutrient application to crops can be achieved with this fertilizer management, particularly with high-frequency drip irrigation. This high efficiency derives from:

(a) Fertigation implies, with drip irrigation, a localized fertilizer application, which is more efficient in poor-nutrient or high fixing capacity soils. This is relevant for nutrients that can be strongly bound to soil particles such as P and K.
(b) Drip irrigation systems cause a concentration of the root system within the wet bulbs; thus the nutrient application is concentrated in areas of high root length density. This contributes to a better uptake of applied nutrients.
(c) Using high-frequency drip irrigation, the water content in wet bulbs is usually close to field capacity of the soil; high water content enhances the flux of nutrients to roots through mass flow or diffusion, thus increasing the efficiency in applied fertilizers, which means that a larger fraction of applied fertilizers is finally used by crops.
(d) Fertigation with drip irrigation allows the very frequent application of very low fertilizer rates which allows adjusting nutrient supply to plant requirements that can vary depending on the growing stage. This has clear advantages for mobile nutrients such as N since large soil N accumulation is avoided thus decreasing losses and opening the opportunity for reducing N application, as can be seen when fertigation with N is compared with a conventional N fertilization combining planting and two side-dress applications (Fig. 27.1). With non-mobile nutrients, such as P and K, this application also have advantages since the frequent application of very low rates enhance fixation in forms (adsorption vs precipitation in calcareous soils in the case of P) in a more ready equilibrium with soil solution thus enhancing a greater efficiency of applied nutrients.

Fertigation can be a cost-effective fertilizer application technique when a drip irrigation system has been installed. Although it requires the installation of a dosing system, after this initial investment the cost of equipment and labor for applying fertilizers are usually lower than with other techniques. On the other side, fertilizers used are usually more expensive.

27.2 Dosing Systems

Fertigation is usually performed by injecting fertilizer in liquid form (fertilizer solution, commercial or prepared in the farm) into the irrigation water flow to the emitters. Two types of dosing methods can be distinguished:

(a) Proportional: It applies a constant nutrient concentration, so the amount of nutrients that enters the system has to be proportional to the irrigation flow.
(b) Quantitative: A total amount of nutrients is added to the irrigation system. The concentration varies with time.

Fertilizer injection can be done by using different types of devices (Fig. 27.2):

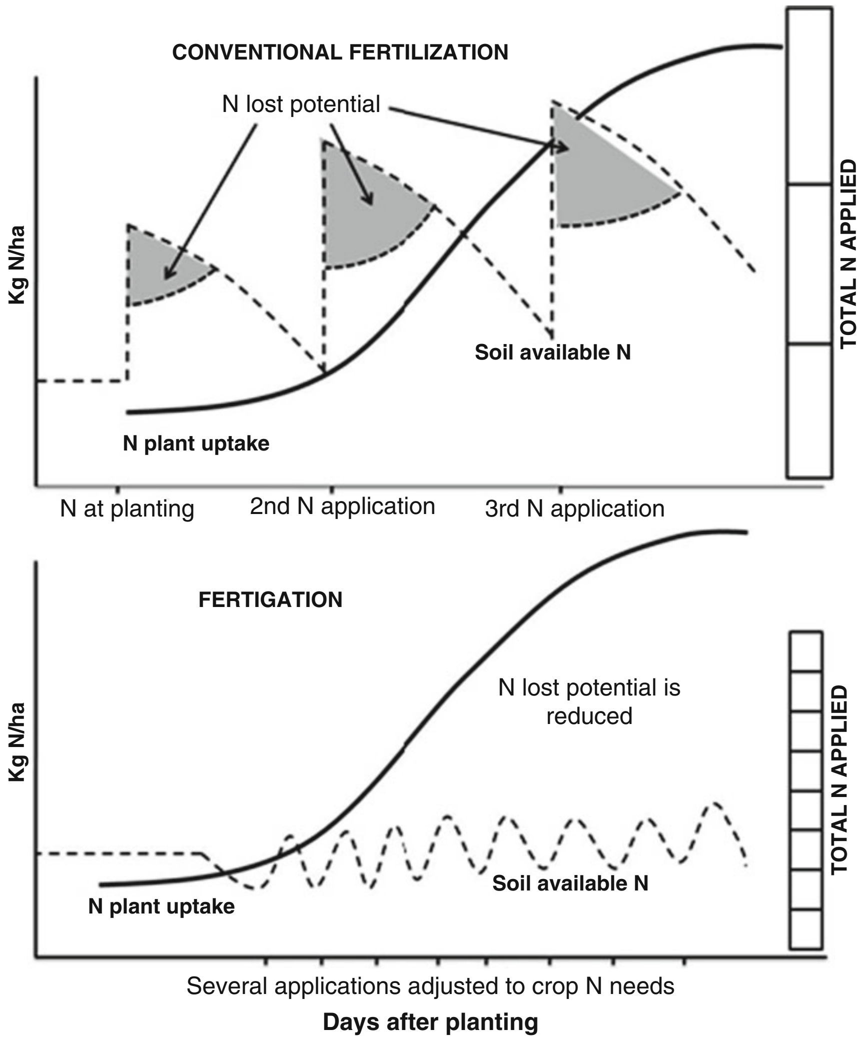


Fig. 27.1 Time course of crop N uptake and soil N availability for conventional fertilization and fertigation

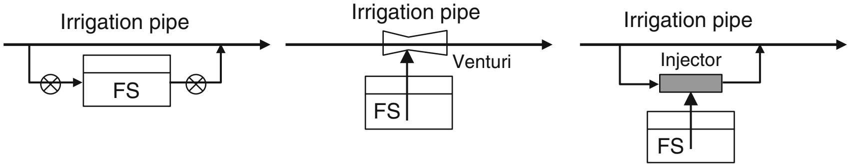


Fig. 27.2 Diagrams of fertigation dosing systems. (**a**) fertilizer tank with pressure differential. (**b**) With Venturi device. (**c**) With hydraulic injection pump

(a) Differential pressure.

A pressure regulating valve is inserted between the inlet and outlet connected to the fertilizer tank. The pressure difference forces the water to flow through the tank, from which it takes the nutrients and transports them to the main line.

It can be used to add solid or liquid products and serves only for quantitative dosing. It is easy to maintain and does not require additional energy but reduces the pressure in the main pipe. This method is best suited for conditions where fertigation is performed at irregular intervals.

(b) Venturi system. It connects a Venturi device (narrowing) in parallel to the main pipe. The depression resulting in the Venturi causes suction of the nutrient solution. This system allows proportional dosing. The rate of application of fertilizer can be adjusted and may provide very small amounts but causes pressure loss in the main pipe.

The depression depends on the water velocity, thus the accuracy of a Venturi dosing system depends on the capacity of the irrigation system to maintain constant flow.

(c) Injection Pump. An electric or hydraulic pump may be used. In the latter case no energy supply will be required. It is a system easy to install and operate, allows adjusting the dose and does not involve loss of pressure in the main pipe. It can be used for proportional or quantitative dosing.

(d) The irrigation pump inlet is connected to the fertilizer tank. The concentration of nutrients is kept constant. If a system for automatic filling of the tank is added then the concentration will vary with time. This is a simple and inexpensive method but difficult to automate. You run the risk of sucking air in the pump or the pump may be damaged by corrosion. This type of system is best suited for small installations.

Whatever the system chosen it is advisable to install check valves to prevent contamination of the supply line if return flow occurs and a filter downstream of nutrient injection.

27.3 Alternatives of Fertigation

Different types of fertigation can be defined depending on the combination of nutrients applied in each fertigation

(a) With complete nutrient solutions: although it is the usual choice for hydroponic systems on artificial substrates such as rockwool and perlite, it can also be used for crops on soil. The nutrient solution applied in each fertigation should include all macro and micronutrients. This will require the use of several tanks to avoid incompatibility problems between different fertilizer products:

Tank A: Macronutrients except Ca in an acid medium, usually applying part of N or P such as nitric or phosphoric acid.

Tank B: Fertilizers with Ca in neutral or acid medium.
Tank C: Micronutrients in neutral medium.

Another alternative for distribution of nutrients:

Tank A: NPK.
Tank B: N, K, Ca, S and micronutrients.
Tank C: Nitric acid.

If only NPK is required for crop fertilization in soil, only one tank may be needed. For hydroponics three tanks for applying all required nutrient is the better choice.

(b) Incomplete solutions: In cropping systems on soil it is usual to apply P as basal fertilizer before sowing to avoid the high cost of P soluble forms and the high probability of P precipitation in the system. In this case only N and K are usually applied through fertigation. Only one tank is required since N and K combinations are not problematic. It is also possible to apply each primary nutrient in different fertigations, with a tank for each primary nutrient. This latter solution reduces the risk of precipitation in the tank or irrigation net.

Whatever the type of fertigation tank, its size and the total amount of fertilized dissolved is determined by the solubility of the less soluble fertilizer.

27.4 Fertilizers for Fertigation

The main properties considered in fertilizers for fertigation are nutrient concentration, purity, solubility, pH effect and compatibility. Also the electrical conductivity in the applied solution should not exceed certain thresholds and the pH should be in the range 5.0–6.5. In that pH range nutrients are available for root uptake. Above this range precipitates can be formed (e.g. Ca compounds with phosphate) while below the root system may be damaged by an excessively acid fertigation solution. The main properties of fertilizers more widely used in fertigation are shown in Table 27.1.

The form in which nitrogen is supplied is a critical aspect in fertigation. Nitrogen cannot be supplied exclusively as NH_4^+ because (a) it is phytotoxic at high concentration in the growing media and (b) it can promote a decreased uptake of other cations such as Ca^{2+}, Mg^{2+} and K^+. This is caused by competition for absorption mechanisms and by decreasing electrochemical potential through plasma membranes which induces an increase excretion of H^+ by root cells to maintain electrochemical gradient. Conversely, when N is provided only as NO_3^-, its absorption promotes an alkalinization of root apoplast and rhizosphere due to the absorption mechanism of nitrate (symport with H^+) which can negatively affect the absorption of some nutrients such as Fe. Therefore it is recommended to apply N as 80–90 % nitrate and 10–20 % ammonium to maintain the pH of the rhizosphere in

Table 27.1 Properties of the main fertilizers used in fertigation. The simplest solid fertilizers are included with the exception of acids that are managed as liquids

		Eq weight	Solubility 20 °C	Concentration (mass percentage)					
		g/eq	kg/m^3	N	P	K	S	Ca	Mg
Monoammonium phosphate	NH_4 H_2 PO_4	115	626	12	22.6	0	1.5	1.5	0
Monopotassium phosphate	K H_2 PO_4	136.1	200	0	22.8	28.7	0	0	0
Ammonium nitrate	NH_4 NO_3	80	1920	34	0	0	0	0	0
Ammonium sulphate	$(NH_4)_2$ SO_4	66.1	730	21	0	0	24	0	0
Calcium nitrate (hidrated)	$Ca(NO_3)_2$ $.4H_2O$	118	1220	12	0	0	0	17	0
Potassium nitrate	K NO_3	101.1	316	13.4	0	39	0.2	0	0
Magnesium nitrate (hidrated)	Mg $(NO_3)_2.6H_2O$	128.2	1330	10.9	0	0	0	0	9.5
Potassium chloride	K Cl	74.6	340	0	0	49.8	0	0	0
Potassium sulphate	K_2 $S0_4$	87.2	110	0	0	41.5	16	0	0
Magnesium sulphate (hidrated)	Mg $SO_4.7H_2O$	123.2	710	0	0	0	13	0	9.9
Urea	CO $(NH_2)_2$	60.1	1033	46	0	0	0	0	0
Phosphoric acid 55 %, 1.38 g/cm^3	H_3 PO_4	98	5480	0	17.4	0	0	0	0
Phosphoric acid 75 %, 1.58 g/cm^3	H_3 PO_4	98	5480	0	23.7	0	0	0	0
Nitric acid 57 %, 1.35 g/cm^3	NO_3 H	63	10,000	12.5	0	0	0	0	0
Calcium nitrate	Ca $(NO_3)_2$	82	1212	17	0	0	0	24	0
Magnesium nitrate	Mg $(NO_3)_2$	74.1	770	18.9	0	0	0	0	16.4

optimum values while taking advantage of the acidification effect of NH_4^+. The application of N only as NO_3^- could be a good choice for fertigation in acid soils.

Temperature is the critical aspect affecting solubility of fertilizers, which is proportional to temperature. Thus, the maximum concentration of fertilizers in a solution is determined by the minimum temperature in the tank. Dissolving fertilizers is usually an endothermic reaction which decreases the temperature of the solution. The effect is important for urea and nitrates (ammonium, calcium and potassium). However, dilution of phosphoric acid is an exothermic reaction which can be used to compensate the effect of endothermic dissolution reactions thus increasing the solubility of the fertilizer added afterwards.

The products most widely used are nitrate (calcium, ammonium, potassium) and potassium chloride, which are very soluble compounds. To ensure the requirement of high purity and high solubility the fertilizer industry produces specific solid fertilizers for fertigation. There are also commercial solutions (e.g. N-20 solution, calcium nitrate, nitric acid, phosphoric acid, ammonium polyphosphates, various complexes, microelements). Composite solid fertilizers are also produced and composite liquid fertilizer solutions are presented in a wide range of ratios N: P: K, with or without micronutrients. Liquid composite fertilizers have a low nutrient concentration due to solubility limitations.

The use of incompatible fertilizers or the interaction of the fertilizer with irrigation water, especially if it is hard and/or alkaline water, can cause the formation of precipitates in the fertilization tank and the clogging of drippers and filters. These problems can be avoided by a proper choice of fertilizers and proper management of the irrigation net which must consider appropriate leaching and the use of acidified fertilizer solutions.

The main incompatibilities among fertilizers in fertigation are those involving the risk of precipitation of Ca and Mg compounds, such as:

Calcium nitrate in combination with phosphates or sulfates leads to precipitates of calcium sulfate or calcium phosphate.

Ammonium phosphate in combination with magnesium sulfate leads to magnesium phosphate (precipitate).

Micronutrients application should take into account the stability of the forms in which they are applied, usually as chelates which is affected by pH and by the presence of other cations in high concentration such as Ca. If Fe and P are applied in acid solutions Fe phosphates can precipitate.

27.5 Quality of Water for Fertigation

The main salts in water are chlorides, sulfates, carbonates and bicarbonates of Ca, Mg, Na and K. Some waters may contain other ions (nitrates, phosphates, ammonium, etc.) and certain metals (iron, manganese, zinc, lead, etc.) which can be toxic (Table 27.2). A standard laboratory analysis of irrigation water includes the major

Table 27.2 Main interactions among ions to be considered in fertigation

Ion	Toxicity	Precipitates with	Impairs absorption of	Favors absorption of
Ca	No	SO_4^-, HCO_3^-, $H_2PO_4^-$		
Mg	No	$H_2PO_4^-$	K^{+}[a]	
Na	Yes			
Cl	Yes		NO_3^-, $H_2PO_4^-$	
SO_4	Yes	Ca^{2+}		Na

[a] This antagonistic effect could be more evident with fertigation than with conventional fertilization since fertigation can keep greater concentrations of Mg and K in the soil solution

cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) and anions (Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-). Boron can also be determined because of its high toxicity even in very small concentrations. Nitrate concentration (dominant N form in water) should also be measured to take it into account in the N balance to estimate N requirement by crops.

The most common problem is the presence of bicarbonate, which combines with Ca and Mg and may precipitate depending on the pH. Waters high in Ca with alkaline pH will cause problems with more than 2 meq bicarbonate/L. To correct these problems and bring the pH to the desired range (5.0–6.5) an acid is added, leaving around 0.5 meq/L of bicarbonate not neutralized.

Another possible problem is related to P fertilizers. Insoluble Ca and Mg phosphates are generated in waters high in Ca or Mg when pH is high. These precipitates are deposited on the walls of the pipes and in the emitters, causing their clogging. The availability of P to the plants is also reduced. It is therefore recommended to use acid P fertilizers (mono-ammonium phosphate or phosphoric acid) to reduce the risk of precipitation of Ca and Mg phosphates.

In any case, dissolved fertilizers remaining in the emitters at the end of the fertigation can precipitate when water evaporates. To avoid this the duration of fertigation should be shorter than that of irrigation allowing flushing with water at the end of the irrigation. To dissolve the precipitates left and unclog the drippers we may use the acidic reaction of some fertilizers and/or the injection of an acid solution that also removes bacteria and algae. After injecting the acid the irrigation and the injection systems should be carefully washed with additional irrigation water.

Other quality issues in irrigation water may be the following:

(a) The presence of algae (irrigation ponds) or bacteria (groundwater, ponds) require additional treatments which may be performed with chlorine, copper sulfate (5 ppm) or potassium permanganate (2 ppm).
(b) Ferruginous underground waters produce rust deposits of Fe or Mn when they oxidize. They require first pre-treatment such as aeration or chelation, and then filtration to retain precipitated oxides.

27.6 Calculation of Stock Solutions

In fertigation systems with proportional dosing, a concentrated solution known as stock or mother solution is prepared in the irrigation head. Fertigation is programmed to dilute the solution with the irrigation water in the ratios of 1:100 up to 1:1000, while controlling the pH and EC. This results in the fertilizer solution that, after being filtered, will reach the emitters. This solution reacts with the substrate and results in the final nutrient solution that is absorbed by the roots.

The electrical conductivity may be calculated approximately as a function of the concentration of cations (CC, in meq/ L) or anions or as a function of the salt concentration (also named total dissolved solids, TDS, in g/L):

$$\mathrm{EC(dS/m)} = \mathrm{CC}/10 = \mathrm{TDS}/0.64 \tag{27.1}$$

For the calculation of the stock solution we may face different situations:

(a) We know the total amount of N and K to add to the total amount of irrigation. Therefore we deduce the concentration of the nutrient, and then we convert it to a quantity of fertilizer to be added using the concentrations indicated in Table 27.1. The maximum solubility (e.g. 80 % of this) should not be exceeded, particularly if temperature oscillations are expected. In the final fertilizer solution the stock solution is diluted M times, so the amount of fertilizer to add to the stock solution (kg fertilizer/m^3) will be:

$$M \cdot \frac{nutrient\ requirement\ \left(\frac{kg\ \ nutrient}{ha}\right)}{irrigation\ \left(\frac{m^3}{ha}\right) \cdot concentration\left(\frac{kg\ \ nutrient}{kg\ \ fertilizer}\right)}$$

(b) We know the ideal concentration of each nutrient (Ne, Pe, Ke) in meq/L and we want to determine the amount of fertilizers to be added to a tank, considering that the stock solution will be diluted M times.

(b.1) No acid correction. In the simplest case we have soft water with less than 0.5 meq bicarbonate/L so pH correction is not required. In hydroponics, dissolved bicarbonate could be the C source for autotrophic nitrifying microorganisms; thus to ensure conditions for rapid nitrification we should use a low NH_4^+/NO_3^- ratio.

We start from the P fertilizer requirement, as it is often the element of lower concentration. We will apply P as monoammonium phosphate (MAP) or monopotassium phosphate to cover the needs. The remaining needs of N (and/or K) will be completed with potassium nitrate, ammonium nitrate and/or potassium sulphate.

Example 27.1 The ideal solución for a given crop is 4-1-2 meq/L. The stock solution is diluted 400 times.

With monoammonium phosphate (MAP):

P: 1 meq P/L $\cdot$115 mg MAP meq $P^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^{3}$ L $m^{-3} = 115$ g MAP m^{-3}

This amount contains also 1 meq/L of NH_4^+, which is discounted from the required N concentration, so we still need to add 3 meq N/L which may achieved using 1.5 mmol/L of ammonium nitrate, AN (as each mol provides 2 equivalents of N).

1.5 mmol AN/L $\cdot$ 80mg AN mmol $AN^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^{3}$ L $m^{-3} = 120$ g AN m^{-3}

Finally we satisfy the K requirement using potassium sulfate (PS):

2 meq PS/L $\cdot$ 87.2 mg PS meq $PS^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^{3}$ L $m^{-3} = 174.4$ g PS m^{-3}

The concentrations in the stock solution will be obtained by multiplying the concentrations above by the dilution factor (400):

MAP	46 kg m^{-3}
NO_3NH_4	48 kg m^{-3}
SO_4K_2	69.8 kg m^{-3}

We should check that the concentrations in the stock solution do not exceed the solubility of the fertilizers used (Table 27.1).

Other possible stock solutions could be:

Monopotassium phosphate	54.4 kg m^{-3}
NO_3K	40.4 kg m^{-3}
NO_3NH_4	48.0 kg m^{-3}

Monopotassium phosphate	54.44 kg m^{-3}
SO_4K_2	34.88 kg m^{-3}
NO_3NH_4	64.00 kg m^{-3}

(b.2) Water with more than 0.5 meq HCO_3^-/L: the pH has to be corrected. Under these conditions, dissolved bicarbonate is not restrictive for nitrification so the ratio NH_4^+/NO_3^- does not matter.

Acid is used to neutralize bicarbonate leaving only 0.5 meq/L. Then the procedure is similar to that explained in the previous case taking into account the nutrients added with the acid.

Example 27.2 Ideal solution 4-1-2 meq/L. Water with 3.5 meq/L of HCO_3^-. Dilution 400 times. Correction with phosphoric acid 55 % (density 1.38 g cm^{-3})

To neutralize 3.0 meq/L of HCO_3^- we need 3.0 meq/L of protons which can be supplied by 1 mmol/L of pure PO_4H_3.

1 mmol PO_4H_3/L· 98 mg PO_4H_3 mmol $PO_4H_3^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^3$ L m^{-3} = 120 g PO_4H_3 m^{-3}

120 g PO_4H_3 $m^{-3} \cdot$ 1 g solution/0.55 g PO_4H_3 · 1 cm^3 solution/1.38 g solution = 158 cm^3 m^{-3} (phosphoric acid 55 %)

We have also covered the need of P (1 meq/L).

We will cover now the need for K using potassium sulfate (PS):

2 meq K/L · 87.2 mg PS meq $K^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^3$ L m^{-3} = 174.4 g PS m^{-3}

To supply 4 meq/L of N with ammonium nitrate, as each mol gives 2 equivalents of N, we will apply 2.0 mmol AN/L:

2.0 mmol AN/L · 80 mg AN mmol $AN^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^3$ L m^{-3} = 160 g AN m^{-3}

Then we apply the dilution factor (400) and therefore we come to the following stock solution:

Phosphoric acid 55 %	63.2 L m^{-3}
SO_4K_2	69.76 kg m^{-3}
NO_3NH_4	64.00 kg m^{-3}

Example 27.3 Ideal solution 4-1-2 meq/L. Water with 3.5 meq/L of HCO_3^-. Dilution 400 times. Correction with nitric acid 57 % (density 1.35 g cm^{-3})

To neutralize 3.0 meq/L of HCO_3^- we need 3.0 meq/L of protons which can be supplied by 3 mmol/L of pure NO_3H.

3 mmol /L · 63mg $mmol^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^3$ L m^{-3} = 189 g m^{-3} pure acid

189 g NO_3H $m^{-3} \cdot$ 1 g solution/0.57 g NO_3H · 1 cm^3 solution/1.35 g solution = 245.6 cm^3 m^{-3} (nitric acid 57 %)

Which contains also 3 meq/L NO_3, thus we need a further addition of 1 meq/L of N to complete the required 4 meq N/L.

We apply P as MAP:

1 meq P/L · 115 mg MAP meq $P^{-1} \cdot 10^{-3}$ g $mg^{-1} \cdot 10^3$ L m^{-3} = 115 g MAP m^{-3}

Which contains also 1 meq/L NH_4, therefore satisfying the whole needs of N.

(continued)

Example 27.3 (continued)

Finally we apply K as potassium sulfate:

$2\ \text{meq K /L} \cdot 87.2\ \text{mg PS meq K}^{-1} \cdot 10^{-3}\ \text{g mg}^{-1} \cdot 10^{3}\ \text{L m}^{-3} = 174.4\ \text{g PS m}^{-3}$

We apply the dilution factor (400) and arrive at the following stock solution:

NO_3H	57 %	98.24 L m^{-3}
MAP		46 kg m^{-3}
SO_4K_2		69.76 kg m^{-3}

27.7 Fertigation Control

Electrical conductivity (EC) in emitters can be estimated from water analysis and amount of applied fertilizers. In any case, EC and pH can be measured in emitters to check the accuracy of the calculations. In systems that allow measuring leachate volume and the characteristics (pH, EC) of the input and output solutions, we can check if the fertigation program is correct and amend it if necessary. This would also serve for automation of the fertigation program.

First we set the leaching requirement (LR) as a function of the nutrient solution EC. The observed values of the leaching fraction should be similar to LR. Otherwise the irrigation volume should be adjusted.

A very low nitrate concentration in drainage may indicate that N is limiting, so its concentration should be increased in the nutrient solution.

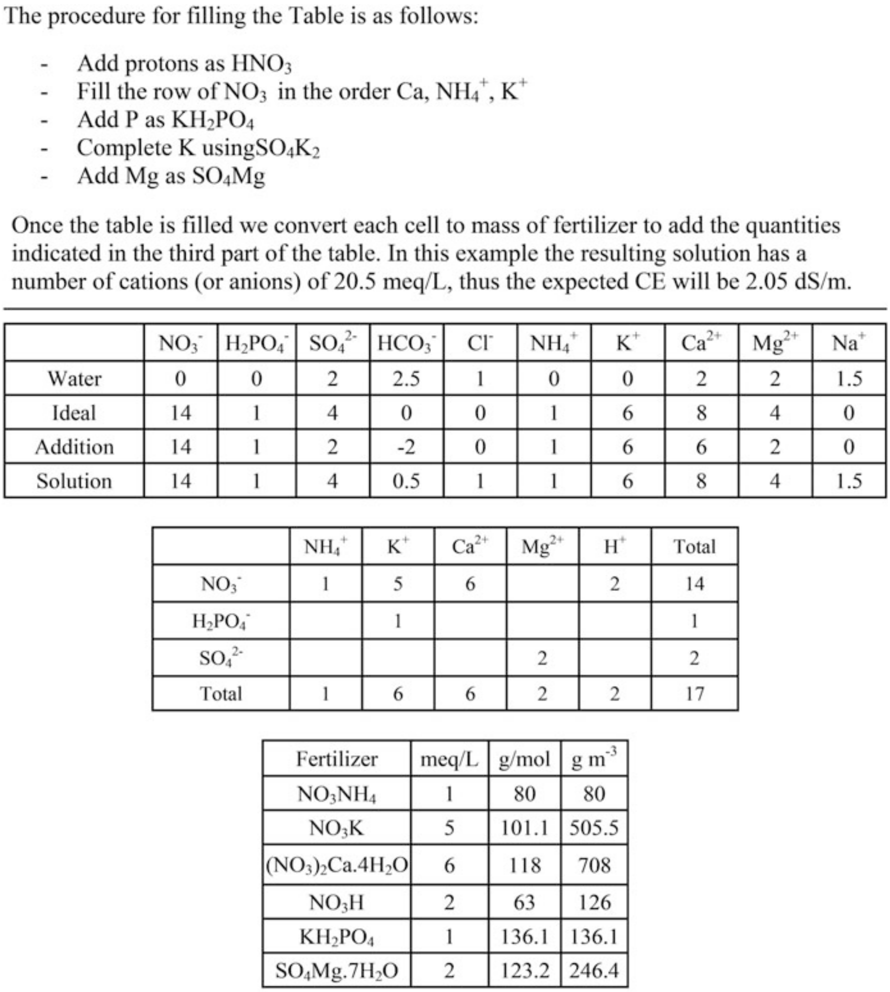
A higher value of EC and/or chlorine in the leachate than in the applied solution indicates an accumulation of salts in the root zone. If the difference between the EC of drainage and that of irrigation is greater than 0.4–0.5 dS/m, and/or if the chlorine concentration in the leachate solution is higher than that of the incoming solution and above 50 mg/L, an irrigation without fertilizers should be applied to leach salts.

The optimum pH of the irrigation solution is 6–6.5 and can be adjusted by acid injection. The drainage water pH should not exceed 8.5. Otherwise the NH_4^+/NO_3^- ratio of the nutrient solution should be increased up to 0.25.

27.8 Calculation of Complete Nutrient Solutions

In the case of hydroponics we need complete solutions including micronutrients. The macronutrients to be added are determined taking into account the composition of the irrigation water and the composition of the ideal solution. A widely used reference nutrient solution is the one proposed by Hoagland and Arnon. The calculation procedure is shown in an example in Table 27.3. Table 27.4 shows the composition of recommended solutions for different species.

Table 27.3 Example of preparation of the Hoagland-Arnon solution. The negative value for addition of bicarbonate indicates the need to apply 2.0 meq/L of a nutrient (e.g. N) as acid



The procedure for filling the Table is as follows:

- Add protons as HNO_3
- Fill the row of NO_3 in the order Ca, NH_4^+, K^+
- Add P as KH_2PO_4
- Complete K usingSO_4K_2
- Add Mg as SO_4Mg

Once the table is filled we convert each cell to mass of fertilizer to add the quantities indicated in the third part of the table. In this example the resulting solution has a number of cations (or anions) of 20.5 meq/L, thus the expected CE will be 2.05 dS/m.

	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	HCO_3^-	Cl^-	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	Na^+
Water	0	0	2	2.5	1	0	0	2	2	1.5
Ideal	14	1	4	0	0	1	6	8	4	0
Addition	14	1	2	-2	0	1	6	6	2	0
Solution	14	1	4	0.5	1	1	6	8	4	1.5

	NH_4^+	K^+	Ca^{2+}	Mg^{2+}	H^+	Total
NO_3^-	1	5	6		2	14
$H_2PO_4^-$		1				1
SO_4^{2-}				2		2
Total	1	6	6	2	2	17

Fertilizer	meq/L	g/mol	g m^{-3}
NO_3NH_4	1	80	80
NO_3K	5	101.1	505.5
$(NO_3)_2Ca.4H_2O$	6	118	708
NO_3H	2	63	126
KH_2PO_4	1	136.1	136.1
$SO_4Mg.7H_2O$	2	123.2	246.4

Table 27.4 Some examples of recommended concentrations (meq/L) of macronutrients in the nutrient solution for different species

	NO_3^-	NH_4^+	$H_2PO_4^-$	K^+	Ca^{2+}	Mg^{2+}	SO_4^-
Tomato and pepper (hydroponics)	15		2	9	10	3	5
Tomato, pepper (on soil)	8.0–12.0	0.9–1.4	1–1.5	4.0–6.0	4.8–7.0		
Melon (on substrate)	6.5–11.5	0.7–1.3	1.2	4.0–7.5	3.5–6.5		
Melon (on soil)[a]	9	0.8	–	7	4.5		
Strawberry[a]	7	3.5	1	4.5			
Bean	9		1	3.3	6.6	2	2
Cucumber	10.5	1	1	5	7.5	2	2
Lettuce, endive	19	1.2	2	9.0–11	9.0–10	2.0–3.0	2.25
Olive	1.4–2.75	0.6–1.25	1	2.0–4.0			2
Citrus	4–5.5	0.5	0.5	1–1.5	2		
Grapevine	2.5–5	0.5–1	1	3.0–6.0			

Adapted from Cadahía (2005)

[a] Supplemented with basal fertilizer for P

The need for adding micronutrients is becoming more frequent as yields have increased which increases the use of micronutrients, the fertilizers used are more pure and thus contain less micronutrients and also because the use of manure has been reduced. The availability of micronutrients usually increases as the organic matter content of the soil or substrate increases and it is reduced by using hard or alkaline water for irrigation. In any case, we should be cautious because micronutrients can become toxic when in excess (Table 27.5). In soils and substrates, metallic micronutrients (Fe, Mn, Cu, Zn, Ni), are usually present as oxides and hydroxides, of low solubility at high pH. Boron and molybdenum, whose concentrations are generally lower than those of metallic micronutrients, are more soluble and may be present in the irrigation water or organic fertilizers. Chlorine is also a micronutrient but is rarely scarce and can be toxic at high concentration.

Micronutrients are added as chelates or salts that can be applied individually or as ready-made solutions. For some species optimal concentrations of micronutrients in the nutrient solution have been determined (Table 27.6). Some authors recommend providing all metallic micronutrients as chelates although there are some available soluble inorganic salts that can be used (e.g. $CuSO_4$), but usually are less effective in providing available nutrient to plants due to oxidation in soil, particularly in the case of Fe. In general inorganic salts, such as sulfates, are the best option for foliar applications. Table 27.7 shows the most commonly used products.

Table 27.5 Allowable concentration of several elements in irrigation water

	Long term mg/L	Short term mg/L	Comments
Aluminium (Al)	5	20	May turn acid soils into unsuited for cropping. Precipitates with pH=5.5–8.0 which eliminates toxicity
Arsenic (As)	0.1	2	Variable toxicity : 12 mg/L (Sudangrass) – 0.05 mg/L (rice)
Beryllium (Be)	0.1	0.5	Variable toxicity : 5 mg/L (cabbage) – 0.5 mg/L (bean)
Boron (B)	0.75	2	Toxic for sensitive species (e.g. citrus) from 1 mg/L. Grasses are tolerant of 2–10 mg/L
Cadmium (Cd)	0.01	0.05	Toxic for beans, beets, radish with 0.1 mg/L
Chromium (Cr)	0.1	1	Scarce information. Caution is recommended
Cobalt (Co)	0.05	5	Toxic for tomato with 0.1 mg/L. It is inactivated in neutral and alkaline soils
Copper (Cu)	0.2	5	Variable toxicity : 0.1–1.0 mg/L
Fluorine (F –)	1	15	It is inactivated in neutral and alkaline soils
Iron (Fe)	5	20	Not toxic in well aerated soils. Induces acidification and losses of P and Mo
Lead (Pb)	5	10	May inhibit cellular growth at high concentration
Lithium (Li)	2.5	2.5	Most crops are tolerant up to 5 mg/L except for Citrus (limit 0.075 mg/L). Moves in the soil
Manganese (Mg)	0.2	10	Variable toxicity in acid soils
Molybdenum (Mo)	0.01	0.05	Not toxic for plants in general. May be toxic for cattle when pastures grow on rich soils
Nickel (Ni)	0.2	2	Toxic for some species at 0.5–1.0 mg/L. Lower toxicity in neutral and alkaline soils
Selenium (Se)	0.02	0.02	Toxic for plants at low concentration. May be toxic for cattle when pastures grow on soils with low concentration
Vanadium (V)	0.1	1	Toxic for many species at low concentration
Zinc (Zn)	2	10	Toxic for many species. Toxicity is reduced when pH>6 and in clay and organic soils

Table 27.6 Recommended concentrations (mg/L) of micronutrients in the nutrient solution

	Mn	Fe	B	Mo	Cu	Zn
Olive, grapevine, citrus	0.5–1	1–1.4	1–1.1	0.01–0.02	0.05–0.8	0.05–0.2
Tomato, pepper, eggplant	0.5–1	0.8–2	0.3–0.5	0.05	0.05–0.1	0.03–0.1
Strawberry, bean, cucumber	0.5	1	0.3–0.5	0.05–0.1	0.1–0.2	0.1–0.2
Lettuce, endive	0.3–0.5	2.2	0.32	0.05	0.05	0.3

Adapted from Cadahía (2005)

Table 27.7 Products commonly used for correcting micronutrient deficiency. It must be noted that for correction of Fe deficiency chlorosis in calcareous soils most of Fe present in EDDHA-Fe should be orto-orto

Element	Chemical	% element	Preferred use
Boron	H_3BO_3	17	
	$Na_2B_4O_7.5H_2O$	20	
	$Na_2B_4O_7.10H_2O$	11	
	$Ca_2B_6O_{11}.5H_2O^a$	10	
Copper	$CuSO_4.5H_2O$	25	Foliar
	CuO^b	50–75	Soil
Iron	$FeSO_4.7H_2O$	20	Foliar
	FeHEDTA	5–9	Soil
	FeEDDHA[1]	6	Soil
Manganese	$MnSO_4.4H_2O$	24	Foliar
	MnO^b	41–68	Soil
	Mn oxisulfate	30–50	Soil
Molybdenum	$Na_2MoO_4.2H_2O$	39	Foliar
	$(NH_4)_2MoO_4$	49	
	MoO_3	66	Soil
Zinc	$ZnSO_4.H_2O$	36	Foliar
	Complex $ZnSO_4$ -NH_3	10–15	
	ZnO^b	60–78	Soil
	Zn oxisulfate	18–50	Soil
	ZnEDTA	6–14	Soil

All products are soluble in water except those marked with [a](slightly soluble) or [b](insoluble)

27.9 Examples of Fertigation Programs

Example 27.4 An orange grove has an annual N fertilizer requirement of 200 kg N/ha. The total amount of irrigation applied is 500 mm. We will calculate the amount of fertilizer to add to the stock solution (dilution ×200) to meet those N needs.

We assume that we want to apply only N so we rule out NP and NK fertilizers, and restrict to urea and ammonium nitrate. We could also apply other fertilizers containing sulfur, calcium or magnesium but they are discarded because of their low N concentration.

Irrigation water should have a concentration:

$$200 \text{ kg N}/5000 \text{ m}^3 = 0.04 \text{ kg N m}^{-3} = 40 \text{ g N m}^{-3}$$

The two alternatives would be:

$$40 \text{ g N m}^{-3}/0.34 = 117.6 \text{ g ammonium nitrate m}^{-3}$$
$$40 \text{ g N m}^{-3}/0.46 = 87 \text{ g urea m}^{-3}$$

(continued)

Example 27.4 (continued)

The alternative stock solutions for a 200 dilution would have concentrations of:

117.6 g ammonium nitrate $m^{-3} \cdot 200 = 23.52$ kg ammonium nitrate m^{-3}
87 g urea $m^{-3} \cdot 200 = 17.4$ kg urea m^{-3}

Example 27.5 A citrus orchard requires 200 kg N/ha and 270 kg K/ha with a total irrigation application of 500 mm. We will calculate the stock solution (dilution ×200) to meet those needs of N and K.

Our first choice is a fertilizer containing both K and N, potassium nitrate. To supply 200 kg N/ha and 270 kg K/ha, as the concentrations of N and K are 13.4 % and 39 %, respectively, we should add:

270 kg K/ha/(0.39 kg K/kg potassium nitrate) = 692 kg potassium nitrate/ha
692 kg potassium nitrate/5000 $m^3 = 138.4$ g potassium nitrate/m^3

That contributes also:

692 kg potassium nitrate/ha · 0.134 kg N/kg potassium nitrate = 92.8 kg N/ha
We still need to add $200 - 92.8 = 107$ kg N/ha
That are equivalent to 315 kg ammonium nitrate/ha or 233 kg urea/ha.

If we choose urea, the concentration in irrigation water will be:

233 kg urea/5000 $m^3 = 46.6$ g urea/m^3

And the stock solution will be:

27.68 kg potassium nitrate m^{-3} and 9.32 kg urea m^{-3}

Alternatively we could have used simple fertilizers (urea and potassium chloride) and the stock solution would be:

21.68 kg potassium chloride m^{-3} and 17.4 kg urea m^{-3}

Considering that the solubility of potassium chloride and urea are much higher (Table 27.1), concentrations could be an order of magnitude greater. This implies a greater dilution factor (2000) that would allow a smaller size of the tank as illustrated in the following example.

Example 27.6 Calculate the minimum size of the fertigation tank for the previous example considering that the maximum irrigation requirement is 4.5 mm day^{-1} and that the fertilizer is added every day. We will consider only the option of using urea and potassium nitrate.

(continued)

Example 27.6 (continued)

The required concentrations in irrigation water were calculated in Example 27.5:

138.4 g potassium nitrate/m^3
46.6 g urea/m^3

Now by looking at Table 27.1 we see that the maximum concentration to be allowed in the stock solution (taken as 80 % of solubility) would be;

Urea: 826.4 kg m^{-3} Potassium nitrate: 252.8 kg m^{-3}

The most limiting case is that of potassium nitrate which leads to a maximum dilution factor of:

252,800/138.4 = 1827

The stock solution should be:

Urea: 85.138 kg m^{-3}
Potassium nitrate: 252.857 kg m^{-3}

The amount of irrigation to be applied is 45 m^3 ha^{-1} day^{-1} which requires 24.63 L ha^{-1} day^{-1} of stock solution. This is the minimum volume required for the tank. For instance in a 10-ha orchard we would require a tank larger than 246 L.

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Chapter 28
Manipulating the Crop Environment

Francisco J. Villalobos, Luca Testi, and Luciano Mateos

Abstract Windbreaks are structures that reduce wind speed and may affect turbulence in the protected zone. The maximum efficiency is obtained with windbreaks of medium porosity that reduce wind speed up to a distance 20–25 times their height. In the area protected by a windbreak temperature oscillations are larger, which in some areas may increase frost risk and dew deposition.

Soil temperature can be modified by changing its exposure to radiation, by artificial heating or by mulching. Mulches can be natural (e.g. crop residues) or artificial, most notably plastic films. Canopy temperature can be reduced by wetting with sprinklers although it is only effective with high VPD and implies excessive water use. Simple models of the energy balance may be applied to calculate the minimum and the maximum crop temperature. Additional environmental control may be performed with row covers and greenhouses that create a warmer wind-protected environment and are increasingly popular in horticultural production.

28.1 Introduction

There are limited possibilities for modifying the aerial environment of crops grown outdoors. In this chapter we discuss these possibilities starting with protecting crops from wind and then proceeding with environmental manipulations to modify soil and crop temperatures.

The main factor that can be manipulated is wind which may be modified by placing physical structures (inert or living) in the edges of fields. The structures may form walls, called windbreaks, whose main objective is to reduce wind speed. The term shelterbelt refers to several rows of trees and shrubs. The structures may be

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scattered isolated trees which not only affect wind flow in the area but also have a protective effect by intercepting rainfall. This association of crops and protective trees is termed agroforestry. In such systems the trees may yield timber and/or fruit which directly contribute to farm income, besides protecting the crops.

The use of windbreaks has been a common practice in agricultural systems of regions with strong winds since long ago. An example would be the protective windbreaks against the mistral wind in the Rhone Valley in southern France. In the Great Plains of the U.S. the use of windbreaks were common after the 1930s to protect the soil from wind erosion after a long period of drought (Dust Bowl). At present they are only used in regions where wind poses substantial risks to agricultural production. Because they use valuable land, windbreaks are mostly used in horticulture (fruit tree production).

In contrast to their beneficial protective effects, windbreaks also have negative effects. First they occupy part of the arable land, and they reduce incident radiation on the cropped areas close to the windbreaks. If they are living structures, they may also compete for water and nutrients and may serve as shelter for some pests. But despite these drawbacks, most studies in windy areas have shown an overall positive effect of windbreaks on crop yields.

28.2 Effects of Wind on Crops

The effects of wind on crops and soils are diverse:

- Growth: Plant movement due to wind can reduce crop growth rate and increase plant's mechanical resistance (shorter and thicker stems, increased root/shoot ratio). This phenomenon called thigmomorphogenesis, does not require a continuous stimulus but may be triggered by infrequent movements.
- Mechanical damage: The wind's force can tear leaves or strip them from the plant. In dense canopies, abrasion may result from the rubbing of plant leaves and stems. An indirect mechanical damage may be caused by the impact of soil particles carried by wind.
- Crop lodging: This is caused by strong winds after wetting the canopy by rainfall or irrigation, which increases the load on the plant and the bending moment and decreases the stability of the root plate. The result is that the stems bend or break at some point near the ground surface and the crop lays on the ground.
- Crop evaporation is proportional to wind speed when crops are well watered. Therefore crops will use soil water faster in unprotected areas.
- Dry and hot winds may cause grain shriveling in cereals during early grain filling.
- Salinization in coastal areas may occur due to wind drifts from the sea
- Wind affects the variation of surface temperature. Therefore the risk of frost may increase in protected areas (see Chap. 29).

28.3 Windbreaks

Windbreaks are structures established to reduce wind speed and change its direction. Hedges may be formed by plants (shrubs, trees or annuals) or inert structures (hurdles, plastic mesh enclosure walls or other specific structures). Apart from reducing wind speed, plant windbreaks provide additional benefits such as providing shelter for wildlife, protecting the livestock from weather elements and becoming a barrier for sound and smell. In addition some agricultural operations are improved in protected areas like reduced pesticide drift and higher uniformity of sprinkler irrigation or pesticide spray application. A better environment for farm workers is also created. In some areas, environmental authorities encourage the development of windbreaks as a means to increase biodiversity and to enhance the landscape by developing specific policies that provide incentives to farmers. The increase in biodiversity (especially animal) is often beneficial as birds and insects often prey on pests helping to reduce their impact. In some cases, however, windbreaks may host detrimental insects, maintaining populations stocks which can feed on the crops once they are established. The species composition of windbreaks should then be chosen following an ecological rationale in addition to the aerodynamic considerations addressed below.

Field windbreaks may be single rows of trees or shrubs or multiple-row shelterbelts. The later provide better conditions for wildlife and may be formed by four to five rows of alternating trees and shrubs. Taller species should be placed in the center of the belt while shorter species can be placed on each side. Deciduous trees have the disadvantage of losing much of their protective capacity during winter. Tall annual crops may be used to protect shorter crops.

28.4 Wind and Turbulence in the Sheltered Zone

Windbreak structure -height, density, number of rows, species composition, length, orientation, and continuity – determines the effectiveness of a windbreak in reducing wind speed and altering the microclimate.

The effectiveness of the windbreak depends mainly on its width, its height and its porosity. Effectiveness is measured as the distance downwind, expressed as number of shelter heights, through which the wind speed is reduced relative to that in the open.

On the windward side of a windbreak, wind speed is reduced upwind for a distance of two to five times the height of the windbreak (2H to 5H). On the leeward side, wind speed may be reduced up to 30H downwind of the barrier (Fig. 28.1).

Windbreak porosity is the ratio of the open fraction of the barrier to its total volume. Wind flows through the open portions of a windbreak, thus the less porous a windbreak, the less wind passes through. Low pressure develops on the leeward

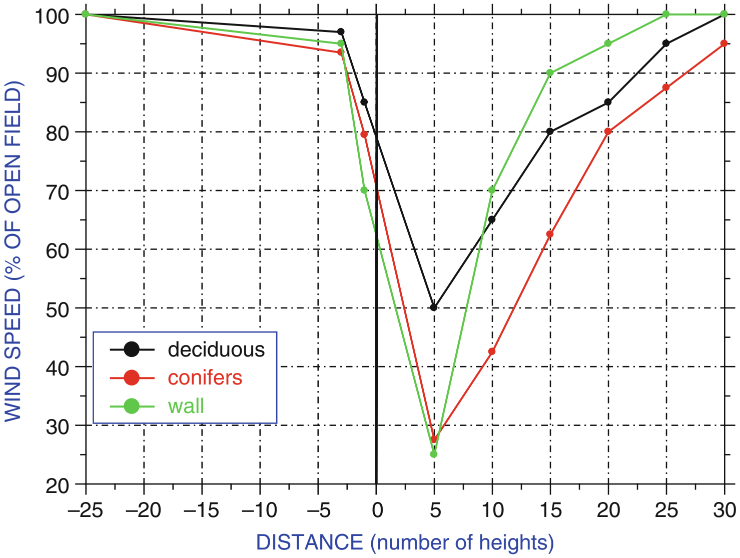

Fig. 28.1 Variation of wind speed (as percent of its value in the open) as a function of distance from the windbreak, expressed as number of heights. Negative and positive values represent the windward and leeward sides, respectively. The porosity is 70–75 % for deciduous and 20–60 % for conifers

side of very dense windbreaks, which pulls down air coming over the barrier, generating additional turbulence and reducing protection downwind. As porosity increases, so does the flow passing through the barrier, thus turbulence is not enhanced, and the effectiveness increases, although the magnitude of wind speed reductions are not as great.

Dense windbreaks (porosity lower than 25 %) show effectiveness (E_w) of 10–15H. With permeability around 50 % the effectiveness increases to 20–25H (Fig. 28.1), without addition of large scale turbulence. These values of effectiveness vary however with different factors such as wind speed (E_w is proportional to wind speed), the atmospheric stability (E_w is larger in unstable conditions), wind direction (E_w is maximum when wind direction is normal to the barrier). Even when wind blows parallel to the barriers some effect is observed. Windbreaks with intermediate porosity (40–60 %) are usually the most effective.

28.5 Establishment and Maintenance of Windbreaks

Trees or shrubs to form windbreaks should grow rapidly, have strong erect stems able to withstand wind forces and a well anchored root system. They should also be able to survive under the prevailing abiotic stresses of the area (drought, cold). Among plant windbreaks, the most commonly used species are conifers such as cypress (*Cupressus spp.)*, spruce (*Picea spp.*) or pine (*Pinus spp.*). Other trees used are poplars, eucalyptus, etc. Each species and, within species, each variety have characteristics of adaptation to the environment that determine which is most appropriate in each case. There are also differences between species and varieties with regard to competition with the crop, which come mainly from the patterns of root growth which may be shallow or able to explore deeper soil horizons.

The orientation of windbreaks depends on the design objectives. Farmsteads and feedlots usually need protection from cold winds and blowing snow during winter. Field crops and fruit trees usually need protection from hot, dry summer winds, or wind-blown soil particles, in special during critical growing periods. Windbreaks for soil erosion control should be normal to the prevailing winds when the soil is bare (winter and early spring). To recharge soil moisture with drifting snow, windbreaks should be placed perpendicular to the prevailing winter winds.

Despite of the existence of a predominant wind direction during given periods, wind direction may vary from day to day or during the day, so the level of protection by the windbreak may be reduced. A set of multiple windbreaks forming parallel lines spaced 10–15H provides a larger protected area than a single windbreak. If protection from several wind directions is required another set of parallel lines, normal to the first, would be established, resulting in a rectangular arrangement of protected fields.

Sometimes gaps have to exist in the windbreak to allow access to the fields. The uninterrupted length of a windbreak should exceed the height by at least 10:1. This is because gaps in a barrier become funnels that concentrate wind flow, leading to wind speeds in the protected area that may even exceed those in the open.

The plantation of a windbreak follows the same rules of other plantations although the distance between trees may be smaller (e.g. 3 m between rows, 2 m between trees in the row) and high survival and rapid growth are critical. It is therefore very important to replace as soon as possible any tree lost and provide the young trees with supplemental irrigation during dry periods and protection against browsing by animals (by planting thorny plants or putting a barbed-wire fence). Control of weeds is critical in particular during the early years of the plantation.

As the trees grow some pruning may be required to keep the required porosity, promote vertical growth and eliminate branches damaged by wind or pests. Tree thinning may be required to enhance trunk diameter growth.

28.6 Microclimate Changes in the Protected Area

Both solar radiation and net radiation are reduced significantly in the area shaded by windbreaks. The effect is almost nil for distances beyond 1–2H. The effect is marginal for north-south oriented barriers, as the shaded area is very small around noon when radiation is at its maximum. Further reduction by shading may occur early in the morning or late afternoon, but is partly compensated by reflection of radiation from the windbreak.

The largest effect on radiation occurs in east-west oriented barriers, on the area to the north (in the North hemisphere) of the windbreak, in special for high latitudes and winter periods.

The reduction of wind speed, and thus, in turbulence in the protected areas has several effects on:

(a) temperature: During the day it favors soil heating (Chap. 6), which usually leads to warmer soil surface and air above. During the night strong temperature inversions will develop leading possibly to lower minimum temperatures. This explains the increased frost risk in protected areas.
(b) vapor pressure: It tends to increase close to the canopy during the day, when plants are transpiring, as mixing is reduced, particularly in calm days. During the night the higher vapor pressure and the lower temperature enhances dew deposition in protected areas. The combination of higher vapor pressure or plants wet by dew with higher temperature may increase the incidence of diseases.
(c) evapotranspiration: For well watered crops reduced wind speed means higher aerodynamic resistance (Chaps. 4 and 9) and therefore, reduced ET. This effect may be offset partly by a reduction in canopy resistance in some species. However, the improved environment in the protected area may increase crop growth and hasten depletion of soil water. In rainfed crops subjected to water stress late in the growing cycle, the overall effect may be a reduction in Harvest Index in protected areas. However, well-watered crops show the same or higher yield with reduced ET, which means a higher Water Use Efficiency.
(d) chill factor. Heat losses of livestock, wildlife and structures (farmstead, greenhouses, etc.) due to wind-chill are reduced on the leeward side of a windbreak.

28.7 Scattered Windbreaks

The presence of scattered trees in the field reduces the average wind speed because of the increase in roughness. The reduction will be proportional to the fraction of area covered by trees. The main difference of scattered trees and regular rows is the degree of interaction (including competition) tree-crop which is higher when trees are scattered. In this case the tree also provides protection to crop and soil from direct rainfall impact. The negative effects are:

- the increased competition for light as isolated trees will intercept more radiation, as well as for water and nutrients with the rest of the vegetation.
- additional difficulties for cultural operations as trees become obstacles for the machinery.
- higher cost of establishing isolated trees, in special when young trees have to be protected against wildlife or farm animals.

28.8 The Importance of Soil, Air and Crop Temperatures

Soil and air temperatures influence numerous critical processes of the crop. Seed germination and plant emergence are extremely sensitive to the temperature of the soil. The time from sowing to emergence increases and seedling growth is also slower when the soil is cold. Canopy temperature has an important effect on critical plant processes (development, growth, assimilation) and thus on crop productivity.

The root distribution is also affected by soil temperature. In some species root growth is restricted to the upper layers when the soil is too cold, while a much deeper root distribution is observed at higher temperatures, which improves water and nutrient uptake. Other processes that respond to soil temperature are symbiotic nitrogen fixation, photosynthesis, water flow in the soil-plant system (water viscosity is high at low temperature), mineralization of organic matter and soil respiration.

In summary, soil and air temperatures have varied effects on crops and their control may increase yields. Therefore artificial soil and/or air heating is sometimes used in high value crops. The alternatives for crops grown outdoors are limited but some may be very effective for manipulating soil temperature.

28.9 Slope and Aspect

The irradiance on a given surface increases as the incidence angle of solar rays decreases, and is maximal when the radiation vector is normal to the surface. The effect of slope and orientation (aspect) of the surface will be proportional to the fraction of beam (direct) radiation reaching the surface, which lies between 0 (cloudy sky) and 0.85 (clear atmosphere with zero zenith angle). Slope and aspect of a plot is less important when solar zenith angle is high or low, although for different reasons. The fraction of direct radiation decreases as zenith angle increases due to the longer path of atmosphere that sun rays cross to reach the earth. Therefore the slope and aspect of a surface will barely affect irradiance in high latitudes. On the other hand, for very low latitudes zenith angle is so small that orientation has little effect on irradiance. The same reasoning may be applied to seasonal changes: slope and aspect are important in spring or autumn but less important in summer (low zenith angle) and winter (high fraction of diffuse radiation).

Figure 28.2 shows the temperature in different places of a field with furrows in the north-south direction. The temperature at the furrow is lower than on the ridge. On the sloping sides, the temperature is typically higher than on the ridge, with the side facing East warmer in the morning and the side facing West warmer in the afternoon.

North-facing and South-facing slopes are colder and warmer, respectively, in the Northern hemisphere.

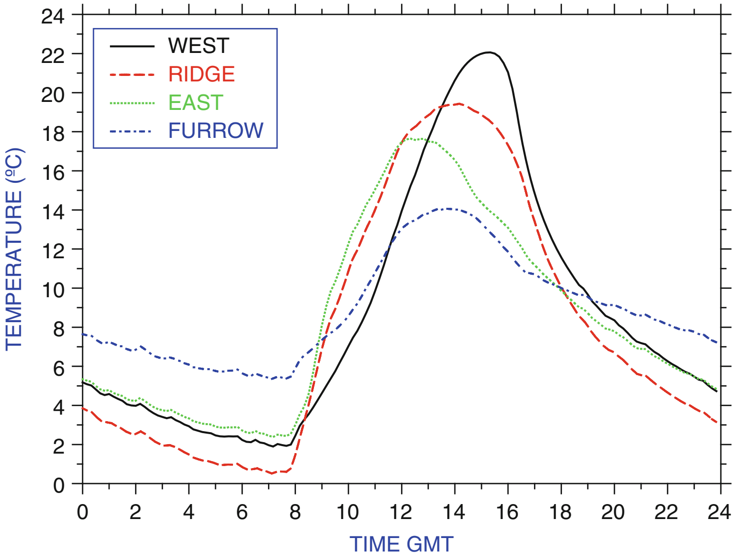

Fig. 28.2 Time course of soil temperature at 2.5 cm depth in a North-South ridged sandy loam soil in Cordoba (Spain)

28.10 Mulching

A mulch is a layer of material covering the soil and acting as a barrier to heat or water transport. Additional functions of mulches include soil protection against erosion and weed control. Some common mulches are weed residues, straw and other crop residues, inorganic mulches (plastic films, gravel, sand) and industrial byproducts (bark, wood chips, etc.).

The effect of mulching on soil temperature has to be evaluated by considering first the possible change in net radiation. Black plastic will increase net radiation (reduced albedo) while straw will reduce it (high albedo). The second aspect to be considered is water transport. Mulches may reduce water flow or even suppress it (plastic films). Therefore in many cases more energy will be available for heating the air (straw) or the air and the soil. A transparent plastic will enhance soil heating much more than a black plastic (Fig. 28.3). The latter absorbs radiation but transmits and reflects little, so the black plastic is heated and may reach high temperatures. However, conduction of heat to the soil is limited by the air layer between the plastic and the soil surface. The transparent plastic is transparent to short wave radiation but blocks little long wave radiation. Therefore during the night the soil under transparent plastic cools like the control (bare soil) while the black plastic keeps the soil warmer due to the low transmissivity for long-wave radiation. Straw transmits little radiation which reduces soil warming during the day and cooling during the night.

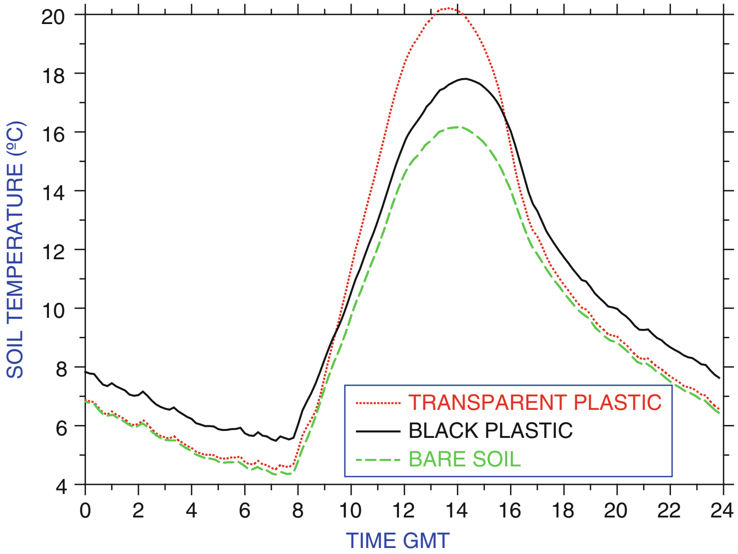

Fig. 28.3 Time course of soil temperature at 2.5 cm depth under black or transparent plastic films in a sandy loam soil in Cordoba (Spain)

Transparent plastic films are used widely in horticultural crops during the spring to increase soil temperature and thus, speed up crop development for early production and to reduce season length. Earlier harvest leads to better prices in many horticultural crops. In addition to the effect on temperature, soil water is conserved in the upper soil layer, which prevents the appearance of a surface crust and improves the conditions for germination, emergence and early seedling growth.

Black plastic is also often used in vegetable crops, but the main objective is weed control . Many weed seeds will remain dormant in the dark and those that do germinate will die soon due to lack of carbohydrates. Another advantage of a plastic cover (valid also for transparent films) is preventing the contact of fruits with the soil thus avoiding diseases.

Most mulches, and especially those of organic origin (straw, crop residues, cover crops) act as insulators, i.e. they damp the soil temperature waves, and therefore will keep the soil cooler when applied in spring (Fig. 28.4) or warmer if applied in the summer. Mulched spring sown crops (e.g. direct sowing with residues) will thus show a slower development. The effect on the water balance depends on rainfall distribution: frequent and light rains will wet the mulch and most water will evaporate directly from it. Heavier and isolated rainfalls will infiltrate better in mulched soil and soil evaporation will be reduced.

Inorganic mulches like sand or gravel have excellent properties as they do not reduce soil heating while are very effective in reducing soil evaporation and increasing infiltration.

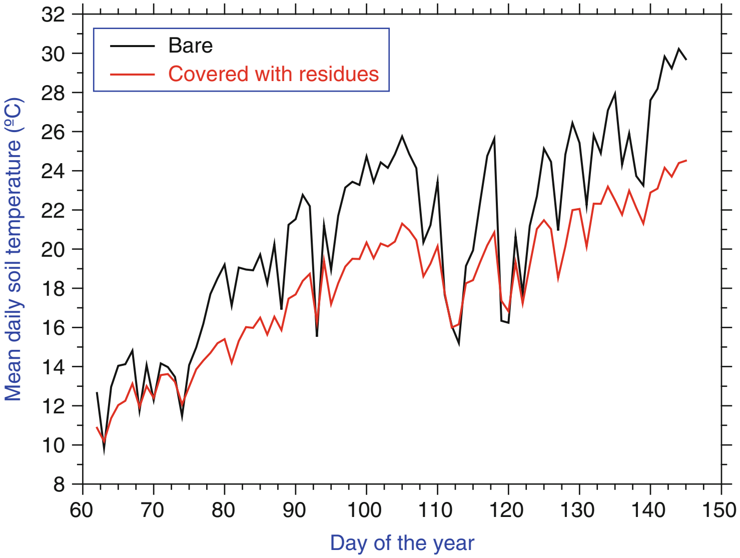

Fig. 28.4 Mean daily surface soil temperature for a sandy loam soil in Cordoba (Spain) in 2011, covered with straw or bare

28.11 Artificial Soil Heating

In very special situations (nurseries, sport stadiums, high value horticulture) the soil may be heated using electrical cables or pipes with hot water. The cost may be reduced when hot water from cooling operations in industry or power plants is available as a byproduct.

28.12 Modifying Canopy Temperature

Windbreaks increase temperature oscillations in the protected area (see 28.5). An alternative for reducing canopy temperature of crops grown in the open is wetting the plants. Some time ago a group of researchers in the USA proposed the use of frequent irrigation to keep the canopy wet, and thus bring canopy temperature closer to its optimum in order to increase productivity.

Using the equations for sensible and latent heat flux we may compute the difference in temperature between the canopy and the air above as:

$$T_c - T_a = \frac{1}{\Delta + \gamma\left(1 + {}^{r_c}/_{r_a}\right)}\left[\frac{\gamma\left(1 + {}^{r_c}/_{r_a}\right)(R_n - G)r_a}{\rho\, C_p} - VPD\right] \tag{28.1}$$

Now, if the canopy is wet, canopy resistance is zero, so canopy temperature is now given by:

$$T_c^w - T_a = \frac{1}{\Delta + \gamma} \left[\frac{\gamma (R_n - G) r_a}{\rho\, C_p} - VPD \right] \tag{28.2}$$

The difference in temperature between the dry and the wet canopy will be:

$$\begin{aligned} T_c - T_c^w &= \frac{\gamma\, r_c}{[\Delta + \gamma\, (1 + {}^{rc}/_{ra})]\, (\Delta + \gamma\,)} \left[\frac{\Delta\, (R_n - G)}{\rho\, C_p} + \frac{VPD}{r_a} \right] \\ &= \left[\frac{\Delta\, (R_n - G) + \rho\, C_p{}^{VPD}/_{r_a}}{\Delta + \gamma} \right] \frac{\gamma\, r_c}{\rho\, C_p\, [\Delta + \gamma\, (1 + {}^{rc}/_{ra})]} \end{aligned} \tag{28.3}$$

The cooling due to wetting the canopy is proportional to radiation, VPD and to canopy resistance. Note that the left term in Eq. 28.3 is the latent heat flux according to the Penman-Monteith equation for zero canopy resistance (LE_w). So the increase of evaporation when the canopy is wet may be written as:

$$\begin{aligned} LE_w - LE &= \left[\frac{\Delta\, (R_n - G) + \rho\, C_p{}^{VPD}/_{ra}}{\Delta + \gamma} \right] - \left[\frac{\Delta (R_n - G) + \rho\, C_p{}^{VPD}/_{ra}}{\Delta + \gamma\, (1 + {}^{rc}/_{ra})} \right] \\ &= LE \frac{\gamma^{rc}/_{ra}}{\Delta + \gamma} \end{aligned} \tag{28.4}$$

Therefore the relative increase of evaporation due to wetting is proportional to r_c/r_a. We can also deduce the reduction in canopy temperature per unit increase in latent heat flux:

$$\frac{T_c - T_c^w}{LE_w - LE} = \frac{r_a}{\rho\, C_p} \tag{28.5}$$

According to this equation, the efficiency of cooling a crop, taken as the ratio of temperature decrease and the increase in water use, will be higher for smooth (short) crops and low wind.

Example 28.1 An irrigated crop with $r_c = 40$ s/m and $r_a = 40$ s/m at midday in summer (R_n-G = 600 W/m^2) in an arid area (air temperature 40 ºC and relative humidity 30 %). At 40 ºC, $\rho\ C_p = 1140\ \mathrm{J\ K^{-1}\ m^{-3}}$

$e_s = 0.6108 \exp[17.27 \times 40/(40 + 237.3)] = 7.37$ kPa
$e_a = e_s \times HR/100 = 2.21$ kPa
VPD = 7.37–2.21 = 5.16 kPa
$\Delta = 4098 \cdot 7.37/(40 + 237.3)^2 = 0.39$ kPa/K

(continued)

Example 28.1 (continued)

If the canopy is dry, latent heat flux according to the Penman-Monteith equation is

$$LE = \frac{\Delta(R_n - G) + \rho\, C_p {}^{VPD}\!/_{r_a}}{\Delta + \gamma(1 + {}^{r_c}\!/_{r_a})} = \frac{0.39 \cdot 600 + 1140 \cdot 5.16/40}{0.39 + 0.067\ (1 + 40/40)} = 727\ W\ m^{-2}$$

and canopy temperature is:

$$T_c = 40 + \frac{1}{0.39 +\ 0.067\ (1 + {}^{40}\!/_{40})} \left[\frac{0.067\ (1 + {}^{40}\!/_{40})\ 600\ \cdot\ 40}{1140} - 5.16 \right] = 35.5°C$$

If we wet the canopy, LE will be:

$$LE_w = \frac{\Delta(R_n - G) + \rho\, C_p {}^{VPD}\!/_{r_a}}{\Delta + \gamma} = \frac{0.39 \cdot 600 + 1140 \cdot 5.16/40}{0.39 + 0.067} = 834\ W\ m^{-2}$$

And the cooling effect would be:

$$\begin{aligned} T_c - T_c^w &= LE_w \frac{\gamma\, r_c}{\rho\, C_p[\Delta + \gamma(1 + {}^{r_c}\!/_{r_a})]} \\ &= 834\ \frac{0.067 \cdot 40}{1140\ [0.39 + 0.067\ (1 + {}^{40}\!/_{40})] = 3.7\ K} \end{aligned}$$

So the temperature of the wet canopy would be 31.8 ºC.

Apart from increasing crop water use, frequent wetting can have adverse effects by promoting some diseases and reducing crop nutrient uptake (less water flowing from the soil through the plant).

28.13 Minimum Crop Temperature

Air temperature is routinely measured in weather stations with shielded sensors at standard height (e.g. 1.5 m). However, actual canopy temperature (T_c) will usually differ from that value (Chap. 5). The main factors determining the difference between air temperature at the weather station (T_{aw}) and T_c are net radiation, wind speed, air humidity and aerodynamic roughness (Chap. 4). The calculation of this difference for the minimum temperature may be performed using a rather simple model as during nighttime net radiation is only long wave, wind speed is

Table 28.1 Calculated difference between crop and air minimum temperature when air temperature at the weather station is 0 ºC and wind speed is low

	Short crop h = 0.1 m		Tall crop h = 1 m	
RH	Cloudy	Clear	Cloudy	Clear
70	1.37	4.05	0.80	2.53
100	0.64	2.41	0.32	1.25

Two conditions of cloudiness (completely overcast or clear) and two conditions of relative humidity (rather dry, 70 % and saturated 100 %) have been considered for crops of height 0.1 m and 1 m

usually low and relative humidity is high. An example of model results are presented in Table 28.1 for two crops with height 0.1 m (e.g. grass) and 1 m (e.g. cereal) when air temperature is 0 ºC and wind speed is low. It is clear that the difference T_{aw}-T_c is smaller for the taller crop, when the sky is overcast and when humidity is high.

28.14 Calculation of Maximum Canopy Temperature

Maximum canopy temperature also differs from maximum air temperature. High canopy temperatures may be detrimental to critical reproductive stages (e.g. pollination in cereals) so it is important to understand how it is affected by environmental factors. Again turbulence is a main determinant of the difference in temperature between the crop and the air above: as wind speed increases the difference between the two is reduced. However, water deficits that induce stomatal closure decrease transpirational cooling and thus increase canopy temperature. Therefore, the impact of high temperatures on crops is amplified by water deficits. Here we present a simple procedure for calculating expected maximum crop temperature from standard weather data.

Using Eqs. 9.10 and 9.12 we compute maximum canopy temperature as:

$$T_{cx} = T_{ax} + [(1 - f_G)R_n - LE]\frac{r_{aH}}{\rho\, C_p} \qquad (28.6)$$

where T_{cx} and T_{ax} are maximum canopy and air temperature (ºC), respectively, f_G is the fraction of net radiation invested in soil heat flux (taken as 0.1 during the daytime), LE is latent heat flux, r_{aH} is aerodynamic resistance for heat exchange, ρ is air density and C_p is specific heat of air.

This equation is evaluated at the time of maximum temperature, which is assumed to occur 3 h after solar noon. At that time, solar radiation on sunny days is approximately 84 % of the value at solar noon. We also assume that on average, net radiation is 60 % of solar radiation, so:

$$R_{nx} = 0.6 \cdot 0.84 \cdot \frac{\pi}{2} \cdot \frac{10^6 R_{sd}}{3600\, N} \tag{28.7}$$

where R_{nx} is net radiation (W m^{-2}) at the time of maximum temperature, R_{sd} is daily solar radiation (MJ m^{-2} day^{-1}), and N is daylength (hour).

The time course of latent heat flux (LE) along the daytime is assumed to follow a sine function, with the maximum occurring at the time of maximum air temperature. Therefore, maximum LE (LE_x, W m^{-2}) is computed as:

$$LE_x = \frac{\pi}{2} \cdot \frac{2.45 ET}{10^{-6}\, 3600 N} \tag{28.8}$$

where ET is daily actual evapotranspiration (mm day^{-1}).

Calculation of r_{aH} for unstable conditions may be performed using a simplified equation derived from the model of Thom and Oliver as a function of wind speed over grass (U_{2g}):

$$r_{aH} = \frac{25.9}{1 + 2.3\, U_{2g}/c_w} \tag{28.9}$$

The coefficient c_w depends on crop height and lies between 7.3 (h = 0.5 m) and 5.5 (h = 3 m).

The calculation of wind speed at the time of maximum temperature is performed by assuming that mean daytime wind speed is twice the mean value during the nighttime, and that the value during the day is a sine function. Therefore, at the time of maximum temperature, wind speed at the weather station is:

$$U_{2gx} = \left(1 + \frac{\pi}{2}\right) \frac{U_{2gm}}{1 + N/24} \tag{28.10}$$

where U_{2gm} is the mean (24-h) wind speed measured at the weather station.

For field crops typical values of r_{aH} are between 6 (high wind speed) and 12 s/m (moderate wind speed) with only a minor effect of crop height.

Example 28.2 Wheat at flowering stage at Cordoba, Spain.

11 April 2014. $C_w = 6.6$, daylength = 13 h

Maximum air temperature 29.7 ºC, Reference ET= 5.1 mm/day, $R_{sd} = 22.7$ MJ m^{-2} day^{-1}

Mean wind speed (weather station) = 2.3 m/s

The maximum crop coefficient of wheat during this period is 1.1 (Chap. 9) so:

$ET = 1.1 \times ET_0 = 5.6$ mm/day

(continued)

Example 28.2 (continued)

Maximum wind speed (weather station):

$$U_{2gx} = \left(1 + \frac{\pi}{2}\right)\frac{U_{2gm}}{1 + {}^{N}\!/_{24}} = 1.667 \cdot 2.3 = 3.84\ m/s$$

Aerodynamic resistance:

$$r_{aH} = \frac{25.9}{1 + 2.3\ \cdot\ 3.84/6.6} = 11.1 s/m$$

Maximum net radiation over the crop:

$$R_{nx} = 0.6 \cdot 0.84 \cdot \frac{\pi}{2} \cdot \frac{10^6 R_{sd}}{3600N} = 384\ Wm^{-2}$$

$$LE_x = \frac{\pi}{2} \cdot \frac{2.45 \cdot ET}{10^{-6}\ 3600 \cdot N} = 460\ Wm^{-2}$$

So maximum canopy temperature will be:

$$\begin{aligned} T_{cx} &= T_{ax} + [(1 - f_G)R_{nx} - LE_x]\frac{r_{aH}}{\rho\, C_p} = 29.7 + [(1 - 0.1)384 - 460]\frac{11.1}{1184} \\ &= 29.7\ - 1.1 = 28.6\ \ ^\circ\mathrm{C} \end{aligned}$$

If water deficit occurs so actual ET is only 50 % of maximum ET (LE = 460/2 = 230 W m^{-2}):

$$T_{cx} = 29.7 + [(1 - 0.1)384 - 230]\frac{11.1}{1184} = 29.7 + 1.1 = 30.8\ \ ^\circ\mathrm{C}$$

If the crop had maximum stress (zero ET):

$$T_{cx} = 29.7 + [(1 - 0.1)\ 384 - 0]\frac{11.1}{1184} = 29.7 + 3.2 = 32.9\ \ ^\circ\mathrm{C}$$

28.15 Greenhouses

The highest level of control of the aerial environment of plants is achieved in growth cabinets and growth chambers which are only used in research and breeding programs due to their high cost. The lowest level corresponds to windbreaks. A second step in environmental control is achieved with mulches and row covers which are pieces of clear plastic stretched over low hoops enclosing the rows of plants. Floating row covers are those supported by the plant itself. Also, shading nets and other types of covers are being used now in fruit tree production as protective covers against hail, to improve fruit quality, and for limiting access to some insect pests. The use of nets of different colors that alter the light spectrum are being tested for improving certain fruit quality features and to disrupt insect flights. The third level is that of greenhouses which are structures covered with a transparent material. A wide range of designs differing in cost, level of control and frame and cover materials is available. The simplest case is the plastic unheated greenhouse for horticulture production in mild-winter areas (e.g. Almeria in Southern Spain). The most sophisticated designs are metallic structures with glass or rigid plastic panels that have artificial heating, supplementary lighting and CO_2 fertilization (e.g. the greenhouse industry of The Netherlands). Greenhouse horticulture is increasingly using hydroponics instead of natural soils, a technology where plants are grown with or without mechanical support on an artificial medium (sand, gravel, rock wool, peat moss, etc.) and watered with a nutrient solution that is recycled through the system.

Glazing materials for greenhouses may be plastic films (e.g. polyethylene, PE), rigid plastic panels (e.g. polycarbonate) or glass. Glazing materials show high transmittance for PAR (above 80 %), but they may be transparent to Infrared (PE) or not (PE with specific additives, glass, any material covered by condensation). In the former case (IR transparent) radiative cooling at night is almost the same as in the open. This may be mitigated by using IR opaque curtains. During the day the problem may be the opposite due to excessive heating of the air and plants inside the greenhouse during late spring or summer. In that case it is possible to use shade cloth to reduce irradiance, increase ventilation or use cooling systems.

In Sect. 9.10 we saw that evaporation inside unheated plastic greenhouses approaches equilibrium evaporation, i.e. it is mostly related to radiation inside the greenhouse. In this case it is easy to deduce the sensible heat flux inside as the difference between net radiation and evaporation. This sensible heat flux will be equal to the transfer of sensible heat between the air inside and the air outside. For a given relative renovation rate (RR, hour^{-1}) and mean greenhouse height (h_g, m) we can calculate the difference in temperature between the inside and the outside as:

$$T_{inside} - T_{outside} = \frac{(1-k_L)\Delta + \gamma}{\Delta + \gamma} \frac{3600}{\rho C_p} \frac{k_{RN} R_{si}}{h_g RR} = \frac{C_T R_{si}}{h_g RR} \qquad (28.11)$$

where γ is the psychrometric constant (approx. 0.067 kPa K^{-1}), Δ is the slope of the saturation vapor pressure function versus temperature (kPa K^{-1}, see Eq. 9.22), ρ is air density, C_p is specific heat of air at constant pressure (see 5.7), k_{RN} is the ratio net radiation/solar radiation inside the greenhouse, which may be taken as 0.7 and R_{si} is solar radiation inside the greenhouse (W m^{-2}). The coefficient k_L represents the fraction of evaporation as compared to equilibrium evaporation. For instance if

75 % of the area the greenhouse is covered by well watered vegetation then $k_L = 0.75$ and C_T varies from 1.16 at 10 ºC to 0.85 at 30 ºC.

Example 28.3 A 3-m high greenhouse of 200 m^2 area located at latitude 37ºS is ventilated with an air flow of 5 $m^3\ s^{-1}$ (18,000 $m^3\ h^{-1}$). Therefore the relative renovation rate is 18,000/(200 · 3) = 30 h^{-1}. On June 21 solar declination is 23.45º so the maximum solar radiation outside at noon on a clear day is 507 W m^{-2} (Chap. 3). The cover is polyethylene with transmissivity 0.7, so estimated radiation inside is 355 W m^{-2}. The temperature outside is 20 ºC and k_L is 0.75 so we can deduce $C_T = 0.99$. Therefore the expected increase of temperature at that time is:

$$T_{inside} - T_{outside} = \frac{C_T\, R_{si}}{h_g RR} = \frac{0.99 \cdot 355}{3 \cdot 30} = 3.9\ K$$

So the temperature inside will be 23.9 ºC.

This simple model is only a first approximation to characterize the micrometeorology of greenhouses as it ignores other processes that contribute to heat exchange (e.g. conduction through the cover) but is very useful to illustrate the possibilities of climatic control in unheated greenhouses, namely changing the radiation inside by putting shade cloth or whitewash painting on the cover or by manipulating ventilation via opening/closing vents or using fans. Apart from keeping the temperature within the optimal range for plant growth, ventilation is needed to prevent excessive air humidity inside the greenhouse as it enhances the risks of fungal diseases. This is especially important at night when temperature approaches the dew point temperature so condensation occurs on plants and on the inner surface of the cover.

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Chapter 29
Frost Protection

José Paulo De Melo-Abreu, Francisco J. Villalobos, and Luciano Mateos

Abstract Frosts affect agricultural production reducing yields and/or product quality. To avoid frost damage the best strategy is to use passive methods which imply a good choice of species, cultivars, planting dates and locations, keeping the soil compacted, wet and smooth, among other options. This requires the knowledge of the frequency distributions of minimum temperatures and the evaluation of the effect of low temperatures on crop performance (i.e., critical damage temperatures). However, the mechanisms of frost damage are rather complex and depend partly on plant hardiness, so predictions of damage are very uncertain. When frost occurs there are active (protective) methods of control that minimize the damage, including the reduction in long wave radiation loss (e.g. plastic covers), direct heating by burning fuel, air mixing (e.g. wind machines), and overhead irrigation for releasing the heat of fusion.

29.1 Introduction

A frost is the occurrence of air temperature equal or lower than 0 °C at a height between 1.25 and 2 m, measured in an appropriate shelter. Most agricultural systems of temperate climates are affected by frost. The limitation to crop production due to frost is usually characterized by the mean frost-free period, which is the time from the last spring frost to the first fall frost. This period limits the growing

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season of many crop species and determines the possibility of growing a crop in a given region.

The potential of frost risk increases as we move away from the Equator, with a band between the two tropics where frost does not occur (except at high elevations). Areas with frost-free periods over 240 days are between 12 and 40° latitude and include the most important agricultural regions. In these regions frost damage is often prevented on fruit and horticultural crops. Areas with frost-free periods of 180–240 days extend to 50°, although they may be found in higher latitudes due to sea influence. When the frost-free period is less than 90 days, agriculture is very limited and most food crops cannot be grown.

Frost is the weather hazard that is responsible for the greatest crop losses in the United States and, probably, in the World. Among frost protection methods, the most useful are preventive methods, such as right choice of species/cultivar, site selection, right choice of sowing date, and appropriate management techniques to keep susceptible organs away from the soil surface, adequate plant nutrition, and measures to enhance soil thermal conductivity. Protective methods, that are implemented in the night of frost are usually expensive and thus can only be performed in high-value crops in horticulture and fruit production.

29.2 Effects of Frost on Crop Production

Frost damage depends on many factors such as the species, the cultivar, the degree of acclimation, the state of the plant tissues (which depends on the stage of development, and on irrigation and fertilization practices, among other factors), the height of the canopy, the type of pruning, the rate of temperature decrease, the duration of the frost and the minimum temperature achieved. This complexity makes it difficult to predict frost damage. An additional problem is that the minimum temperature recorded at weather stations (according to standard rules) is not the same as the canopy temperature in a given field nearby.

The resistance of crops to cold is evaluated according to the lowest average minimum temperature at which they can survive. In tropical areas, plants are generally tender, and damage may result from exposure to low temperatures above the freezing point, sometimes as high as 12 °C. The plant tissue damage caused by low temperatures above 0 °C is termed *chilling injury*. Chilling injury is a particular problem in horticultural plants when unseasonal weather causes damage to chilling-sensitive species (most tropical vegetable crops). As with frost, many physiological and environmental factors affect the magnitude of the injury, for instance, immature fruits are more sensitive than mature fruits. Contrary to frost, chilling injury symptoms may be reversed, at least partially, if exposure to low temperatures is brief.

Frost damage in plants occurs below 0 °C, at temperatures ranging from about -1 °C down to -196 °C. This offset is explained by two mechanisms: avoidance and/or tolerance of freezing. Plants avoid intercellular freezing either because the solutes outside the protoplast lower the freezing point of these aqueous solutions or because there is supercooling (the temperature of the liquid drops below its freezing point without becoming solid), due to absence of freezing nuclei. Tolerance happens when, despite the occurrence of intercellular freezing and the concomitant shrinking and dehydration of the protoplast, after thawing there is full recovery of the protoplast structure and function. Intracellular freezing, if it ever occurs under natural crop growing conditions, is always lethal for the cell. When freezing occurs it starts in the intercellular spaces due to the lower concentration of solutes outside than inside of the protoplasts. The decrease in water potential due to freezing and solute concentration induces loss of water by the protoplast, resulting in its shrinkage and increase of solute concentration inside the protoplast.

Many mechanisms of frost injury have been put forward, but it is possible that in general tissues are either injured by direct mechanical injury inflicted by the ice formed outside cells or by the shrinkage and dehydration experienced by the protoplast. In this case, denaturation of nuclear proteins may be the ultimate cause of injury.

Initially, *critical damage temperature* (T_{crit}) was defined as the maximum temperature that results in frost injury to a plant organ that is subjected to it for more than thirty minutes. The term has been extended to specific levels of injury. For example, T_{10} for apple flowers refers to the T_{crit} that inflicts 10 % loss of the total flowers, and T_{90} would correspond to 90 % loss.

Let us issue some general considerations for cereals and fruit trees that are not of tropical origin. During rest, plant organs have often very low T_{crit}. However, after bud burst critical temperatures slowly approach their upper limit. During active growth, most plant organs have T_{crit} that are only a few degrees below 0 °C. Moreover, the difference T_{10}–T_{90} tends to decrease as plant phenological development progresses attaining a minimum that occurs, usually, around grain/fruit set (see Fig. 29.1). During the rest period and onset of growth, plants have a considerable capacity to keep low (or actively lower) T_{crit}, in response to the continued occurrence of low temperatures, in a process called *hardening* or *acclimation*. From flowering onwards, hardening capacity is inexistent or reduced. On the other hand, after exposure to a period of high temperatures de-hardening may occur.

The nature of freeze damage varies with the plant/organ affected. Most vegetables that are injured present either a "burned" appearance, or seem "soggy", or present changes in color or texture. Under rigorous winters, when the protective snow cover is insufficient, winter cereals may get leaf injury or even tillering node injury. After emergence, frost damage is usually at flowering or at grain set. In temperate climates, in general, deciduous fruit trees and the vine during winter frosts are not affected. Only when temperatures are very low, in some extreme environments or when there is substantial de-hardening, there is frost damage to dormant buds or, even more rarely, to tree trunks. After bud burst, in the case of apples, pears and stone fruits, flowers and small fruits are very tender and sensitive to frost that causes substantial losses at those stages. Sometimes, however, after pollination there is only partial loss of seeds which affects the growth of the fruits, particularly in the case of stone fruits that only have one or two seeds per fruit.

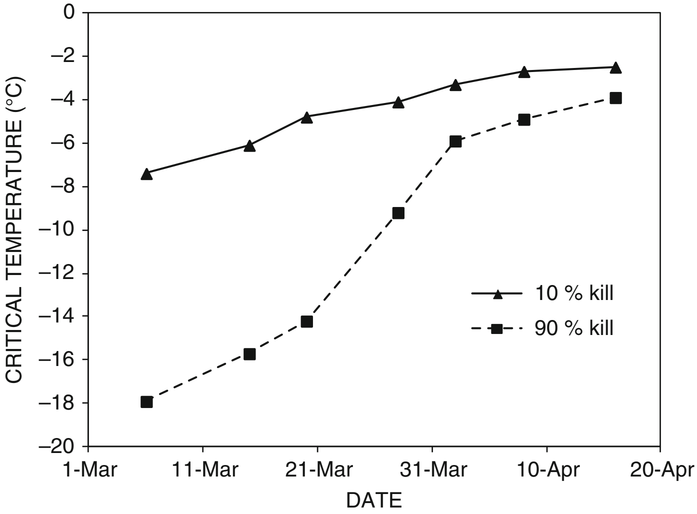

Fig. 29.1 Typical 10 % and 90 % bud kill temperatures for cherry trees corresponding to average dates observed at the Washington State University, Prosser Research and Extension Centre (Adapted from Proebsting and Mills (1978))

When a small fruit experiences light freeze injury, a coarse russet tissue grows and covers a portion of the fruit, resulting in the deterioration of fruit quality.

A detailed list of critical temperatures may be found in the review by Snyder and De Melo-Abreu (2005). Most vegetables and fruits have maximum freezing temperatures between −0.4 and −2.7 °C, which represents the upper limit of critical temperature, since the heat capacity of the structure and some (small) degree of supercooling may result in actual freezing temperatures that are somewhat lower. More juicy tissues tend to have higher critical temperatures.

A series of crops of tropical origin (tobacco, tomato, cucumber, peanut, rice, melon and cotton) present T_{crit}, for all the crop cycle, that decrease from 0 to −2 °C. Millet and corn have a T_{crit} that is around −2 °C or −3 °C at germination and grain filling, and one degree higher around flowering.

Table 29.1 shows some critical temperatures in relation to stage of small grains, silage and forage crops, sugar beet and the olive crop. Table 29.2 shows critical temperatures in relation to stage for some important deciduous fruit trees and grapevines.

29.3 Frost Types

Radiation frosts occur on calm nights with a clear and dry atmosphere, which enhances long wave radiation losses (Chap. 3). The low wind speed determines a temperature inversion. Figure 29.2 shows an example of evolution of temperature

Table 29.1 Critical temperatures (ºC) in relation to stage of different crop species (Adapted from Snyder and De Melo-Abreu (2005))

Crop	Critical temperature[a]	Stage
Alfalfa	−6/−14	
Barley (winter)[b]	/−17.3 to −12.9	Tillering
Barley (winter)[b]	−1 to −2	Flowering
Barley (winter)[b]	−2 to −4	Grain filling
Oat	/−10.5 to −6.5	Tillering
Oat[b]	−8 to −9	Germination
Oat[b]	−1 to −2	Flowering
Oat[b]	−2 to −4	Grain filling
Olive	−12.4 to −4.1/−19.3 to −8.1	Rest
Potato[b]	−2 to −3	Germination
Potato[b]	−1 to −2	Flowering
Rye (winter)[b]	/−19.5 to −25	Tillering
Ryegrass (Italian)	/−8.4 to −7.4	3–4 leaf-stage
Ryegrass (Perennial)	/−13.95 to −10.31	Mature
Soybean	/−4.5	Seedlings
Soybean[b]	−1	Pod filling
Subterranean clover	−5.5/−7.8	Seedlings
Sugar beet[b]	−6 to −7	Germination
Sugar beet[b]	−2 to −3	Flowering
Sunflower[b]	−3.9	Bud formation
Sunflower[b]	−0.6 to 0	Flowering
Triticale	/−17.5 to −9.2	Tillering
Wheat (spring)	−2/−5.5	Tillering
Wheat (winter)	−3/−18	Tillering
White clover	−7.7 to −4.9/−20.3 to −7.4	

[a] Before the slash (/) temperatures correspond to unhardened plants and after to hardened
[b] Under field conditions

profiles during the night. When the wind blows at night the temperature profile becomes more uniform and the air temperature rises (Fig. 29.3). When the wind stops, the temperature drops again (Fig. 29.3).

Advection frosts occur as a result of large-scale transport of cold air masses. They occur on cloudy days or nights with moderate or strong wind coming in the wake of a cold front. Temperature inversions are not present, at least in the first phase of such events. Later, after the wind weakens, an inversion may develop if surface cooling conditions occur.

Hoar frost occurs when ice crystals appear on the crop by deposition of water vapor or freezing of dew. Both processes release heat and therefore delay freezing of crop tissues. If the amount of ice is large the term *white frost* is used. When the concentration of water vapor in the air is very low (dew point below the minimum

Table 29.2 Critical temperature (ºC) values for several deciduous fruit tree crops and grape vines. The 10 % kill and 90 % kill imply that 30 min at the indicated temperature is expected to cause 10 % and 90 % kill of the plant part affected during the indicated phenological stage. The values for bloom are the average from early to late bloom (Adapted from Proebsting and Mills (1978) and Snyder and De Melo-Abreu (2005))

Crop	Stage	10 % kill	90 % kill
Apple	Silver tip	−11.9	−17.6
	Bloom	−2.4	−3.9
Peach	First swell	−7.4	−17.9
	Bloom	−2.8	−4.9
Pear	Scales separate	−8.6	−17.7
	Bloom	−2.9	−5.3
Grape	First swell	−10.6	−19.4
	Bud burst	−3.9	−8.9
	First leaf	−2.8	−6.1
	Fourth leaf	−2.2	−2.8

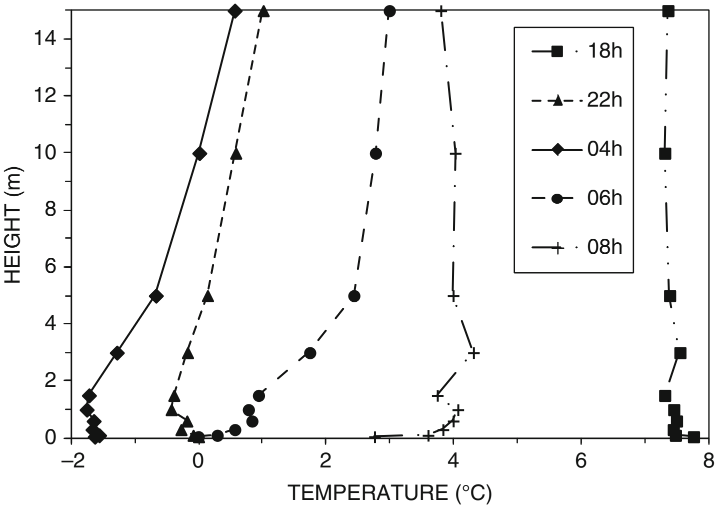

Fig. 29.2 Development of a temperature inversion over an apple orchard in Northern Portugal (Adapted from Snyder and De Melo-Abreu (2005))

temperature), there is no dew to freeze and no possibility of deposition and the tissues are affected without prior formation of ice, causing necrosis of the tissues (“black frost”). The presence of white frost indicates that damage may occur, but black frost is the visualization of the damage that already occurred.

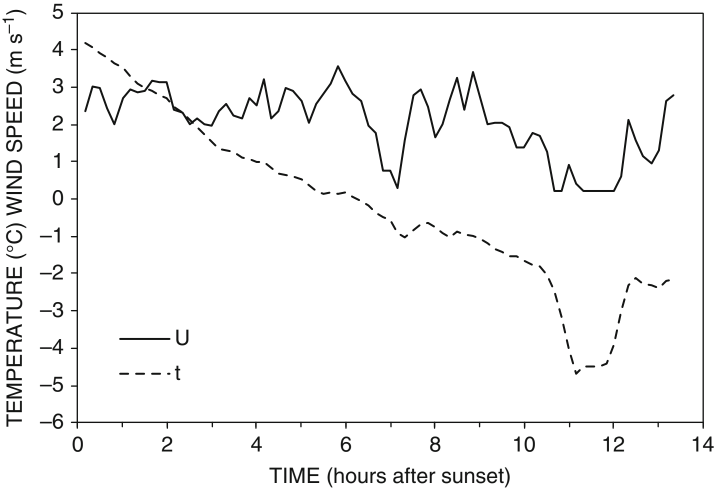

Fig. 29.3 Time course of temperature and wind speed over bare soil during the night. Espiel (Spain), February 3–4, 2012

29.4 Climatology of Frosts

The frost-free period is the time between the last frost (late winter or spring) and the date of the first autumn frost. This period is highly variable from year to year, so it is of limited value to assess the risk of frost damage, which should be based on the frequency distribution of frost dates. The dates of the first and the last frost may be considered as independent random variables that follow the normal distribution. This allows the calculation of the probability of frost during specific periods. For instance, the probability of spring frost after a given day is:

$$P(frost\ after\ day\ t) = P_y \cdot P\left[z > \frac{t - m_{LF}}{s_{LF}}\right] \tag{29.1}$$

where P_y is the fraction of years when frost occurs, m_{LF} is the mean date for the last frost, s_{LF} is the corresponding standard deviation and z is the standard normal distribution which can be calculated using tables or the following approximate function:

$$P(z \le x) = 0.5\left(1 \pm \sqrt{1 - exp\left(\frac{-2x^2}{\pi}\right)}\right) \tag{29.2}$$

where the positive root is used if $x > 0$ and the negative root when $x < 0$. We have to remember that $P(z > x) = 1 - P(z \le x)$.

Similarly, the probability of autumn frost before a given day is:

$$P(\mathit{frost\ before}\ \ t) = P_y \cdot P\left[z < \frac{t - m_{FF}}{s_{FF}}\right] \tag{29.3}$$

where m_{FF} and s_{FF} are the mean and standard deviation for the date of the first frost. Note that these statistics are only computed for years when frosts occur.

Example 29.1 The dates of the first and last frost (expressed as days from September 1) during 15 years are given in Table 29.3 for two locations (Gibraleon and Jerez del Marquesado) in Southern Spain.

Table 29.3 Dates of the first and last frost (expressed as days from September 1) during 15 years for two locations (Gibraleon and Jerez del Marquesado) in Southern Spain. The minimum temperature observed each year is also shown

	Gibraleon			Jerez del Marquesado		
	Date of frost		Tmin	Date of frost		Tmin
Year	First	Last	°C	First	Last	°C
2000			2	69	181	−2.9
2001			1.7	70	185	−5.7
2002	133	133	−0.6	94	217	−8.6
2003			0.7	88	223	−7.3
2004	119	168	−3.9	73	223	−15
2005	166	166	0	75	222	−10.2
2006	147	147	−0.6	98	219	−7
2007			1.2	77	212	−7.1
2008	131	132	−2.6	60	226	−6.1
2009	106	242	−1	45	247	−5.9
2010	156	156	−0.2	77	197	−5.4
2011	122	167	−3.1	104	229	−10.4
2012			0.8	88	243	−4.7
2013			1.1	76	208	−4.6
2014	123	129	0	96	207	−4.7
Average	133.67	160.00	−0.30	79.33	215.93	−7.04
Std. deviation	19.24	34.52	1.75	15.65	18.54	3.02

In Gibraleon no frost occurred in 6 out of 15 years, so the statistics for the mean and standard deviation (shown also in Table 29.3) are computed for the remaining 9 years and $P_y = 0.6$. The mean dates for the first and last frost are day 134 (January 12) and 160 (February 10). The probability of frost after March 1 (day 182) will be:

(continued)

Example 29.1 (continued)

$$P(frost\ after\ day\ 182) = P_y \cdot P\left[z > \frac{t - m_{LF}}{s_{LF}}\right]$$

$$= 0.6 \cdot P\left[z > \frac{182 - 160}{34.5}\right] = 0.6 \cdot P[z > 0.64] = 0.6\,(1 - P[z \leq 0.64])$$

$$= 0.6 \cdot (1 - 0.74) = 0.156$$

Now we will calculate the probability of frost before December 1 (day 92):

$$P(frost\ before\ 92) = P_y \cdot P\left[z \leq \frac{t - m_{FF}}{s_{FF}}\right] = 0.6 \cdot P\left[z \leq \frac{92 - 133.7}{19.24}\right]$$

$$= 0.6 \cdot P[z \leq -2.17] = 0.6 \cdot 0.012 = 0.007$$

In Jerez del Marquesado the mean dates for the first and last frost are day 79 (November 18) and 216 (April 4). The probability of frost after March 1 and before December 1 are 97 and 80 %, respectively.

29.5 Risk of Extreme Cold Temperatures

Historically, farming has been pushed towards the environmental limits where risks of extreme events are on the increase. Many agricultural decisions have to be based on the probability of damaging events that can kill the plants or reduce yield substantially thus making farming unviable. For frost risk analysis we distinguish the probability P(T<Tc) of occurrence of temperature below a critical threshold in any year and the risk (R) which is the probability of the event occurring at least once over a design period (n_d) (n_d would be the expected duration of the orchard in years, for example). Instead of risk we may use certainty (C=1−R) which is then the probability of the event not occurring over the design period. Assuming a Bernouilli distribution, the certainty (C) is related to the probability of having a temperature below Tc in any given year:

$$C = [1 - P(T < T_c)]^{n_d} \tag{29.4}$$

For example, if the probability of temperature below −10 °C in any given year is 0.003 (i.e. it happens three times in 1,000 years) then the certainty for 20 year project duration is 0.94, i.e. we are 94 % certain that temperatures will never fall below −10 °C in 20 consecutive years.

The probability of an extreme event occurring in any given year should be calculated as the ratio of the observed extreme events over the number of years of record. As they are rare events we would require a very long weather record (e.g. more than 1,000 years) which is never available. Instead, for limited data sets we calculate the parameters of the underlying statistical distribution. Haan recommended the type I extreme value (Gumbel) probability distribution:

$$P(T < T_c) = 1 - exp\left[-exp\left(\frac{T_c - \beta}{\alpha}\right)\right] \quad (29.5)$$

where α = σ/1.283, β = μ + 0.577 α, μ is the average of the minimum temperatures recorded each year and σ is the corresponding standard deviation. The parameter β is the mode (most frequent value) of the distribution.

From the equations above we may deduce another for calculating the certainty:

$$C = \left\{exp\left[-exp\left(\frac{T_c - \beta}{\alpha}\right)\right]\right\}^{n_d} \quad (29.6)$$

Example 29.2 The minimum temperature in Jerez del Marquesado (Spain) has an average of −7.04 °C with standard deviation 3.02 °C (Table 29.3). Therefore the parameters of the Gumbel distribution are α = σ/1.283 = 2.355 °C and β = μ + 0.577 α = −7.04 + 0.577·2.355 = −5.68 °C. If we are planning to establish an orchard during 20 years and the critical temperature is −12 °C the certainty will be:

$$C = \left\{exp\left[-exp\left(\frac{-12 - (-5.68)}{2.355}\right)\right]\right\}^{20} = 0.255$$

which is very low. This value indicates that the risk of failure of our orchard is 75 %. In the other location (Gibraleon) the certainty will be 0.998 which indicates a negligible risk for the orchard.

29.6 A Simple Model for Nocturnal Surface Cooling

Soil surface cooling during the night may be analyzed using the energy balance of the soil (Chap. 6):

$$\mathrm{R_n = -C + H + LE + G} \quad (29.7)$$

where R_n is net radiation, C is heat released by freezing of water, H is sensible heat flux and LE is latent heat flux. Combining the equations of heat flux in the soil (Chap. 6) and the loss of long wave radiation (Chap. 3) Brunt proposed a very simple model to calculate the variation of surface temperature during the night. The assumptions include LE = 0, H = 0 and an isothermal soil profile at sunset. This implies that soil cooling during the night is equivalent to the loss of long wave radiation while the other processes are ignored. Brunt also assumed that net radiation does not change during the night.

The analytical solution for T_{s0} is

$$T_s - T_{s0} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{k\, C_v}} R_n \sqrt{t} \tag{29.8}$$

where T_{s0} is surface temperature at sunset, C_V is specific heat of the soil per unit volume ($J/m^3/K$), k is thermal conductivity (W/m/K) and t is time elapsed after sunset (s). Note that the square root of k Cv is the thermal admittance (Chap. 6). This equation implies that temperature during the night will decrease in proportion to long wave radiation loss and the square root of time after sunset. Soils with low admittance (sandy, dry) will cool faster.

Example 29.3 For a loam soil at Permanent Wilting Point admittance is 1,057 $W\ m^{-2}\ s^{1/2}\ K^{-1}$ (Table 6.2). For $R_n = -70\ W/m^2$, the drop of temperature after sunset would be 10, 14.2 and 17.4 K after 5, 10 or 15 h, respectively. If the soil was at saturation (thermal admittance 1,835 $W\ m^{-2}\ s^{1/2}\ k^{-1}$) the temperature would decrease only 5.8, 8.2 and 10 K.

The above example illustrates the important effect of soil water content on nocturnal cooling.

29.7 Frost Protection

Frost protection methods include those methods that are implemented before the frost night in order to avoid or minimize frost damage (i.e., *passive*, *indirect*, or *preventive*), and methods that are implemented during the frost night (i.e., *active*, *direct*, *protective*). Often, the effect of passive methods, which are relatively cheap, adds up to the effect of the active methods. Therefore, passive methods should always be considered and, when suitable, implemented in conjunction with one or more active methods, or in isolation. A complete description of most of the existing methods and related computational tools is available in Snyder and De Melo-Abreu (2005).

29.7.1 Passive Protection Methods

29.7.1.1 Site Selection

Section 29.6 described the physics of the cooling process in a specific location ignoring the horizontal movement of air. As the air cools, its density increases, and will tend to flow to areas of lower density, typically downwards to valleys and depressions. The degree of accumulation of cold air or ventilation depends on the topography, the wind speed and the temperature gradients.

Frost sensitive crops should not be placed in locations where cold air accumulates due to orography (depressions) or to the existence of artificial obstacles (fences, windbreaks).

The presence of large bodies of water (lakes, sea) in the direction where cold winds come from can reduce the risk of frost due to heat exchange between water and air.

If possible the most critical areas should be detected using maps of minimum temperatures which could be obtained using remote thermal infrared imagery. As a rule of thumb places where radiation fog is more frequent are also those where radiation frosts are more likely.

29.7.1.2 Selection of Species, Cultivars and Cultural Techniques

Crop species differ in their sensitivity to cold and frost, and genetic variability may exist within each species. Taking into account the climatology of frosts in the location and the critical temperatures for the crop alternatives to that location, we will choose the species and the cultivar in order to reduce the risk of frost damage.

Some cultural techniques may be beneficial, when they explore the knowledge of the biometeorology of frost. In deciduous fruit trees, pruning is usually done in winter but, in locations prone to severe frost, late pruning is advisable from the viewpoint of frost damage prevention, since plants are more sensitive just after pruning and the probability of severe frosts decreases as the spring approaches. In the same regard, pruning promotes bud burst, hence late pruning exposes new growth to less-frequent and less-severe frosts. Training pruning techniques that elevate the level of tender organs are beneficial because in frost nights there is, usually, a temperature inversion, which results in lower levels being colder. Delayed bud break has been achieved in pome fruits by periodic overhead irrigation in late winter that cools the buds and delay their development until past the most frost risky period. Nitrogen fertilization and high water status tend to elevate the critical temperature. Hence, when there is a strong probability of frost in the upcoming days it is not wise to N-fertilize or irrigate (but see also next section).

Some bacteria called Ice Nucleating Active (INA) may act as freezing nuclei and therefore initiate the freezing process. These bacteria are often concentrated on the cover crops and weeds present in the orchard and their removal may help in preventing frost damage.

29.7.1.3 Soil Management

Minimum surface temperature may be increased by increasing the thermal admittance (irrigating, compacting the soil) or increasing the radiant energy reaching the soil during the daytime (avoid opaque mulches or cover crops). Soil heating during the day depends also on the partitioning between G and H (Chap. 6) so a smooth soil surface (high aerodynamic resistance) will improve soil heating as compared to a rough soil surface. Therefore tillage operations (reduce thermal admittance, increase surface roughness) are not desirable if frost is expected.

Irrigation increases soil thermal admittance, which reduces nocturnal cooling but reduces also diurnal soil heating as the energy spent in evaporation from the soil surface increases (Chap. 6). The best situation would be to have a wet soil covered with transparent plastic. If that's not possible the best choice is to irrigate some days in advance to let the upper soil layer dry, and thus reduce soil evaporation, while the rest of the profile is wet (high thermal admittance).

Soil heat flux is also increased after removal of cover crops or weeds in orchards. Their removal should preferably be done by using herbicides that eliminate the cover but do not include tillage and the concomitant change in soil surface bulk density. When tillage is used it should be done well in advance of the sensitive frost period for the soil to settle and the residues to decompose.

29.7.2 Active Protection Methods

29.7.2.1 Increasing Radiation Interception

Radiation frosts occur when long wave radiation loss is high (absence of clouds, low air humidity). Thermal radiation may be intercepted partly to reduce long wave loss by spraying water. For the water spray to be effective, the diameter of the droplets or particles should have a diameter of the same order as that of thermal radiation (8–12 μ).

Artificial clouds of smoke may be produced by burning different materials (tires, wood or fuel) but are inefficient and therefore rarely used nowadays (small diameter of particles, rapidly vanishing, high energy cost, pollution problems).

Another way to trap the longwave radiation is by using commercial solid acid clouds or aerosols that have a suitable particle size and are produced in situ by combining several products.

Some materials which are almost opaque to long wave radiation (e.g. thermal blankets) may be used to cover high value crops.

29.7.2.2 Air Mixing

Inverted temperature profiles typical of nights with radiation frost may be homogenized by mixing air of different heights, thereby increasing the temperature at canopy height. The effectiveness of air mixing will be proportional to the temperature gradient.

Although helicopters have been used, the best choice for air mixing is a wind machine which consists of a steel tower with a large rotating fan near the top. Fans, with blades of diameter between 3 and 5 m, are located about 10–11 m above ground and are oriented to blow at a slight downward angle (e.g. 7°) to improve mixing.

29.7.2.3 Heating the Air or the Canopy

The losses of energy from a crop during frost may be compensated burning fuel (solid, liquid or gas) in heaters, which transfer energy by thermal radiation and convection. The energy loss from the crop is usually in the range 20–40 W m^{-2}, while input from heaters is typically between 140 and 280 W m^{-2}, which indicates a very low efficiency. The best conditions for this method are no wind and the presence of a strong inversion.

The temperature of air leaving the heater is very high, so it will rise rapidly mixing with colder surrounding air, until it reaches the height where the air has the same temperature. Eventually, the mixed air will cool, become denser and descend, which creates a circulation pattern within the inversion layer. When there is a strong inversion (i.e. a low ceiling), the heated air rises to a lower height and the volume influenced by the heaters is smaller so efficiency is higher. Efficiency is low when heaters are too big or hot as the warmed air can break through the top of the inversion layer.

29.7.2.4 Irrigation

Irrigation is a very useful tool for protecting crops against frost and it relies mostly on the release of heat by water cooling (4.18 10^{-3} MJ/K/kg) and by freezing (0.334 MJ/kg), but some heat may be spent in evaporation. In the best case, when we irrigated with water extracted from wells it has a temperature close to the mean annual air temperature at the site so the contribution of water cooling is very small compared with that of freezing. This is the basis of using sprinkler irrigation for frost protection which usually requires lower application rates (ca. 1 mm h^{-1}) than typical sprinkling systems for water supply to the crop. One needs to supply water continuously to the whole area to be protected, so that there is always a thin layer of water over the ice that is formed, thus keeping the temperature at the freezing point. Surface irrigation may also be used and is also based upon the same principles (use of the heat of fusion and specific heat of water), but the heat is liberated to the air near the soil surface, and it may not be sufficient to prevent frost damage.

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Chapter 30
Control of Weeds and Other Biotic Factors

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Abstract Weeds are plants whose presence is undesirable at a time and/or place because they compete with crops for resources, deteriorate the quality of the harvested product and can hinder harvesting. The most important weed species include C4 perennials with vegetative propagation. Usually weeds are able to produce many seeds that often present dormancy, which generates a soil seed bank which germinate over many years. This prevents weed eradication and forces us to use control techniques to keep weed populations at tolerable levels. Weeds adapt in a few years to the cropping system, in particular to control methods. Control techniques include the use of herbicides and of cultural practices such as tillage, mulching, mowing, and crop rotation. Crop management has an important effect on the incidence of pests. Irrigation method and irrigation frequency determine the germination of weeds and influence the infection by aerial or soil pathogens. Biological control is effective with invasive weeds and some insects. The ability of weeds to evolve in response to the selection pressure exerted by control measures forces us to establish long-term strategies (weed management) which should be based on detailed knowledge of the ecology of the weed species. Then different types of control should be alternated to improve the efficiency of control.

30.1 Introduction

Weed control has always been an important part of agricultural practices and is often considered as part of agronomy. Traditionally, only manual weeding was specifically aimed to control weeds, but many practices, such as tillage, burning and

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rotations, contributed in some way to this control. In 1944, when 2,4-D was introduced as a herbicide, Weed Science appeared as a discipline within the techniques of Plant Protection, although much more tied to crop production techniques.

It is estimated that not more than 250 species have become important weeds for agricultural production.

In this chapter we will review the main ecological characteristics of weeds and the methods of control with the exception of pesticides which will be dealt with in next chapter. For some specific control techniques we will also mention their impact on other pests.

30.2 Characteristics of Weeds

A weed is a plant growing where it is not wanted, i.e. in the wrong time or location. This is a relative definition, as seeds left from a crop after harvest may lead to weeds for the next crop. However, the most troublesome weed species usually show special characteristics that allow their dispersal and persistence in agricultural systems and increase their ability to compete with crop plants.

30.2.1 Dispersal of Weeds

Weeds use the general dispersal mechanisms of plants (wind, animals, water, gravity) but also present among their invasion strategies the so called anthropocory (dispersal by human action). The commerce of agricultural products, seeds, and other materials has contributed to the dispersal and homogenization of weeds worldwide. The most damaging species are found in many environments and systems all around the world. Table 30.1 shows the most important weed species on a global scale. Most of this species are C4 perennials.

The invasion of a new site is usually based on a small but continuous flow of propagules transported from short distances. However, the most effective dispersal strategy of a weed is based on adaptations that ensure the return of weed seeds along with the crop seed at the time of planting.

30.2.2 Persistence of Weeds

The persistence of weed populations is often guaranteed by the production of a large number of seeds per plant which often exhibit dormancy mechanisms. These allow germination to spread over a long period (years) and ensures the survival of the population.

Table 30.1 Top 10 worst weed species on a global scale. The number of crops and countries where it is consider an important weed are also presented

	Species (photosynthesis type)	Common name	# Crops	#Countries	Cycle	Propagules
1	*Cyperus rotundus* (C4)	Purple nutsdege	52	92	Perennial	Rhizomes with tubers
2	*Cynodon dactylon* (C4)	Bermuda grass	40	80	Perennial	Rhizomes with stolons
3	*Echinochloa crus-galli* (C4)	Barnyard grass	36	80	Annual	Seed
4	*Echinochloa colona* (C4)	Jungle rice	32	60	Annual	Seed
5	*Eleusine indica* (C4)	Indian goose grass	46	60	Annual	Seed
6	*Sorghum halepense* (C4)	Johnson grass	30	53	Perennial	Rhizomes and seeds
7	*Imperata cylindrica* (C4)	Cogon grass	35	73	Perennial	Rhizomes
8	*Eichhornia crassipes* (C3)	Water hyacinth	1		Perennial	Stolons
9	*Portulaca oleracea* (C4)	Purselane	45	81	Annual	Seeds, rooting at nodes
10	*Chenopodium album* (C3)	Lambs quarters	40	47	Annual	Seed

The community of buried propagules (soil seed bank) consists of rhizomes, stolons, bulbs and seeds of different species. The seeds entering the soil may be dormant or enter into secondary dormancy. The most important factors for germination or dormancy release are: water, temperature, light, NO_3, O_2 and CO_2.

The permanence of some form of dormancy in buried seeds is an adaptive advantage as it allows adjusting seed germination to ecological conditions favorable to the survival of seedlings.

The loss of seed dormancy in the soil occurs especially if the water content and aeration are adequate. Germination is very sensitive to the quality of light (phytochrome system), especially to that resulting from radiation interception by vegetation. Thus, by detecting the light quality, the seed not only receives information about the depth at which it is buried, but can also detect the presence of a canopy above, which may limit the growth of the seedling. Apart from that, some species respond to short light pulses as those that the seed may experience during secondary tillage.

Other factors contributing to end the seed dormancy is a low concentration of CO_2, a high concentration of nitrates and the oscillation of temperature. The latter allows the seed to "detect" its depth in the soil because the temperature range decreases with depth. A buried seed which is subjected to a very wide temperature variation is probably near the surface and it is likely to stay on a clear area without vegetation, since the presence of the latter buffers the variation of soil temperature.

On the other hand, weeds often show a great capacity for acclimation and adaptation. In many cases this is associated to annual cycles, reduced number of chromosomes and self- pollination or vegetative propagation.

The most important selective force acting on weeds in agricultural systems is human action including type, depth and timing of tillage, sowing date, timing and type of herbicide application, etc. There are selection pressures that select weed genotypes suitable to endure in the system due to adjusted mechanisms of dormancy and germination, and, more important, that there are similarities to the crop in height, seed size and maturity period to ensure the joint harvest with the crop. It is clear then that the main determinant of weed flora in a given area will be the main crops grown in addition to management practices.

In some cases, besides selective forces, the system provides genetic information that can contribute to the evolution of the weed (crossing between weeds and crop plants).

Unlike insects and fungal pathogens weed populations do not suffer sudden changes in population density due to the damping exerted by the seed bank. Therefore, weeds are usually a chronic but not an epidemic problem, but the variability is large. Some species with high reproductive potential but with low seed dormancy and low persistence in the soil, such as *Alopecurus myosuroides* (green foxtail) are typically aggressive opportunistic invaders, but are also easily removable. By contrast, other species with low reproductive potential but with strong dormancy in seeds, as *Veronica hederifolia* (speedwell), tend to persist and it is difficult to alter the size of their populations. These differences in the population dynamics of different weed species have implications for their control which should try to eradicate populations of the first type with intense short-term measures while maintaining reduced population sizes for the second type.

30.3 Classification of Weeds

According to their life cycle weeds are classified as:

- Annual weeds: they complete their life cycle in 1 year. We may distinguish two groups:
    i. Winter annuals, that germinate in the fall and set seed in spring or summer. They are usually found in winter cereals. Examples: *Avena sterilis* (wild oat), *Sinapis arvensis* (wild mustard).
    ii. Summer annuals that germinate in spring and set seed in autumn. Examples: *Amaranthus retroflexus* (redroot pigweed), *Portulaca oleracea* (common purslane).

- Biannual weeds: they require 2 years to complete the cycle, devoting the first year to vegetative development and storage of carbohydrates (rosette stage in many species) and flowering in the second spring.
  Example: Thistles
- Perennial weeds have cycles of several years: in some cases they show vegetative reproduction from organs (roots, stems, rhizomes, stolons, tubers, bulbs) that remain dormant until suitable conditions for sprouting occur.
  Examples: *Cyperus rotundus* (purple nutsedge), *Cynodon dactylon* (Bermuda grass) and *Sorghum halepense* (Johnson grass).

Weeds can also be classified according to the habitat where they are usually found (crops, pastures, orchards or forests, surface waters, roadsides and waste places).

30.4 Crop-Weed Interactions

Weeds always compete for resources (water, light, nutrients) and often show certain competitive advantages such as high density, earlier emergence or high early vigor. Some morphological (taller plants, deeper roots) or physiological (C4 photosynthesis, allelopathy) mechanisms may also enhance weed growth when in competition with crop plants.

Apart from yield losses due to competition, weeds have other negative effects such as hindering harvest or degrading crop quality by altering the color, smell, taste or adding toxins.

In all cases the level of competition and thus of yield loss will be directly proportional to the earliness of weed emergence relative to that of the crop, as discussed in Chap. 12. Therefore it is difficult to establish general relationships between crop yield and weed density (D_{pw}). If we use the reciprocal yield law (Chap. 12) we may calculate yield (kg/ha) as:

$$Y = \frac{10\,HI\,D_p}{b_1 + b_2\,D_p + b_{2w}\,D_{pw}} \tag{30.1}$$

where b_1 and b_2 are empirical coefficients that determine the response of the crop to plant density. The factor 10 in Eq. 30.1 is used to convert g/m^2 to kg/ha. Now we have added a term (b_{2w} D_{pw}) that incorporates the competition of the weed. If the crop and the weed are very similar in form and cycle then the coefficients b_2 and b_{2w} should be the same.

Example 30.1 Let's calculate the yield of a cereal crop as a function of weed density. We'll asume that:

$$\mathrm{b_1 = 0.01\ plant/g, b_2 = b_{2w} = 0.001m^2/g,\ HI = 0.4\ and\ D_p}$$
$$\mathrm{= 200\ plants/m^2.}$$

According to Eq. 30.1 yield may be calculated as:

$$Y = \frac{10\,HI\,D_p}{b_1 + b_2\,D_p + b_{2w}\,D_{pw}} = \frac{800}{0.01 + 0.20 + 0.001 D_{pw}}$$

Values of yield for weed densities of 0, 100 and 200 plants m^{-2} would be 3,810, 2,581 and 1,951 kg/ha.

Many studies indicate that the 30–40 days after emergence are critical for determining yield losses due to weeds. If the crop is kept clean during this period any later invasion will not cause yield reduction but may lead to other problems (e.g. harvest problems). On the other hand, if weeds are completely removed at the end of this period, yield reduction should be small.

30.5 Economic Threshold

An economic threshold or action threshold for a given pest is the density of the pest at which control should be applied. Otherwise the pest will reach a higher density level (called Economic Injury Level) at which the cost of control equals the economic loss due to the yield reduction effected by the pest, quality loss or harvesting difficulties. Note that if the action level is exceeded there will be an economic loss. For weeds the action threshold may be equal to the EIL but for insects it may be much lower if the insect population increases rapidly.

Using Eq. 30.1 we may calculate the yield loss (YL, kg/ha) for weeds as:

$$YL = \frac{10\,HI\,D_p}{b_1 + b_2\,D_p} - \frac{10\,HI\,D_p}{b_1 + b_2\,D_p + b_{2w}\,D_{pw}} \tag{30.2}$$

One important difference between weeds and other pests is that weeds have a negative effect for any density as they always use resources (water, nutrients). Other pests (e.g. insects) may not have any negative effect in terms of yield loss when populations are low.

If the selling price of the harvest is $\mathrm{P_Y}$ (euro/kg) and the cost of weed control is $\mathrm{C_H}$ (euro/ha), then the economic threshold (taken as equal to EIL) corresponds to a yield loss of C_H/P_Y. Using Eq. 30.2 we may deduce that it will occur when the weed density is:

$$D_{pwu} = \frac{10\, HI\, D_p C_H}{b_{2w}\, Y_x (P_Y Y_x - C_H)} \tag{30.3}$$

where Y_x is yield in the absence of weeds. We see that the economic threshold is directly proportional to planting density and to the cost of weed control, while it is inversely proportional to weed competitive ability (b_{2w}), to crop yield and to selling price.

Example 30.2 Using the data of Example 30.1 we may calculate the economic threshold if the grain price is 0.25 euro/kg and the cost of weed control is 150 euro/ha:

$$D_{pwu} = \frac{10 \cdot 0.4 \cdot 200 \cdot 150}{0.001 \cdot 810(0.25 \cdot 3810 - 150)} = 39\ plants\ m^{-2}$$

In this case control measures should not be taken unless weed counts exceed 39 plants m^{-2}.

The economic threshold thus defined is valid in the short term as it affects only the current crop. Lower values of economic threshold will result if one considers a longer perspective. For example, in organic farms in the Netherlands the main problems of weeds in certain crops (e.g. onion) are due to seeds from some weed plants that had not been controlled in the previous wheat crop. This implies the need for more intensive weed control during the wheat season at a higher cost that this crop would need.

Some species (e.g. *Chenopodium album*) are easy to control with hormonal herbicides but difficult to eradicate, due to their long seed persistence. In these cases we may use the short term economic threshold. In other species that are difficult to control with herbicides but have little seed persistence (e.g. *Avena sterilis*) it is better to apply intense control measures using a long-term economic threshold.

The effect of a given weed density on yield depends on many factors, in special the time of weed emergence relative to the crop. Furthermore weeds can be gradually emerging, which further complicates the prediction of its ability to compete, given also that there is substantial spatial variability in the distribution of weeds within a field. Thus the empirical equations between yield and weed density have a limited validity, and economic thresholds deduced from them, too.

The concept of economic threshold may be difficult to apply to many situations as the effect of pest densities on crop yield has to be known a priori. However it serves to illustrate some important concepts on pest control. First, low population levels of the pest do not have a negative effect on farmer's profits, i.e. complete suppression of the pest is not usually the best alternative, unless we can ensure long term eradication. Second, the tolerable population density depends on both biological (competitive ability of weeds, damage capacity of insects, response of plants to damage, etc.), economic (market value of crop, cost of control) and agronomic (e.g. planting density) factors.

30.6 Pest Control

Pest control aims at reducing populations of pests to acceptable levels.

The complete elimination of weed plants and seeds is expensive and almost impossible due to the soil seed bank. Fumigants will control nematodes, soil borne fungi and bacteria, soil insects, and weeds (both weed seeds and germinating seedlings). Their use is restricted by their high cost and the toxicity risks. A less aggressive option than to fumigate the soil is called soil solarization whereby a transparent plastic sheet is placed on the soil surface following irrigation in summer. The high temperatures (>60 ºC) and high humidity that is generated by the treatment eliminate most of the soil borne pests down to about 30 cm or deeper.

As eradication of weeds is not possible we need to keep their populations low by preventing the entry of new propagules to the field and by reducing their population. Prevention is based on using seed free of pest propagules and viruses and clean machinery and keeping the field margins free of dangerous weed species which may also host other pests.

30.6.1 Mechanical Control

Tillage in general stimulates the germination of weed seeds in the soil. The main effects of tillage on emerged weed plants are due to the burial of the aerial part (reduced assimilation), mechanical wounding of shoots and roots and uprooting of the weed that then dies by desiccation. Tillage is effective against annual weeds, but may increase infestation of creeping perennials by breakage and spreading of propagules (rhizomes, stolons) when the soil is wet. The effect of tillage depends on the type and depth, with deep moldboard being very effective in killing plants by burial but also promoting the transfer of seeds from deep to surface layers. Vertical tillage will act mostly by mechanical wounding but has little effect on seed distribution.

In earlier times the only measures available for weed control in growing crops were pulling, harrowing and hoeing. Pulling is very effective against annuals and tap-rooted plants but may not be so if the plant is able to re-sprout from root segments. Therefore its effectiveness depends on the ability to remove as much root system as possible, which is quite difficult in perennials.

Mowing reduces the growth of weeds and is very effective in preventing seed production. However, mowing alone selects creeping genotypes or species that escape control.

Burning stubble or crop residues has been used since ancient times not only to control weeds, insects and pathogens but to facilitate seed bed preparation. However, burning is being restricted in many areas because of several disadvantages (wildfire risk, smoke control, loss of organic matter and nitrogen). High temperatures kill seedlings and may kill or reduce the viability of weed seeds, insects and fungi close to the soil surface. This may also be achieved by solarization as discussed above. Another possibility is flaming of weeds using a torch that directs the flame to the weed for a short period, which causes plant death after some time and is more effective on weed seedlings.

Flooding prevents the germination of seeds and kills submerged plants. It is the basic weed control measure in continuous flooded rice crops.

Opaque mulching will prevent seed germination and kill weeds by carbon starvation. For that one may use black or gray plastic films or thick layers of other materials (gravel, sand, sawmill residues).

30.6.2 Other Control Techniques

Crop management affects weed populations in many complex ways. The crop rotation may help in reducing weed problems, e.g. alternating winter and spring crops. Rotations are also very effective for reducing the incidence of soil borne diseases. The management of residues plays also a major role in the control of pests as they serve as a reservoir for pest propagules.

Irrigation management also affects pests. The germination of weeds will not occur in dry soil, thus partial wetting or underground irrigation will be helpful. On the other hand preplant sprinkler irrigation may be used to induce germination of weeds which are then controlled using herbicide or shallow tillage. This system is called stale or false seed-bedding. Some soil borne fungi are promoted by continuous wetting of the soil so reducing the frequency of irrigation may be an effective control measure. Wetting of plants shoots promotes the infection by aerial fungal diseases (e.g. rusts) but may help in controlling other pests (e.g. mites).

Selection of adequate genotypes may help in improving the competitive ability of the crop. In the case of aerial diseases the use of resistant genotypes is one of the major alternatives for control (see Sect. 30.7). Cultivars which are Genetically Modified Organisms (GMO) have been bred that include resistance to certain herbicides (e.g. soybean resistant to glyphosate) thus allowing the application of the specific herbicide to the field areas where weeds appear after the crop has been established. In other cases, bacteria (*Bacillus thuringiensis*) genes that produce a toxin have been inserted in cultivars of some major crops such as corn and cotton, and these cultivars produce the Bt toxin that kills *Lepidoptera* larvae feeding on the crop. In all cases, weed and insect control costs have been greatly reduced in the GMO cultivars.

Planting density also affects the incidence of pests. On the one hand a high planting density may compensate for plant losses due to pests. On the other, crops with high LAI suffer a more humid microenvironment and stay wet for longer after wetting which increases the incidence of aerial pathogens.

Biological control involves the introduction of organisms that are consumers, pests or diseases of other pests. The agent should not affect the crop and should be able to adapt successfully in the area where it is introduced. The most famous example of biological control of weeds was that of *Opuntia stricta* in Australia which was controlled successfully using a moth (*Cactoblactis cactorum*). Insect control may be performed by *Coccinellidae* (ladybugs, ladybirds) which feed on aphids and scale insects.

Chemical control is one of the main alternatives for pest control and will be considered in detail in the next chapter.

30.7 Using Cultivars with Resistance to Pests

One of the best alternatives for reducing the impact of insects and diseases is using resistant cultivars. We distinguish two types of resistance:

(a) Qualitative or vertical resistance is that controlled by one or a few genes so we find distinct resistant and susceptible cultivars. The continuous use of the resistant cultivar may lead to the appearance of a new race of the pathogen for which resistance is lost, forcing the development of a new resistant cultivar.
(b) Quantitative or horizontal resistance is that controlled by many genes so there is a continuous variation in the level of resistance of different genotypes. This type of resistance holds for many races of the pathogen so it will last much longer than vertical resistance, but is difficult to transfer between genotypes.

We can also distinguish between resistance, if the pest does not infect the host plant, or the infection is very limited, and tolerance, when infection occurs but the impact on yield is very low.

Several alternatives may be used to reduce the selection pressure on the pathogen so the resistance holds longer:

(a) Alternating resistant and susceptible cultivars in the crop rotation.
(b) Sowing a mix of resistant and susceptible cultivars
(c) Using a multiline which is an ensemble of cultivars with resistance to different pathogen races
(d) Including the resistance to different races in a single cultivar

Options a and b are not very attractive to farmers, while options c and d require huge efforts by breeding companies, so in the end plant breeders keep track of new pathogenic races and breed for new cultivars in a never ending race against the adaptation of pathogens. This is called maintenance breeding and is essential for the sustainability of agriculture even though it is not high in the priority list of agricultural research in many countries.

30.8 Weed Management

Weed management is a set of strategies of weed control aimed at controlling the weed populations in the long term (years) in a cropping system. It involves a more comprehensive and longer term approach than weed control. This technology is based on better knowledge of the ecology of weed populations, their critical periods for the formation of propagules and their interactions with cultural practices. With that knowledge it is possible to design long-term strategies to keep weed populations at acceptable levels from the point of view of crop production. For example, models of germination of weeds may be used to adjust the dates of tillage, herbicide application or crop planting before the emergence of the weeds.

Another important aspect of weed management is to develop long-term strategies that are necessary if we look at weeds as a phenomenon at the farm or even at the agricultural system level. In this case we should be concerned about the production and dispersal of propagules. For instance, the better the separation between crop and weed seeds in the combine, the better the dispersal of the weed will be.

Strategies for long-term management must also consider the evolution of weeds which may be very fast (several years) in response to the strong selective pressure exerted by agricultural practices (including herbicides). One interesting choice is alternating control measures. An example would be the application of herbicides for several years leading to a reduction of genetic variability, which often leads to very strict temperature requirements for germination. After several years we may exploit the characteristics of the target population using tillage at the right time or by changes in cultural practices (e.g. earlier sowing). In this second phase the weed population is selected to broader forms which include greater sensitivity to herbicides.

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Chapter 31
Application of Herbicides and Other Biotic Control Agents

Francisco J. Villalobos and Elias Fereres

Abstract The main characteristics of pesticides to consider from an agronomic viewpoint are selectivity, mobility within the plant and toxicity on non-target plants, insects and other fauna. Pesticide application should be aimed at maximizing the protective effect while preventing drift, which is increased with high wind speed, unstable conditions and high evaporative demand. There is a general trend towards using molecules in pest control that have less persistence and less negative impacts on the environment. Pesticide doses for trees may be adjusted depending on the actual canopy volume (TRV method). In the case of annual crops the dose may be calculated as a function of Leaf Area Index.

31.1 Introduction

In this chapter we discuss the types of chemicals normally applied to crops and the environmental factors to consider for their application. The main types of pesticides used in agriculture are herbicides, insecticides and fungicides for controlling weeds, insects and pathogen fungi, respectively. The term pesticide also includes other products which are not exactly control agents like defoliants, desiccants and plant growth regulators (Table 31.1).

Pesticide use is almost as old as agriculture with elemental sulfur being the first known pesticide as it was employed by Sumerians to control insects and mites about 4500 years ago.

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Table 31.1 Classification of pesticides according to the target organism

Pesticide type	Target
Algicide	Algae
Avicide	Birds
Bactericide	Bacteria
Fungicide	Fungi
Herbicide	Weeds
Insecticide	Insects
Miticide	Mites
Molluscicide	Snails, slugs
Nematicide	Nematodes
Piscicide	Fish
Rodenticide	Rodents
Plant growth regulators	
Dessicants	
Defoliants	

31.2 Pesticides

In general a small amount of pesticide active ingredient (a.i.) has to be applied uniformly over a large area. To improve distribution and application uniformity the active ingredient is usually made up into a formulation, which combines the active ingredient with various inert carriers, and other ingredients to improve shelf-life, enhance dispersal in water and prevent clumping (solids). The type of formulation can affect the toxicity, the persistence and the rate of release.

The concentration of active ingredient in a formulation may be expressed as % weight (% w/w) or g/100 g for solids. For liquids there are several alternatives: % weight (% w/w), g/100 g, % volume (% w/v), g/100 cm^3 or g/L.

Pesticides can be presented as liquids (solutions or suspensions) or solid (powder or granules). They may be applied with spray bars or dispensers, either over the entire surface, or localized over only a fraction.

It is common to use mixtures of pesticides to expand the range of action (control a larger number of species), save on applications and in some cases produce synergism (the action of a pesticide enhances the effect of another). Compatibility is the possibility of mixing two pesticides without reducing their efficiency.

According to their mobility in the plant, pesticides may be called systemic when they are absorbed and translocated inside the plant or contact when they affect only the plant part in contact with the chemical.

We may also classify pesticides according to their persistence (residual or non-residual) or their selectivity (selective versus non-selective) depending on the number of species affected.

31.3 Application of Pesticides

Most pesticides are applied by spraying liquid formulations but other methods may also be used (Table 31.2), like baits, fumigants, dusts or addition to irrigation water. Spray methods may be classified according to the volume application rate (VAR, L/ha) (Table 31.3).

Spray application is a relatively complex process that can be divided into a transport phase and another of interaction with the surface to be treated. A set of droplets, characterized by a diameter distribution and an initial velocity, is released from the nozzle at a given height. These droplets suffer a vertical force, resultant of the forces of gravity and friction, and a horizontal force (wind drift) that determine the trajectory and hence the drop point. During transport, droplets are subjected to direct evaporation so the diameter decreases. The fall speed decreases as does the diameter of the droplets. Very small droplets may remain practically suspended in the air and fall very slowly, which increases horizontal displacement and thus, drift.

The interaction phase is that occurring when the drops reach the surface. If the droplet is too large it tends to bounce or drain down to the ground. Small droplets will likely stick to the crop surfaces.

Therefore, optimal droplet diameter is generally in the 150–250 μm range depending on the type of product (Table 31.4). The density of impacts required also depends on the type of product. For example, non-systemic fungicides and preventive contact insecticides for very mobile pests require full coverage of plant organs and therefore a very high density of impacts. In the case of insecticides that are toxic by ingestion with highly mobile insects the required density will be much lower.

31.4 Drift

Drift is a side effect of pesticide use associated with ground and aerial application and is an important environmental concern. Drift is the uncontrolled airborne movement of spray droplets, vapors, or dust particles, away from the intended point of application, therefore reducing the actual dose applied. Drift can cause injury to non-target plants and animals, and has the potential for contaminating non-target sites, in special, surface waters, sensitive crops, warehouses, populated areas and flowering crops with bees present.

Any pesticide application may produce some amount of drift. The actual amount will depend on the formulation of the material applied, the application method, the volume used and the weather conditions during application.

Pesticide drift is usually greater when application height is large (e.g. by aircraft) so it is recommended not to exceed 1.2 m (above the crop) for ground applications. Drift is also more important when particles are light (e.g. dusts, low volatility oils) or drops are small. For sprays, droplet size increases with nozzle opening and

Table 31.2 Classification of pesticides according to presentation

Name	Description	Advantages	Disadvantages	Typical use	Applied as
Solids					
Bait	Mixture of a.i. and food that attracts pests. Made as meal, pellets or liquid	Easy to spottreat and apply by hand. Ready to use	Risk for pets and wildlife	Insects, rodents, birds, slugs	Solid
Dust	Finely ground inert particles (e.g. talc) with 1–10 % a.i.	Ready to use. No mixing	Visible on plants. Easily inhaled. Risk of drift	Spot or seed treatment	Solid
Granules and pellets	Dry inert materials (e.g. corn cob) with 2–25 % a.i.	Ready to use. No mixing. Minimal drift.	May be eaten by birds. May need incorporation.	Soil treatment for insect or weed control. Baits	Solid
Impregnated fertilizer	Granular fertilizer containing a low concentration of pesticide	One step application.	Special equipment required	Soil application	Solid
Soluble powder	Dry powder or granules which dissolve in water to make spray solution. Often > 50 % a.i.	Agitation not needed after mixing.	Hazardous if inhaled	Mostly sprays for insect and weed control. Few formulations available	Liquid
Wettable powder	Finely ground inert ingredients with >50 % a.i. forms a suspension in water	Less hazard than emulsifiable concentrate	Hazardous if inhaled. Dusty	Sprays for insect, disease, and weed control	Liquid
Dry flowable, water dispersible granules	Mixture of a.i. and inert material forming pellets or granules. Forms suspension in water	Less dusty and lower inhalation hazard than powder	Spray mix requires agitation	Sprays for insect, disease, and weed control	Liquid
Liquids					
Aerosol (A)	Usually contain small amounts of a.i. and a petroleum solvent	Low concentration of a.i.	Inhalation hazard.	Inside greenhouses	Gas

(continued)

Table 31.2 (continued)

Name	Description	Advantages	Disadvantages	Typical use	Applied as
Emulsifiable concentrate	Contains a.i., petroleum solvent, and emulsifiers. Pesticide is suspended in spray which is milky coloured	High concentration of a.i. Easily mixed	Amount of a.i. increases mixing hazard	Sprays for insect, disease, and weed control	Liquid
Flowable	Finely ground particles suspended in an inert liquid carrier. Forms suspension in spray mix	No dust	Spray mix needs constant agitation	Sprays for all types of pesticides	Liquid
Gel	Semi liquid emulsifiable concentrate	Used with water soluble packaging		Herbicides and insecticides	Liquid
Micro-encapsulated materials	Consist of pesticide surrounded by a plastic coating. Mixed with water and sprayed	Reduced hazard to applicator. Easy to mix and apply	Agitation needed. High risk for bees	Insecticide and pheromone sprays	Liquid
Solution	A.i. comes dissolved in liquid. Forms a solution in spray mix	Easily mixed	High concentration of a.i. increases mixing hazard	Spray of herbicides	Liquid
Ultra low volume concentrate or sprayable concentrate	Liquid with very high concentration of a.i. Used as it is or slightly dilluted	Requires little or no mixing. Few formulations available	Needs special application equipment	Insecticide sprays inside greenhouses	Liquid
Gases					
Fumigants	Volatile liquids or solids packaged to release a toxic gas	Wide spectrum of pests and stages of development. Good penetration of structures and soils	Highly toxic. Treated area must be sealed	Greenhouses, granaries. Pre-plant soil treatment for resistant pests	Gas

(continued)

Table 31.2 (continued)

Name	Description	Advantages	Disadvantages	Typical use	Applied as
Package					
Water-soluble packets	Pre weighed amount of wettable or soluble powder in plastic bag that dissolves in water	Safe and easy to use		Sprays for insect, disease and weed control.	Liquid

Table 31.3 Classification of spray methods according to the volume of spray applied

	Trees and shrubs	Annual crops
	Dose (L/ha)	
High volume	>1000	>700
Medium volume	500–1000	200–700
Low volume	200–500	50–200
Very low volume	50–200	5–50
Ultra low volume	<50	<5

Table 31.4 Desired parameters for spraying the main types of pesticides. The volume of spray for LAI = 1 has been calculated for nearly optimal conditions (10 % loss by drift and 10 % not intercepted by the canopy)

		Required droplet diameter	Impact density	Spray volume for LAI = 1	Main concern
Pesticide	Type	μm	cm^{-2}	L/ha	
Herbicide	Contact	300	60	106	Drift
Herbicide	Systemic	700	20	449	Drift
Fungicides	Contact	150	60	27	Areas wetted
Fungicides	Systemic	250	20	20	
Insecticides	Contact	200	60	63	Impact number
Insecticides	Systemic	350	20	56	
Fertilizers		>1500			

decreases with pressure. Droplets with diameter lower than 100 μm favor drift so the 150–200 μm range is recommended. Thickeners reduce the frequency of small droplets.

Fumigants and highly volatile formulations may produce vapors which easily drift. Vaporization (volatilization) is proportional to evaporative demand and inversely proportional to drop size. Water-based sprays will volatilize more quickly than oil-based sprays. However, oil-based sprays can drift farther because they are lighter, especially at high temperatures.

To minimize drift it is better to work under low evaporative demand (temperatures below 32–35 ºC), and low wind (1–2 m/s) with consistent direction and close to neutral conditions. These conditions usually occur in the early morning and late afternoon. Unstable conditions favor the rise of droplets and therefore the horizontal displacement. Under stable conditions (temperature inversion) a highly concentrated cloud is formed which can move outside the target area. This is highly risky for herbicides but might be more acceptable for insecticides or fungicides. Spraying of pesticides, in special herbicides, should be avoided for calm (wind speed below 1 m/s) and windy conditions (above 2.5–3 m/s). Note that atmospheric instability adds thermal turbulence to mechanical turbulence due to wind so for any given wind speed the conditions for spraying get worse as instability increases.

Pesticide applications should also be avoided when rain is expected in the short term. Wind direction should be taken into account to analyze the risk of drift arriving at sensitive areas. Untreated buffer zones should be established if needed.

31.5 Persistence of Pesticides

Persistence of pesticides is important as it determines the duration of the protective effect and the safety period in terms of harvesting the crop after the application. The persistence of a given herbicide also may preclude planting a sensitive crop species in the same field.

The degradation of pesticides is caused by:

- Microbial decomposition so environmental conditions that favor microbial activity contribute to the degradation of the pesticide.
- Chemical decomposition by oxidation, reduction or hydrolysis.
- Photolysis, i.e. chemical degradation due to light absorption by the product.

Pesticides can also be immobilized in the soil (adsorption by soil colloids). Most adsorption occurs with organic colloids, so soils high in organic matter or clay soils will require larger doses of herbicide.

Pesticides can be lost by leaching or volatilization. Leaching depends on its solubility and its adsorption to colloids. To avoid volatilization the more volatile products should be incorporated into the soil. Residual herbicides (e.g. atrazine) can cause serious environmental problems as they accumulate in groundwater after leaching which has led to their banning in some countries (e.g. Atrazine was banned in the European Union in 2004).

31.6 Herbicides

31.6.1 General Characteristics

Herbicides are phytotoxic products. They may be classified as total or selective, when they affect all or some species. In terms of time of application we may distinguish among preplant, preemergent and postemergent (in reference to the crop) and in terms of mobility we have systemic and contact herbicides.

The dose of herbicide to be applied depends on its phytotoxicity to the weeds and the crop, and the density of weeds present.

Herbicides may be absorbed by the roots, the leaves or the stems. Leaf absorption is increased by adding wetting agents. The absorption of polar herbicides is more effective by the roots than by the leaves. Herbicides interfere with some metabolic process of the plant (photosynthesis, respiration and metabolism of nucleic acids and proteins). Visual symptoms of herbicide damage include reduced growth, malformation of leaves and plant wilting.

The translocation of systemic herbicides can follow two paths. If it is absorbed by the roots, the herbicide passes to the xylem, and then it is distributed by the sap flow. If it is absorbed by the leaves it moves via symplast to the phloem, and then it is transported to the growing tissues.

31.6.2 Selectivity of Herbicides

The selectivity of an herbicide implies its ability to control weeds without causing significant damage to the crop. The selectivity depends on several factors:

(a) Plant: Sensitivity is higher in young and fast growing plants. The highest sensitivity in seedlings is due to their thinner cuticle. The morphology of the plant may be responsible for the selectivity. It may be due for example to differences between the crop and the weed in the root system or the location of sensitive organs such as the apical meristem.

(b) Climate: The selectivity of foliar absorbed herbicides is reduced at high temperatures. However in these conditions the rate of metabolism of the herbicide in the plant is higher which helps reduce its negative effects. In conditions of high humidity and/or high soil water content the leaf cuticles have a higher degree of hydration which facilitates herbicide leaf absorption and can increase the potential damage to the crop.

(c) Soil: Texture and organic content determine the degree of fixation of the herbicide to soil colloids and hence the concentration of the active ingredient in the root zone.

The high sensitivity of seedlings is the basis of the technique of split dosing which involves making a number of small dose post-emergence applications when weeds are emerging so that the crop hardly suffers their effects while weed seedlings are killed. The main groups of herbicides and their characteristics are presented in Table 31.5.

31.7 Insecticides

Insecticides are agents that control insects by killing them or preventing them from destructive behaviors. Insecticides may be natural or artificial and are applied in a wide range of formulations and delivery systems (sprays, baits, slow-release diffusion, etc.). Some G.M.O. genotypes incorporate bacterial genes coding for synthesis of insecticidal proteins.

Table 31.6 shows a classification of insecticides according to several criteria.

By 1940 only some inorganic (e.g. sulfur) or botanical (e.g. pyrethrum) insecticides were available. Then the first synthetic organic insecticide, DDT, an organochlorine, appeared. After that the history of insecticides has been a mixture of success (high levels of control at reduced cost, development of more specific products with low persistence) and failure (e.g. organochlorines are toxic for animals, accumulate in the trophic chain and had to be banned).

31.8 Fungicides and Control of Diseases

Plant diseases are best controlled by integrating a number of practices including sowing date, planting density, crop rotation, cultivar selection (using disease-tolerant or disease-resistant genotypes), fertilizer and irrigation programs, microclimate modification and application of fungicides.

Knowledge of the disease cycle of the pathogen is important when developing disease forecasting systems or economic thresholds. Forecasting systems are based on temperature and relative humidity or leaf wetness. Thresholds-based programs involve periodical monitoring of symptoms (e.g. number of disease spots per leaf). Important aspects of the disease cycle include the number of generations per year of the pathogen and the time between infection and the appearance of symptoms (latent or incubation period) which may be a few hours for aerial diseases up to several weeks for soil borne pathogens.

Fungicides are products that kill or prevent the growth of fungi and their spores. They may be classified according to different criteria.

(a) Mobility in the plant.

Contact fungicide is that that remains on the surface where it is applied but does not enter the plant and has no after-infection activity. Repeated applications are needed to protect new growth and to replace losses by rain or irrigation, or degraded by environmental factors.

Table 31.5 Classification of herbicides according to their main characteristics

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Photosystem II inhibitors	Triazines (eg Atrazine), Ureas (eg Diuron)	S, Lf	Temp., placement, metabolism	Lf	Ap	M-H	L
Photosystem I inhibitors	Benzotidiazoles. (Ex. Bentazon)	Lf	Metabolism	Lf	No	L	L
Membrane synthesis inhibitors	Bipyridylium (Ex. Diquat, Paraquat)	Lf	Temp., placement, metabolism	Green tissue	No	Nil	H
Membrane disrupters	Diphenylether, Dinitrophenols	Lf	Pubescence	Green tissue	No	L	M
Aminoacid synthesis inhibitors (selective)	Sulfonylureas	Lf	Metabolism	Enzimes	Ap, Sy	M-H	L
Aminoacid synthesis inhibitors (not selective)	Aminoacid derivatives (Ex. Gliphosate)	Lf	Placement, genotype	Enzimes	Sy	L	L
Lipid synthesis inhibitors	Aryloxyphenoxypropionate and cyclohexane derivatives	Lf	Not affecting dicots	Meristem	Sy	Nil	M
Growth regulators	Phenoxy-carboxylic acids (eg 2,4-D), benzoic acid, piridines	S, Lf	Not affecting monocots	Auxines	Ap, Sy	V	M
Cell division inhibitors	Dinitroanilines (eg Trifluraline)	S	Placement	Contact tissue	No	V	M
Protein synthesis inhibitors	Chloroacetamide and thiocarbamates	S	Placement, metabolism	Seedlings	Little	L-H	M
Pigment synthesis inhibitors	Piridinones	S	Placement, metabolism	Chloroplast	Ap	M-H	L

1: Herbicide type	
2: Chemical groups	
3: Activity	S: soil, Lf: leaf
4: Basis for specificity	
5: Site of action	Lf: leaf
6: Translocation	Ap: Apoplast, Sy: symplast
7: Persistence	L: low, M: medium, H:high, V: variable
8: Toxicity	L: low, M: medium, H:high

Table 31.6 Classification of insecticides according to their main characteristics

Type	Main effect on insect	Toxicity for other organisms	Main targets
Organochlorine	Nervous system	High	Broad spectrum
Organophosphate	Neuromuscular system	Very high	Broad spectrum
Organosulfur	Ovicidal	Very low	Mites
Carbamates	Nervous system	High, in special to fish	Broad spectrum
Formamidines	Nervous system	Medium	Organophosphate and carbamate-resistant pests
Dinitrophenols	Synthesis of ATP	Slight to moderate	Withdrawn from use
Organotins	Synthesis of ATP	High for aquatic life	Mites in trees
Pyrethroids	Nervous system	High for fish	Most agricultural insects
Nicotinoids	Nervous system	Low	Sucking insects, soil insects, whiteflies
Spinosyns	Nervous system	Low	Caterpillars, lepidopteran larvae, leaf miners, thrips
Pyrazoles	Synthesis of ATP	Low	Psylla, aphids, whitefly and thrips
Pyridazinones	Mitochondrial electron transport	Medium for aquatic life	Mites
Quinazolines	Blocking the synthesis of chitin at larval stage	Medium	Broad spectrum
Botanicals	Pyrethrum – nervous systems	Low	Lice
	Nicotine – nervous systems	Low	Aphids and caterpillars
	Rotenone – respiratory enzyme inhibitor	High to fish	Fish
	Limonene – nervous systems	Low	Fleas, lice, mites, and ticks
	Neem - reduces feeding and disrupts molting	Low	Moth and butterfly larvae
Antibiotics	Blocking the neurotransmitter GABA	Toxic to fish and bees	Spider mites, leafminers
Fumigants	Act as narcotics	Depends on compound	Depends on compound
Inorganics	Dependent upon type of inorganic	Depends on compound	Depends on compound (e.g. sulfur for mites)
Biorational	Act as attractants, growth regulators or endotoxins	Very low	Very specific
Benzoylureas	Insect growth regulators	Some may affect other invertebrates	Caterpillars and beetle larvae

Systemic fungicides are absorbed into the plant and move within it. They may offer some after-infection activity. Very few fungicides are truly systemic (the group of the phosphonates) but some are acropetal penetrant (moving upwards in the xylem), and some are localized penetrant (i.e. redistribute within the treated leaf).

(b) Role in protection (some fungicides can fall into more than one of the following categories)

- Preventive fungicides offer a protective barrier that prevents infection.
- Early-infection activity: the product enters the plant and stops the pathogen, being usually effective until several days after infection. This type has also preventive activity and is most effective when applied before infection.
- Eradication: a few products have the ability to stop disease development after symptoms have developed. Even then the damage caused by the disease on the plants often does not disappear.
- Anti-sporulant activity (ability to prevent spore formation). In this case, disease continues to develop, but spores are not produced, so the amount of inoculum available to infect surrounding plants is reduced.

(c) Mode of action.

The mode of action is how a fungicide acts on a target fungus, i.e. which is the specific process in the metabolism that is affected (e.g. damaging cell membranes, inactivating critical enzymes). A single-site fungicide affects only one point in one metabolic pathway or a single critical enzyme or protein. These fungicides are less phytotoxic and tend to have systemic properties, but show a higher risk of pathogens developing resistance, as the mode of action is so specific that small genetic changes in fungi can overcome the effect of the fungicide.

On the other hand, a multi-site fungicide affects a number of different metabolic sites within the fungus.

31.9 Calculation of the Volume Application Rate of Pesticides

The minimum volume of pesticide to apply or Volume Application Rate (VAR, L ha^{-1}) may be calculated as a function of the desired impact density (N, impacts cm^{-2}) and the droplet diameter (d, μm) as:

$$VAR = f(LAI)\ \frac{10^{-7}\pi}{6}\,\frac{d^3\,N}{1-p_s-p_d} \qquad (31.1)$$

where p_s and p_d are the probability of droplets not being intercepted by the canopy and the fraction of droplets lost as drift, respectively. The f (LAI) function depends on the type of pesticide. For contact fungicides and contact insecticides f (LAI) = 2 LAI, while for systemic fungicides and insecticides f (LAI) = LAI. For herbicides f (LAI) = 1. The same value should be adopted if the calculated value of f (LAI) is lower than 1.

Example 31.1 We want to apply a contact fungicide on a wheat crop with full ground cover and LAI = 3. The required impact density is 60 impacts cm $^{-2}$ and our sprayer generates droplets of diameter 150 μm. We will perform the application with good conditions (drift loss 10 %). With full ground cover we can assume that almost all droplets will be intercepted by the canopy ($p_s = 0.1$). With a contact fungicide we take f (LAI) = 2 LAI = 6. Therefore:

$$VAR = f(LAI)\,\frac{10^{-7}\pi}{6}\,\frac{d^3N}{1-p_s-p_d} = 6\cdot\frac{10^{-7}\pi}{6}\,\frac{150^3\cdot 60}{1-0.1-0.1} = 80\ L\ ha^{-1}$$

31.10 Calculation of Spray Volumes for Fruit Tree Orchards

The Tree-Row-Volume (TRV) system was developed for hedgerow apple orchards in the United States. Instead of using a standard volume application rate (3741 L/ ha = 400 gal/acre), the VAR was corrected in proportion to tree volume per unit area (TRV, m^3 ha^{-1}):

$$VAR\left(L\ ha^{-1}\right) = 0.0937\cdot TRV \tag{31.2}$$

where 0.0937 is the volume (in liters) of spray necessary to wet 1 m^3 of crown (of low leaf area density). This value increases to 0.1337 L m^{-3} for dense trees. This same approach may be applied also to orchards where tree crowns do not overlap. However, the specific factor of volume per unit volume may change for high density orchards or differences in leaf anatomy (e.g. for grapevines, 0.3 L m^{-3}).

If the recommended dose of pesticide is δ_p (kg active ingredient ha^{-1}) for a standard VAR of 3741 L/ha, then the actual dose of pesticide should be:

$$Actual\ dose\left(kg\ a.i.\ ha^{-1}\right) = \frac{0.0937\cdot TRV\cdot\delta_p}{3741} \tag{31.3}$$

Example 31.2 An apple orchard has trees spaced 7 × 5 m. We want to apply a fungicide with recommended dose of 2 kg a.i./ha. The horizontal radius of

(continued)

Example 31.2 (continued)

the trees is 2.0 m and the vertical radius is 1.5 m. The trees have a low leaf area density. The tree volume per unit area is:

$$TRV = \frac{\frac{4}{3}\,\pi \cdot 2 \cdot 2 \cdot 1.5}{7 \cdot 5}\,10^4 m^2 ha^{-1} = 7181\; m^3 ha^{-1}$$

For low leaf area density the volume application rate is:

$$VAR = 0.0937 \cdot TRV = 0.0937 \cdot 7181 = 673\; L\; ha^{-1}$$

And the actual dose:

$$Actual\ dose = \frac{0.0937 \cdot TRV \cdot \delta_p}{3741} = \frac{0.0937 \cdot 7181 \cdot 2}{3741} = 0.36\; kg\; a.i.\; ha^{-1}$$

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Chapter 32
Harvest and Conservation

Francisco J. Villalobos and Elias Fereres

Abstract Harvesting is the key operation in farming that culminates the season's efforts. It represented an important fraction of all labor used in agriculture until recently and the equivalent in production costs. With the advent of mechanical harvest, costs have decreased dramatically contributing greatly to the reduction of food prices in recent decades. Determining the time of harvest is normally a compromise between factors that increase profits (e.g., delaying it for greater biomass) and increased risks (e.g., lower product quality or persistent bad weather). There are yield losses during harvest that must be prevented and also during postharvest, in this case related to storage conditions. Drying grains and storing them under low relative humidity (RH) minimizes the incidence of fungal diseases that deteriorate the product. The water content of the seeds after harvest tends to an equilibrium value in storage which depends on the RH and air temperature, such seed water content may be determined through Moisture Release Isotherms. Forage crops may be consumed directly by animals or cut and conserved as silage, haylage or hay, with each process requiring more drying of plant materials before safe storage. Harvest of fruits for the fresh market is still done by hand and quality considerations are important in determining its timing. The harvest of fruits and vegetables for processing has been extensively mechanized; determining its timing is based on a tradeoff between quality factors and yield and marketing objectives.

32.1 Introduction

Harvest is a key activity as it culminates all farming operations leading to the ultimate goal of agriculture, producing food and obtaining useful materials. The first agricultural practice in history was harvest. Long before actual crop husbandry began humans were collecting seeds from some grass species as part of a diverse

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diet. These hunter-gatherers processed the seeds to produce ale and bread. A great advantage of seeds was the possibility of long term storage for later use in contrast with the very limited time that meat from hunting lasted in storage. Furthermore the low efficiency of collecting seeds from natural populations where useful plants are scattered probably fostered the idea of agricultural crops. Someone must have wondered: what if this field would be filled only with the plant that I want every year? What if all the plants ripened at the same time, with larger seeds that would not shed before I collected them? Thus, harvesting the edible parts of plants in natural environments probably was pivotal to the invention of agriculture.

The great advances in crop productivity of recent decades have often been associated with a reduction in harvesting costs through mechanization. In many cases harvest costs limit the economic viability of crops. Traditionally harvesting was based only on human labor with the partial support of beasts of burden for gathering and transport. The availability of labor for harvest often limited the area of arable land. For instance hand harvesting 1 ha of wheat required about 130 - man-hours of work (13 days of 10-h days) while current mechanized harvesting requires only 0.4 man-hours. Therefore if the time available to harvest is between 30 and 60 days it follows that one person could harvest 2.3–4.6 ha manually but as many as 750–1500 ha using a standard combine harvester.

One important decision for the farmer is when to harvest. Physiological maturity is defined as the time when biomass of the harvested part reaches a maximum. However, the best conditions for harvesting (harvest maturity) may occur much later because, in most cases, reducing further the water content of the product is beneficial in terms of handling less weight and to reduce the risk of fungal diseases.. In the case of fruits the level of ripeness involving color, accumulation of secondary products, and taste has also to be considered. In the case of many vegetables the date of harvest may not be associated to physiological maturity when special quality characteristics are the main concern.

The harvest method and associated operations also affect other components of the farming system. Normally the harvested product represents only part of the biomass and the rest must be managed in such a way that it contributes to the subsequent crop and does not interfere with subsequent farming operations. Actually, the management of crop residues has a major impact on the organic matter and nutrient balances of the soil and offers great opportunities for contributing to soil conservation. Harvesting can also have adverse effects on the agricultural system like the spread of pathogens, insects and weeds and soil compaction due to the traffic of the heavy machinery used.

32.2 Harvest Operations

Harvest can affect the whole plant or only part of it. In this case the harvested organ may be aerial or underground (Table 32.1). The crop residues may be also harvested and exported outside the field, either separately, or still attached to useful parts, for

Table 32.1 Classification of products harvested in agriculture according to the final use or the harvested organ

Use		Harvested organ and products	
Food	Fresh	Shoot	Vegetative
	Transformation		Reproductive (flowers, fruits, seeds)
Fodder			Sap (e.g. maple)
Industrial products	Textile		Latex (e.g. rubber, opium)
	Chemical (oil, paint, varnishes)		Resins (e.g. pine)
	Fuels	Subterranean organs	Roots (e.g. beet, carrot, cassava)
	Perfumery and cosmetics		Bulbs (e.g. onion)
	Pharmaceutical		Tubercules (e.g. potato)
			Rizhomes (e.g. ginger)
Seeds and propagules for agriculture			

Table 32.2 Some basic operations in the harvest of different crops

Harvesting operations	Crops
Mowing	Forage crops, medicinal crops
Reaping, threshing, and winnowing	Cereals, pulses, oil crops
Combing and pulling	Fruits
Digging, sieving and loading	Tubercules, roots
Cutting	Vegetables
Gathering	Fruits
Shaking, sweeping, loading	Nuts, olive

further separation. In the best case only the useful organs are exported while crop residues remain in the field.

Decisions about when and how to harvest depend on the final use of the product (Table 32.1). For example, vegetable and fruit products for fresh consumption are frequently gathered by hand and harvest may be performed in several passes as the crop ripens.

The operations involved in crop harvesting are varied and depend on the species and its use (Table 32.2). In most cases the harvest consists of cutting part or the total above ground part of the plant and separating the useful fraction (e.g. seeds) from the residues. These two processes may occur at about the same time (e.g. combine harvest of grains) or the cut plants may be left in the field for drying and then either combined or transported out of the field for threshing and winnowing. Before harvest it may be necessary to prepare the crop (using defoliants or abscission promoters) and/or the soil (compaction, irrigation, etc.).

After harvesting some post- harvest operations may be performed in the field/farm or outside, like drying, cleaning, removal of plant parts, sorting by size, etc.

Finally the harvested product may go directly to the packing plant or to the storage facility, which may require aeration and/or temperature control. For horticultural crops a controlled atmosphere is usually employed, that is, with low oxygen and high carbon dioxide concentration that greatly slow down fruit ripening.

32.3 Yield Losses During Harvest

Not all crop biomass but only part of it (yield, Y) is useful. The ratio yield/biomass was defined as the Harvest Index in Chap. 13. However, the harvested yield (Y_c) is always less than Y (measured at physiological maturity) because of losses:

(a) Before harvest, due to:

- Respiration of the harvestable organ, which is proportional to the time the organ is in the field after reaching maturity and to its water content and temperature.
- Loss of harvestable structures (dehiscence of pods, abscission of fruits, consumption by herbivores, fire, hail, etc.).

(b) During harvest:

- Inaccessible parts of the plant: e.g. plant parts below the cutter bar.
- Not captured by the harvest system or dropped by it.
- Deterioration of structures collected (broken grains, damaged fruits)
- Rejection due to low quality: Although not exactly a loss, part of yield may be left uncollected because of poor quality or excessive harvest costs. For instance a very low grain yield may not compensate for the cost of mechanical harvesting.

(c) After harvest (during packaging, transport or storage)

- Respiration of the harvested organ: dependent on water content and temperature
- Consumption or deterioration caused by pests and diseases: dependent on the sanitary conditions of the storage facility and on the water content and temperature of the product and air humidity.
- Rejection due to postharvest quality criteria: The collected product (or a fraction of it) may not meet quality standards implying a loss or an additional cost for sorting and separation of those products not meeting the standard.

Box 32.1 The Year Without a Summer

Weather conditions in 1816 turned extremely cold as a result of the volcanic eruption of Mount Tambora in Indonesia that ejected an enormous amount of ash into the atmosphere, thereby reducing transmissivity and global radiation.

(continued)

Box 32.1 (continued)

It is estimated that global average temperature decreased after the eruption and for almost 3 years between 1.5 and 3ºC. Heavy rainfall and cold temperatures during the summer in Western Europe resulted in the delayed development of many crops that did not reach maturity. Those that did could not be harvested in many cases, and when harvested, the grain was lost later during storage. At that time, subsistence agriculture was common and people in the cities lived from harvest to harvest depending on fragile agricultural systems that did not produce sufficient food. Food shortages were dramatic during 1816 and the two following years, not only in Europe but globally. In Asia, the monsoon patterns were disrupted and that caused not only famine but epidemics that killed millions, and political unrest was at a high point in China.

32.4 Agricultural Operations Affected by Harvest

Harvesting normally requires the concentration of efforts by the farmer and its labor force thus restricting other simultaneous farm operations. The date and method of harvest of a given crop determines the possible choices for the next crop in the rotation. The harvest method determines the amount and distribution of residues in the field, which determines the need for additional operations (burning, chopping, removal) and thus, the time required for land preparation before sowing the next crop.

Irrigation may be used to improve soil conditions before harvest (e.g. before digging of tubers or roots). Irrigations may also be stopped to promote abscission (of leaves or fruits) and to prevent soil compaction due to traffic on wet soil during harvest.

Some tillage operations may be required before harvesting (e.g. surface soil compaction to facilitate sweeping of fallen fruits after tree shaking of almond trees). Pesticide treatments must be stopped for some time before harvest to comply with the safety periods. In other cases (e.g. cotton) defoliants are applied to facilitate mechanical harvesting.

32.5 Harvest of Grains and Seeds

While there is some leeway in harvest time, in winter cereals delaying harvest while leads to lower grain water content and therefore, reduced drying requirements, it has negative effects by increasing:

- dry matter losses and/or reduced grain quality
- seed losses by dehiscence.
- likelihood of deterioration by adverse conditions (lodging, hail) or destruction by fire

Table 32.3 Status of seeds of major agricultural crops as a function of water content

Water content g water/g	Water potencial Mpa	Seed status	Activity of biotic factors	Degradation under storage
>0.41	>−1.5	Physiological maturity		
0.30–0.40	−5 to −1.5			
0.20–0.30	−11 to −5	High respiration rate	High (bacteria, fungi)	Fast
0.13–0.20	−100 to −11	High mechanical resistance (0.13–0.16)	High (insects, fungi)	Fast
		Fit for combine harvesting		
0.10–0.13	−120 to −100		High (insects)	Slow
<0.10	< −120		Low	Slow (may increase with high temperature)

- production of mycotoxins, toxic chemicals produced by naturally occurring moulds and some plant pathogens like *Fusarium*. The most common type is aflatoxins, generated by moulds of *Aspergilus flavus* and *A. parasiticus*. The probability of contamination with aflatoxins is higher when harvest is delayed during wet weather or when grain is harvested with high moisture and drying is delayed. Water stressed crops are more susceptible to infection. Aflatoxins contamination not only occurs in cereal grains, but also in other agricultural products (sunflower seeds, nuts, cassava, cottonseed, spices, pepper, hay). Maize harvest can be delayed longer than winter cereals but only if weather conditions are dry, thereby reducing drying costs without risking aflatoxin contamination.

In many cases harvest is performed before reaching the minimum water content required for safe storage and then the seed water content must be reduced afterwards out of the field. In species where pod shedding is an issue (e.g. rapeseed), or when time is limited, harvest is performed in two stages. The first is swathing, i.e. cutting the crop and leaving it forming windrows where it will dry for 5–10 days until the desired water content in seeds is achieved, when the second stage to separate the seed from the pods (combining) is performed. In general, grain can be stored safely when it is clean, dry, healthy and intact. Conditions improve if it is cold at the time of storage.

The water content of the grain affects (Table 32.3):

(a) The risk of physical damage during harvest
(b) The incidence of insect pests and fungal diseases
(c) The metabolic activity of the seed, which affects its rate of deterioration, the release of oxygen by respiration and heat generation in the stock.

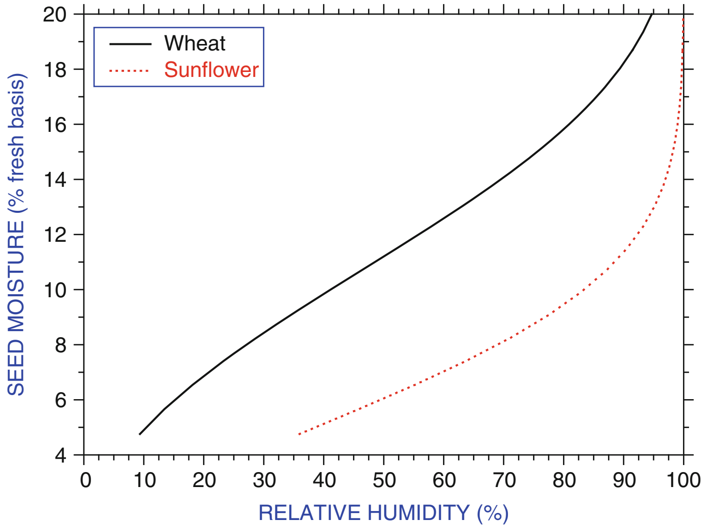

Fig. 32.1 Seed moisture isotherms for seeds of wheat and sunflower at 20 °C

The water content of the seeds after harvest in storage tends to an equilibrium value which depends on the relative humidity (RH) and air temperature. Strictly equilibrium is reached when the water potential is equal in the air and the seed, which can be calculated as

$$\Psi_{seed} = -\frac{RT}{M_w}\ln a_w \tag{32.1}$$

where Ψ_{seed} has units of J/kg (or kPa), $R = 8.3143$ J mol^{-1} K^{-1}, T is air temperature (K), $M_w = 0.018$ kg mol^{-1} and a_w is the water activity, which is equivalent to the equilibrium RH/100. Therefore, for a given air temperature and RH the grain will reach an Equilibrium Moisture Content (EMC). This relationship is called Moisture Isotherm (Fig. 32.1) and is applied not only to seeds but to any type of material. The main factor determining EMC is RH, while temperature plays a minor effect. For instance cereal grains at 25 °C and 70 % RH show EMC between 13 % and 14 % (wet basis). Using Eq. 32.1 this corresponds to a water potential of −49,095 kPa (−49.1 Mpa). One of the main factors affecting the relationship between EMC and RH is the oil content: seeds rich in oil will show a lower EMC for a given RH. This is clearly seen when comparing seeds of wheat and sunflower (Fig. 32.1). It is important to point out that seed moisture may be expressed on a dry basis or wet basis:

$$EMC_d = 100\frac{mass\,water}{mass\,dry\,seed} \tag{32.2}$$

$$EMC_w = 100\frac{mass\,water}{mass\,wet\,seed} \tag{32.3}$$

Therefore:

$$EMC_w = \frac{EMC_d}{100 + EMC_d} \tag{32.4}$$

The seeds are classified as orthodox (can be dried to very low water content without being damaged) as in most agricultural species and recalcitrant (desiccation kills the seed) like those of *Quercus spp*., oil palm, chestnut and cacao. The seed longevity in orthodox seeds decreases linearly with water potential from -350 (2–6 % water) to -14 MPa, which is equivalent to a range in a_w from 0.1 to 0.9, regardless of species. Seed longevity decreases also with temperature. Simple rules have been proposed for seed storage. For instance, the James' rule establishes that the sum of temperature (°C) and relative humidity (%) should be lower than 60. According to Harrington's rule seed longevity decreases by one half for every 1 % increase in seed moisture content or every 6 °C increase in temperature.

To be on the safe side the RH in the space between grains has to be lower than 67–70 %, so that spore germination of pathogens is prevented. Therefore keeping a low RH will ensure that the seeds do not lose viability or mass (by respiration) and are not attacked by pathogens and insects.

The grains may require conditioning (drying, cleaning) before they can be stored safely. Conditioning systems are divided into aeration systems, natural air drying or low temperature (heating of 3–7 °C) systems and high-temperature systems. Postharvest losses of grains due to different causes are significant, particularly in developing countries where much of the production is conserved at the household level. Although figures as high as 40 % are frequently cited, the World Bank estimated that in 2010, the value of postharvest losses amounted to 15 % of grain production in Sub-Saharan Africa.

Table 32.4 presents values of seed water at physiological maturity and recommended for harvest and storage.

32.6 Harvest of Forage Crops

In pastures and some forage crops harvest may be performed directly by grazing animals. In this case it is important to adjust the density of animals to maximize productivity. Animals may also graze field crops during specific growth stages or after harvest to use the stubble. The former is the case of dual purpose crops (cereals, rapeseed) that may be grazed during vegetative growth, as the meristems are not affected, so crop growth can resume afterwards and lead to seed production if the season length is sufficient.

In general the harvested forage crops are stored as silage (50–65 % water content), haylage (30–50 %) or hay (15–25 %). The best nutritive quality in most forage crops is achieved around flowering time. Delaying mowing after that time implies greater (and drier) biomass but lower quality. The other factor that

Table 32.4 Water content of harvested organ at physiological maturity and at the time when it is suitable for harvest and recommended values for harvesting and long term storage

Crop	Physiological maturity	Suitable for harvest	recommended water content for harvest: No air drying	recommended water content for harvest: Air drying	Long term storage
Winter cereals	35–40	<17–18	12		13.7–15.2
Maize	25–30	18–23			12.5–15.5
Rice	30–33	22–28			
Rapeseed	40	<15	8		8
Sunflower	30–40	9–10			7.0–8.3
Lentil		<13			
Soybean	50	14–20	14	18	12
Sorghum	25–30	12–25	14	20–25	12
Bean	38–44	30–40			
Pearl millet	30	<20			<13.5

determines mowing dates is the weather, as conditions after mowing must be dry enough for successful drying.

For silage the crop is cut and chopped and taken to the silo where it is compacted to exclude air and then sealed with plastic to ensure anaerobic conditions. These are required for lactic bacteria to operate and reduce pH thus ensuring long term conservation. Some crops (maize, sorghum) may be taken to the silo just after cutting while others are left in the field drying for 1–2 days before silage starts. For haylage the crop is left longer in the field for drying and then it is wrapped tightly in plastic-covered bales.

Hay production requires a longer drying period. After mowing (and sometimes conditioning) the harvested parts (crushing of plant material to speed up drying), tedding (mixing and upturning) and windrowing (piling the plant material in rows) are followed by baling. The time to dry has to be minimized to reduce respiration losses. This time is proportional to forage biomass and inversely proportional to swath area and evaporative demand.

32.7 Harvest of Underground Organs

In this category we include species that are harvested for their storage organs which are located underground such as tubers (e.g. potato, yam), roots (sugarbeet, turnip, cassava) and bulbs (onion, garlic).

Harvesting date of underground organs should be performed around physiological maturity when little green area is left, although there are tradeoffs between maturity and market targets; for instance, in some areas potatoes may be harvested earlier than at maturity to fetch better prices, even though some yield is sacrificed. Removal or killing of the shoot before harvest enhances periderm thickening of tubers which reduces the risk of peeling or bruising during harvest. Some root crops such as carrots are harvested when size is adequate for the market.

The harvest process of underground organs includes cutting, digging and lifting. The product may be transferred directly to a trailer after separating soil and plant residues or left in the field for drying.

As opposed to seeds, desiccation of harvested underground organs should be prevented under storage. As water loss is proportional to Vapor Pressure Deficit, it will be reduced by applying cool moist (almost saturated) air.

32.8 Harvest of Fruits and Vegetables

Fruits for the fresh market are usually collected by hand at the time when they reach the desired size and are approaching ripening. Quality considerations are critical in some crops such as wine grapes. Here, harvest is delayed until a certain level of sugar content is reached in the grapes, as determined by periodic monitoring, and/or the desired colors are achieved as required by the enologists. In olive oil production, early harvest produces higher quality oil as demanded by markets (more fruity) at the expense of lower oil content in the fruit and thus lower oil yields. An important difference between species is the production of ethylene for ripening. Climacteric fruits (e.g. pear, Appendix) can ripen off the plant once they have reached physiological maturity, so they can be harvested at any time after reaching marketable size and ripened later or they may be harvested when fully ripe. Non-climacteric fruits (e.g. orange) have to be on the plant to complete ripening, so harvest must be delayed until that time.

Fruits for processing (canning, dried, preserves, oil extraction, juice) may be mechanically harvested (e.g. using shakers) when ripe.

Harvest of nut crops occurs after physiological maturity considering two factors: the decreasing water content and the formation of an abscission zone to promote fruit detachment at the time of harvest. Waiting for too long leads to significant fruit drop, causing a fraction of the fruits to be on the ground with increased costs. Nut harvesters are usually based on shaking the tree and collecting the fruits on inverted umbrellas or lateral boards before they are transferred to a trailer.

Appendix: Composition of Harvested Products

Percentage of dry matter, gross energy per unit dry mass and main composition of harvested products. Fresh fruits are also classified according to the capacity for ripening after detaching from the plant at physiological maturity (climacteric, C) or the lack of it (non climacteric, NC)

		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Cereals and pseudocereals			**%**	**MJ/kg**	**% Over dry mass**		
Barley (2 row)	*Hordeum vulgare*	Grain	86.5	18.4	14	3	3
Barley (6 row)	*Hordeum vulgare*	Grain	88.5	18.4	12	2.5	3
Maize	*Zea mays*	Grain	86	18.7	9.4	4.3	1.4
Millet-Foxtail	*Setaria italica*	Grain	90.5	18.8	11.9	4.9	3.6
Millet-Pearl	*Pennisetum glaucum*	Grain	89.5	18.8	12.4	4.9	2.7
Millet-Proso	*Panicum miliaceum*	Grain	90.5	19	14.2	5.5	3.7
Oats	*Avena sativa*	Grain	91	19.5	11	5.4	3
Rice (milled)	*Oryza sativa*	Grain	87.5	18	10.4	0.5	0.6
Rice	*Oryza sativa*	Grain	88	17.6	8.3	2.1	5.9
Rye	*Secale cereale*	Grain	87	18	10.3	1.4	2
Sorghum	*Sorghum bicolor*	Grain	88	18.8	10.8	3.4	2.1
Triticale	*X Triticosecale rimpaui*	Grain	89	18.1	11.7	1.5	2.1
Wheat- Spelt	*Triticum spelta*	Grain	89	19	12.2	3.9	2
Wheat (bread)	*Triticum aestivum*	Grain	87.5	18.2	12.6	1.7	1.8
Wheat-durum	*Triticum durum*	Grain	87.5	18.5	16.5	2	2.1
Quinoa	*Chenopodium quinoa*	Seed	89	19.4	15.2	7.3	3
Buckwheat	*Fagopyrum esculentum*	Seed	89.7	19	18.5	4.9	4.2
		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Legumes			**%**	**MJ/kg**	**% Over dry mass**		
Bean (dry harvest)	*Phaseolus spp.*	Seed	89	18.6	24.8	1.7	4.6
Chickpea (desi)	*Cicer arietinum*	Seed	89.5	19.6	22.1	5	3.3
Chickpea (kabuli)	*Cicer arietinum*	Seed	89.5	19.6	22.3	6.4	3.5
Cowpea	*Vigna unguiculata*	Seed	90	18.7	25.2	1.6	4.1
Faba bean	*Vicia faba*	Seed	90	18.7	29	1.4	3.9
Lentil	*Lens culinaris*	Seed	89	18.5	26.9	1.6	3.8
Pea (dry harvest)	*Pisum sativum*	Seed	90	18.3	23.9	1.2	3.5
Peanut	*Arachis hypogaea*	Pod	93	27.5	27	39	2.6
Soybean	*Glycine max*	Seed	87.5	23.6	39.6	21.3	5.8

(continued)

		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Forages			**%**	**MJ/kg**	**% Over dry mass**		
Alfalfa (hay)	*Medicago sativa*	Biomass	25	18.2	18.2	2.1	10.7
Clover (white, hay)	*Trifolium repens*	Biomass	25	17.4	22.7	2.2	12.3
Maize (silage)	*Zea mays*	Biomass	30	18.9	8.1	2.6	4.8
Sorghum (silage)	*Sorghum bicolor*	Biomass	26	18.1	6.7	2.6	8.8
		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Sugar, oil and fiber crops			**%**	**MJ/kg**	**% Over dry mass**		
Cotton	*Gossypium hirsutum*	Fiber +seed	91	23.8	21.8	19.7	4.4
Flax	*Linum ussitatisimum*	Seed	93.5	27	22	34	
Rapeseed	*Brassica spp.*	Seed	91	28.8	20.9	46	4.3
Safflower	*Carthamus tinctorius*	Seed	92	26.1	15.6	32.2	2.4
Sugarcane	*Saccharum spp.*	Stalk	26	19	0.8	1.1	0.6
Sunflower (for oil)	*Helianthus annuus*	Seed	91.5	28.7	20	44	4
Sunflower (for seed)	*Helianthus annuus*	Seed	91.5	24	24	25	3
Tobacco Virginia	*Nicotiana tabacum*	Leaf	8		35		19
		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Horticultural crops			**%**	**MJ/kg**	**% Over dry mass**		
Artichoke	*Cynara cardunculus*	Flowers	17	13.1	21.8	1	7.5
Asparagus (white)	*Asparagus officinalis*	Stems	7	12.5	32	1.8	8.5
Been (green)	*Phaseolus vulgaris*	Pods	8.7	11.7	24.1	4.6	8.0
Beet	*Beta vulgaris*	Root	12	14.5	13	1.4	9
Broccoli	*Brassica oleracea*	Flower heads	11.8	12.4	36.4	5.1	5.1
Brussels sprout	*Brassica oleracea*	Leaf	13	12.8	24	2.1	9.8
Cabbage	*Brassica oleracea*	Leaf	9.9	10.2	12.1	1.0	7.1

(continued)

Carrot	*Daucus carota*	Root	11	13.3	4.5	3.6	5.5
Cauliflower	*Brassica oleracea*	Head	8.9	14.4	28.1	4.5	7.9
Celery	*Apium graveolens*	Leaf	5	14.6	15	3.7	16.3
Chicory	*Cichorium intybus*	Leaf	8	12	21	3.8	16.3
Cucumber	*Cucumis sativus*	Fruit – NC	3.5	17.1	28.6	17.1	11.4
Eggplant	*Solanum melongena*	Fruit – NC	7	13.5	12.7	2.3	8.6
Endive	*Cichorium endivia*	Leaf	6	11.5	20.2	3.2	22.7
Faba bean (green)	*Vicia faba*	Fruit	27	13.4	29	2.7	4.1
Leak	*Allium porrum*	Bulb	17	15	8.8	1.8	6.2
Lettuce Iceberg	*Lactuca sativa*	Leaf	5	13.2	20.5	3.2	8.2
Lettuce Roman	*Lactuca sativa*	Leaf	3.9	12.3	30.8	2.6	10.3
Melon	*Cucumis melo*	Fruit – C	12	14.7	5.3	1.4	4
Muskmelon	*Cucumis melo*	Fruit – C	10	14.4	8.6	1.9	6.6
Parsley	*Petroselinum crispum*	Leaf	10	12.6	24.8	6.6	18.3
Pepper (green)	*Capsicum annuum*	Fruits	7.2	13.8	11.1	2.8	8.3
Pepper (red)	*Capsicum annuum*	Fruits	7.1	16.1	11.3	2.8	11.3
Pumpkin	*Cucurbita spp.*	Fruit – NC	9	13	11.9	1.2	9.5
Radish	*Raphanus sativus*	Root	6	13.2	13.6	2	11
Spinach	*Spinacia oleracea*	Leaf	6.5	10.6	40.0	9.2	30.8
Squash	*Cucurbita pepo*	Fruit – NC	14	13.8	7.4	0.7	5.9
Strawberry	*Fragaria x ananassa*	Fruit – NC	9	15.1	7.4	3.3	4.4
Tomato	*Lycopersicon esculentum*	Fruit – C	5.4	11.3	9.3	1.9	7.4
Watermelon	*Citrullus lanatus*	Fruit – NC	9	14.8	7.1	1.7	2.9
		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Fruit trees, vines and shrubs			**%**	**MJ/kg**	**% Over dry mass**		
Almond[a]	*Prunus amygdalus*	Fruit	93	21.4	11.4	22.4	5
Apple	*Malus sylvestris*	Fruit – C	13.8	15.6	4.3	3.6	1.4

(continued)

Apricot	*Prunus armeniaca*	Fruit – C	14	14.8	10.3	2.9	5.5
Avocado	*Persea americana*	Fruit – C	27	25	7.5	55	5.9
Banana	*Musa paradisiaca*	Fruit – C	26	17.1	5.5	1.3	4.5
Cherimoya	*Annona cherimola*	Fruit – C	21	15.2	7.6	3.3	3.2
Cherry	*Prunus avium*	Fruit – NC	19	14.9	6	1.1	2.7
Coconut (copra)	*Cocos nucifera*	Fruit	92	32.1	8.6	66	2.5
Date palm	*Phoenix dactylifera*	Fruit – NC	77	14.7	2.3	0.2	2.2
Fig	*Ficus carica*	Fruit – C	21	14.8	3.6	1.4	3.1
Grape (table)	*Vitis vinifera*	Fruit – NC	17.3	15.2	4.0	1.2	2.9
Grape (wine)	*Vitis vinifera*	Fruit – NC	18.9	15.1	3.2	0.5	2.6
Grapefruit	*Citrus paradisi*	Fruit – NC	11	14.7	6.9	1.1	3.4
Hazelnut[a]	*Corylus avellana*	Fruit	91	24.5	13	33	1.9
Kiwi	*Actinidia spp.*	Fruit – C	17	13.3	6.7	3.1	3.6
Lemon	*Citrus limon*	Fruit – NC	13	11	10	2.7	2.7
Mango	*Mangifera indica*	Fruit – C	18	15.2	5	2.3	3.2
Oil palm	*Elaeis guineensis*	Fruit bunch	58	23.5	7.8	47	3.6
Olive	*Olea europaea*	Fruit – NC	50	24	4.2	53	11
Orange	*Citrus sinensis*	Fruit – NC	18	14.6	7.2	1.7	3.4
Peach	*Prunus persica*	Fruit – C	12	14.6	8.1	2.2	3.8
Pear	*Pyrus communis*	Fruit – C	14.8	12.3	2.0	0.7	1.4
Persimmon	*Dyospiros kaki*	Fruit – C	20	14.9	2.9	1	1.7
Pinapple	*Ananas comosus*	Fruit – NC	14	14.9	3.9	0.9	1.6
Plum	*Prunus domestica*	Fruit – C	15	15.1	5.5	2.2	2.9
Pomegranate	*Punica granatum*	Fruit – NC	25	15.7	7.6	5.3	2.4
Quince	*Cydonia oblonga*	Fruit – C	16	14.7	2.5	0.6	2.5
Walnut[a]	*Juglans regia*	Fruit	93	24.7	12.3	32.1	2.4

(continued)

		Part harvested	**DM**	**GE**	**Protein**	**Fat**	**Ash**
Roots, tubers & bulbs			**%**	**MJ/kg**	**% over dry mass**		
Cassava	*Manihot esculenta*	Root	37.6	17.1	2.6	0.8	2.8
Garlic	*Allium sativum*	Bulb	39	15	15.4	1.2	3.6
Onion	*Allium cepa*	Bulb	10.9	13.8	9.2	0.9	3.7
Potato	*Solanum tuberosum*	Tuber	23.5	16.9	10.8	0.5	7
Sugar beet	*Beta vulgaris*	Root w/o crown	20	16.9	7.8	0.5	6.9
Sweet potato	*Ipomoea batatas*	Tuber	30	17.4	5.5	1.1	3.6
White yam	*Dioscorea rotundata*	Tuber	26.2	17.1	5.9	0.5	4.3
Yam chinese	*Dioscorea opposita*	Tuber	18.6	17.3	8.7	0.5	4.2
Yellow yam	*Dioscorea cayenensis*	Tuber	16.6	17.3	6.2	0.4	3.2

[a] Including shell

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Chapter 33
New Tools and Methods in Agronomy

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Abstract As developments in information and communication technologies increase, new opportunities are becoming available to refine agronomic management. Precision agriculture, or site-specific crop management, is a farm management concept based on observing and responding to intra field variability. This concept is being increasingly applied to irrigation and fertilizer management with the aid of remote sensors of vegetation in the visible and thermal bands and automatic guidance systems based on precision GPS. Remote sensing is the acquisition of information about an object without making physical contact by using satellites, aircraft, and/or land platforms. Other tools include crop simulation models which are computer programs with equations that represent the response of the crop to management practices (e.g. planting density) and the environment (meteorology, soil). They may be combined with remote sensing data for large scale analyses and predictions and for refining site-specific management.

33.1 Introduction

Agriculture started around 10,000 years ago and since then, improvements of agricultural technology have contributed to increasing the productivity. Intensive agriculture in the second half of the twentieth century was able to achieve high productivity from high inputs but also with some important environmental impacts.

The next step in agricultural technology is based on the use of proximal or remote sensors and computers that allow a more precise and/or efficient application of inputs in the field. This is based on the improved knowledge of crop physiology

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and the advances of agronomy during the twentieth century. At this point we see that agriculture evolved from low input/low control to high input/low control during the 1950s–1960s and is now turning to optimal input based on high control. In this chapter we review some of the technologies that contribute to better control in crop management.

33.2 Remote Sensing Principles

33.2.1 Definition of Remote Sensing

Remote sensing can be defined as the acquisition of information about an object without making physical contact. Although it has been generally related to the acquisition of images from satellite platforms, the term remote sensing is actually broader and it relates to data collection from objects without physical contact. In other words, remote sensing is both the acquisition of data from long distances (i.e. 36,000 km from the Earth using a satellite) as well as that obtained at just a few centimeters using a camera or an instrument that we place near the object (i.e. a leaf).

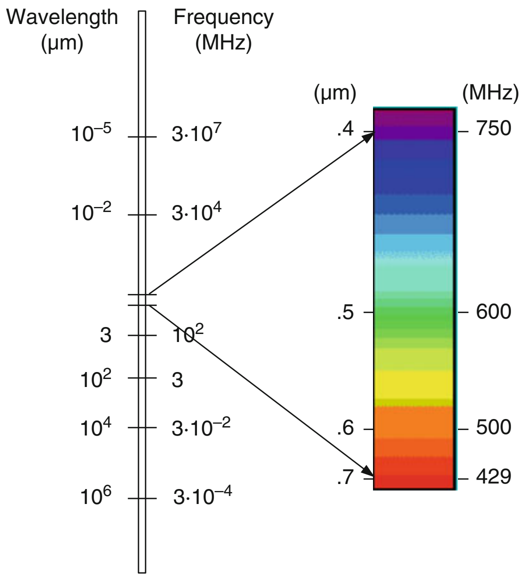
33.2.2 Active and Passive Remote Sensing

The remote sensing of objects using different types of sensors is necessarily conducted through a physical carrier that travels from the objects to the sensors through an intervening medium. This carrier in remote sensing is the electromagnetic radiation, and the medium is the atmosphere. A general classification of remote sensing can be made depending on the nature of the radiation used to gather information from the objects: (i) active remote sensing is when a signal is emitted and received by the sensor used, and (ii) passive remote sensing uses naturally occurring energy (e.g. reflected from solar radiation).

33.2.3 The Electromagnetic Spectrum and the Spectral Bands

Electromagnetic radiation is energy propagated through space between electric and magnetic fields. The electromagnetic spectrum is the extent of that energy ranging from cosmic rays, gamma rays, X-rays to ultraviolet, visible, and infrared radiation including microwave energy as a function of their wavelength (Fig. 33.1).

Fig. 33.1 The electromagnetic spectrum classified as a function of wavelengths



Our eyes detect radiation in the so-called "visible" spectral region, ranging between 400 and 700 nm in wavelength. Nevertheless, there are sensors that can detect and measure radiation coming from below and above the visible spectral region, i.e. below 400 nm and above 700 nm wavelengths. Remote sensing of objects is generally conducted with sensors working in wavelengths in the ultraviolet (UV) below the visible region, and then in the reflected infrared, thermal infrared and microwaves in the spectral region above the visible part of the spectrum. It is important to clarify that above the visible region some sensors detect reflected radiation while others detect the emitted radiation. The reflected infrared region therefore is used to collect data in the infrared wavelengths reflected by the objects, while the thermal infrared region is used to gather emitted radiation to obtain information about the object's temperature.

33.2.4 The Concept of Multispectral

The collection of reflected or emitted data by sensors needs to be conducted in the so-called "spectral bands". This is because each detector used to collect reflected or emitted energy is sensitive to a different range and number of these specific spectral bands. The width in wavelengths units and the number of these spectral bands enable the acquisition of data from objects in a multispectral way. Therefore, multispectral remote sensing is defined as the collection of reflected or emitted energy from an object in multiple bands of the electromagnetic spectrum

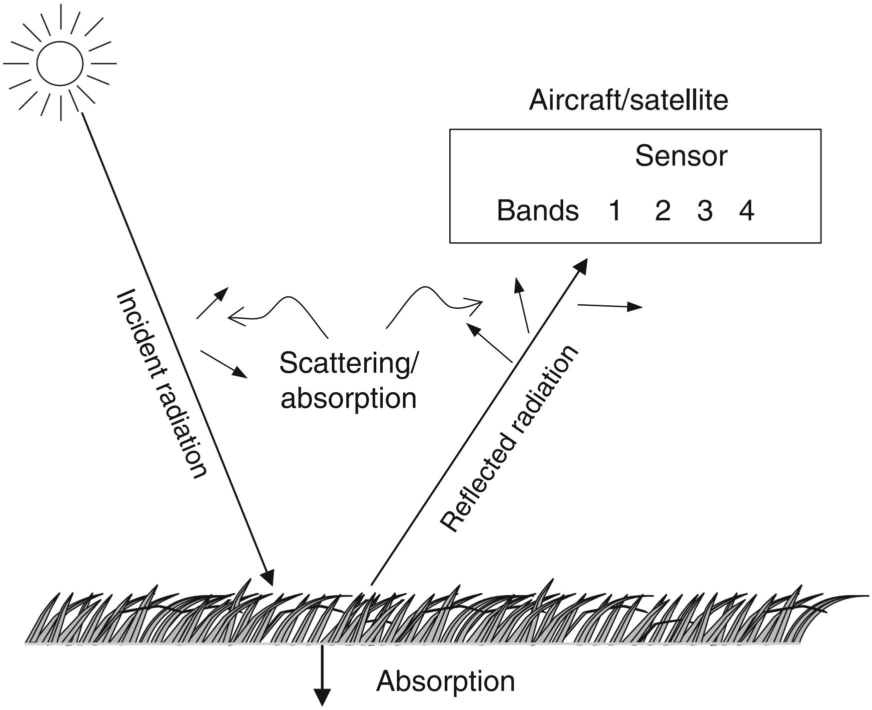


Fig. 33.2 Multispectral remote sensing

(Fig. 33.2). The more the number of bands, and the narrower these bands are, the more information can be gathered from the object.

33.2.5 Reflectance and Spectral Signatures

The energy measured by the sensor is a function of the total incoming radiation at such particular moment. In other words, measuring the energy reflected by the same object at two different times would give us a different amount if the energy coming from the sun changes. For this reason, remote sensing methods rely on normalizing such reflected energy to the incoming radiation at the time of the measurement. Reflectance is defined as the ratio of the total amount of radiation reflected by a surface to the total amount of radiation incident on the surface. Remote sensing methods are based on this reflectance as a function of wavelength, developing the so-called spectral signatures (Fig. 33.3). In Fig. 33.3 we can observe the reflectance measured for three different objects: (i) green vegetation; (ii) dry vegetation; and (iii) soil. The amount of reflected energy changes as a function of the wavelength, which is function of the pigment absorbing and reflecting energy from each object under study. By looking and analyzing these spectral signatures it is possible to

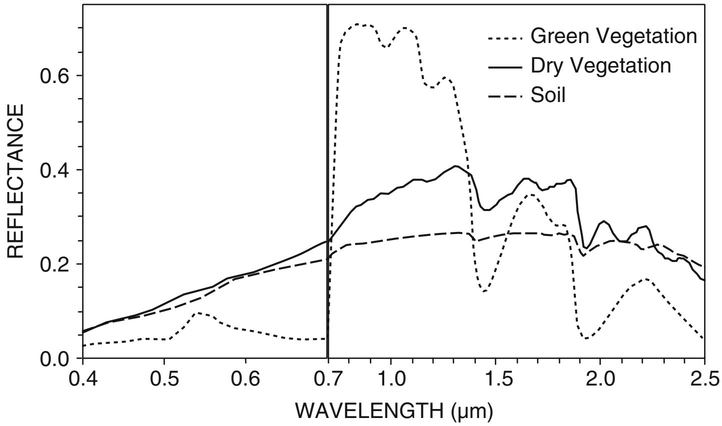


Fig. 33.3 Spectral signatures from green vegetation, dry vegetation and soil

infer the status of the vegetation and soils by estimating the amount of photosynthetic pigments (chlorophyll content, carotenoids, xanthophylls), the amount of vegetation layers (leaf area index, canopy densities), and water content, among others.

33.2.6 Remote Sensing Resolution

There are four definitions than are critical in remote sensing to understand the data quality and image characteristics: (i) spatial resolution. (ii) spectral resolution, (iii) radiometric resolution and (iv) temporal resolution.

Spatial resolution is the size of a pixel that is recorded in an image typically corresponding to square areas. The minimum detail discernible in an image is dependent on the spatial resolution of the sensor and refers to the size of the smallest possible feature that can be detected. The spatial resolution of passive sensors depends primarily on their Instantaneous Field of View (IFOV) of the system comprised by the detector and the lens. The area on the ground represented in the pixel is called the resolution cell and determines a sensor's maximum spatial resolution.

Spectral resolution is the wavelength width and the number of the different frequency bands recorded by the detector, which determine the spectral signatures used to assess the objects by remote sensing methods.

Radiometric resolution is defined as the number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the grayscale and up to 16,384 intensities in each band. It also depends on the instrument noise.

Temporal resolution is the frequency of satellite or plane overpasses over the same place. The temporal resolution is relevant in time-series studies in cases in which collecting data over the same site is required to understand seasonal changes.

33.3 Sensors and Platforms for Remote Sensing

The sensors are generally classified as: (i) optical; and (ii) microwave sensors.

Optical sensors detect visible and infrared radiation in different sub-regions: (i) near infrared, (ii) intermediate infrared and (iii) thermal infrared. There are two types of radiation that can be measured from optical sensors: (i) visible/near infrared (reflected); and (ii) thermal infrared (emitted).

In the Visible and Near Infrared region the sensors detect radiation of sunlight reflected by the objects which is used to quantify land surface conditions such as the distribution of plants, forests and farm fields, rivers, lakes, urban areas, etc. Obviously this technique can only be used during the daytime under clear sky conditions.

In the Thermal Infrared region the detected radiation is that emitted by the objects, which is typically used to monitor the temperature of the land's surface (see Chap. 3) and is not restricted to the daytime period but is affected by cloudiness.

Microwave sensors may be active or passive and are designed to measure radiation in the microwave spectral region, with longer wavelengths than those of the visible and infrared regions. The observation is not affected by period (day or night) or weather as microwaves penetrate the clouds.

The platforms generally used for remote sensing can be divided into the following classes:

(a) proximal sensing platforms are used for acquiring high spatial resolution imagery from towers, cherry pickers, trucks and mobile platforms in the field.
(b) airborne platforms (i.e. planes of different sizes and weights) are generally used for acquiring imagery at typical altitudes between 300 m and a few kilometers over the ground. They can be divided into manned and unmanned aerial vehicles.

    1. Manned vehicles are the traditional platforms for aerial photography and remote sensing operations using heavy cameras working in the visible, near infrared and thermal regions. Access to these sensors is limited, as they have a high cost of operation, so they are generally used for research purposes but sometimes for operational applications. Sensors that can be installed in these platforms are generally very expensive, but they obtain very high quality imagery which helps validating remote sensing models and methods.
    2. Unmanned aerial vehicles (UAV) also known as Remotely Piloted Aircraft (RPAS) or "drones" are new methods recently available which are the result of transferring this technology from the military to civil applications. These drones are small planes that can fly autonomously over desired areas at low altitudes, therefore acquiring high resolution imagery using miniature sensors

carried on-board. Wingspan and weight for these platforms range between less than a meter up to 5 m, and between under 2 kg up to several hundred kilograms. The sensors used weigh between a few grams up to several kilograms, and they are currently available to collect images from drones in the visible, near infrared and thermal regions. Despite the legal limitations on the use of drones for civil applications, they offer high flexibility in acquiring imagery at low cost, higher spatial resolution and easy operation by end users.

(c) The satellite platforms follow typically elliptical orbits around the earth. The time taken to complete one revolution of the orbit is called the orbital period. The satellite traces a path on the earth surface as it moves across the sky. As the earth below is rotating, the satellite traces a different path on the ground in each subsequent cycle. Remote sensing satellites are launched into orbits such that the satellite repeats its path after a fixed time interval. This time interval is called the repeat cycle of the satellite.

When a satellite follows an orbit parallel to the equator in the same direction as the earth's rotation and with the same period of 24 h, the satellite will appear stationary with respect to the earth surface. In other words, the satellite will be positioned all the time over the same spot over the Earth. This orbit is called geostationary. Satellites in the geostationary orbits are located at a high altitude of 36,000 km. The geostationary orbits are commonly used by meteorological satellites as they can monitor large areas continuously (i.e. acquiring one image every 30 or 60 min to monitor weather).

A near polar orbit is one with the orbital plane inclined at a small angle with respect to the earth's rotation axis. A satellite following a properly designed near polar orbit passes close to the poles and is able to cover nearly the whole earth surface in a repeat cycle. Nevertheless, earth observation satellites usually follow sun synchronous orbits, i.e. an orbit whose altitude is such that the satellite will always pass over a location at a given latitude at the same local solar time. In this way, the same solar illumination condition can be achieved for the images of a given location taken by the satellite.

As a function of the orbit (distance to the Earth) and the type of sensors carried by the satellite platform, the satellite imaging systems can be classified into low ($>$1000 m), medium (100–1000 m), high (5–100 m) and very high resolution ($<$5 m).

33.4 Site-Specific Irrigation Management

33.4.1 Site-Specific Crop Management

Although the term precise irrigation usually refers to the application of precise amounts of water to crops at precise locations and at precise times – but uniformly across the field–, precision irrigation, as part of the precision agriculture concept, differs markedly from this common meaning. Precision agriculture, or site-specific crop management, is a farming management concept based on observing and responding to intra field variability. Precision agriculture has been practiced for site-specific nutrient or pesticide application, for varying seeding rate, for control of traffic on fields, etc. Precision irrigation falls in the precision agriculture category since it consists on the application of water to predefined zones in a volume and at a time needed for optimum crop production, maximum profitability or other management objective at each particular zone in the field.

Precision agriculture involves a number of methods, technologies and equipment. Site-specific (SS) irrigation has so far been developed commercially for self-propelled center pivot and linear move irrigation systems, whereas site-specific microirrigation (drip/trickle, microsprinkler) has not yet emerged from academia or industry. Center pivot and linear move manufacturers have produced commercial equipment to regulate water application in time and space (VRI, variable rate irrigation). The irrigation machine is governed by a GPS controller and the operator can enter irrigation prescriptions in the control panel directly or remotely. Prescriptions are based on maps of soil and crop attributes. Moreover, field-distributed sensors can collect and transmit data to support real-time management decisions.

33.4.2 Opportunities Provided by Site-Specific Irrigation

SS-VRI adapted to center pivot or linear move machines allows stopping irrigation over roads, ponds, water courses, rocky outcrops, or any other landscape element that doES not require irrigation. If various crops are grown under the same center pivot or linear move system, irrigation can be scheduled according to the needs of each crop.

Another situation for using SS irrigation is when runoff occurs. This is more likely to happen in steep slopes, where soil infiltration capacity is low, and at the distal end of center pivots, where the application rate is highest. SS-VRI allows applying water at reduced rate at the zones where infiltration should be increased to minimize runoff. The irrigation machine should then move at slower speed to maintain the irrigation depth uniform.

The response of yield to evapotranspiration of most crops is a linear function (Chap. 14). If irrigation ensures that the field does not suffer water scarcity at all, then yield would be maximal and SS irrigation would not represent any yield advantage. However, some indeterminate crops and trees yield maximum under moderate deficit irrigation. For those crops, any deviation from optimal evapotranspiration will translate into yield loss. This deviation may be caused by variations in soil water storage due to precipitation (rain, snow or irrigation) non-uniformity, to variability of the soil water holding capacity, and to lateral flow during or after the precipitation event.

In very arid environments, rainfall contribution to soil water storage is usually negligible for irrigated crops. There, uniform irrigation designed to prevent surface flow will result in uniform soil water storage as long as irrigation is scheduled for the field zone where the critical soil water deficit (SWD_c, Chap. 20) is lowest. Therefore, in arid and semiarid environments, SS irrigation does not help in saving water or improving yield. The situation is different in sub-humid or Mediterranean environments, where the contribution of rainfall to the water consumption of irrigated crops may be significant. Using SS-VRI, the irrigation depth can be adjusted to each zone by applying less water where the water storage is greater. The crop will keep using the rainfall water storage, where available, so total irrigation will be reduced.

Evapotranspiration differences may occur across the field due to differences in canopy cover. An appropriate way to estimate evapotranspiration for SS irrigation schedules is computing spatially distributed crop coefficients based on multispectral vegetation indices that are related to the fraction of intercepted radiation as the NDVI (Normalized Difference Vegetation Index). The so derived evapotranspiration would account for the spatial variation of canopy cover and would represent the water needs of the non-stressed crop. The idea is only valid before full canopy cover.

33.4.3 Definition of Management Zones

The technique most widely used by site-specific irrigation practitioners to define field zones is electromagnetic induction survey of soil apparent electrical conductivity (EMI-ECa). In non-saline soils, EMI-ECa varies primarily with soil texture, water content, and cation exchange capacity. Therefore, EMI-ECa maps are used in combination with soil sampling to determine those spatially variable soil properties efficiently. EMI-ECa mapping is usually complemented by topographic, yield, soil, and multispectral vegetation indices maps to delimit management zones. Canopy temperature of crops entering into crop water stress could be used to determine the spatial variability of the critical soil water deficit. If the crop is not watered for some time after heavy rainfall or uniform irrigation, canopy temperature will increase first where SWD_c is lowest.

Continuous monitoring of soil water content or potential allows introducing real time management decisions. The location of the sampling points may be based on EMI-ECa maps. Neutron probes provide accurate measurements of soil water content, but are expensive and labor intensive. Capacitance sensors are inaccurate for determining soil water content due to the multiple environmental effects that affect their readings. Travel time sensors (e.g. TDR) are more accurate than capacitance sensors and are becoming less expensive and more adaptable to field conditions. Tensiometers are difficult to maintain in the field. However, resistance blocks can be left installed in the field and connected to dataloggers and wireless transmitters. Their problem is that they may lose contact with the soil matrix as it dries. The development of robust wireless networks is facilitating the installation of sensors in the field without interference with cropping operations.

An alternative to soil water measurement is sensing plant water status. Canopy temperature has been used since the 1980s to determine crop water stress indices. Stationary infrared thermometers installed at strategic locations pointing to the crop canopy, or moving sensors mounted on the sprinkler lateral to scan the crop across the field, can be connected to dataloggers and wireless transmitters to continuously measure canopy temperature. Satellite and airborne high-resolution visible and thermal infrared images provide snapshots of canopy cover and temperature over the entire field. These are zenithal views that, under partial ground cover, integrate soil and vegetation, making difficult discriminating plant stress from dry soil effects. Infrared sensors mounted on center pivot laterals change their orientation with respect to the sun and the crop rows, which affects temperature readings. This is less of a problem if mounted on linear move laterals.

There are several handicaps for the adoption of remote sensing techniques in SS irrigation. Satellite images are inexpensive, but their frequency and/or spatial resolution might be insufficient. Aerial imagery may be expensive for the required frequency. The apparatus involved in mounting sensors on the moving lateral has been a handicap for commercial application. The other barrier for adoption of this type of information is the difficulty for farmers to understand and process this information in a timely manner.

33.5 Positioning and Automation

High precision positioning systems like GPS are key technologies for precision, site-specific agriculture. The systems record the geographic coordinates of the field and management zones and locate and navigate agricultural vehicles with accuracy of few cm.

There are different levels of automated steering. Assisted steering systems simply show drivers the path to follow in the field, thus the farmer still needs to steer the wheel. Automated steering systems take full control of the steering wheel along the row, allowing the driver to watch the machine in use (sprayer, seeder). Intelligent guidance systems allow different guidance patterns adapted to the shape of the field.

Management zone maps, automated steering, and variable rate technology are used jointly to adjust machines to apply, for instance, seed or fertilizer according to the spatial variations in plant needs.

Data sensors can be mounted on moving machines also. Grain yield monitoring is becoming very popular. It consists of devices and sensors installed in the harvester that calculate and record grain yield and machine position as it moves. Yield maps can be useful for delineating management zones.

33.6 Crop Simulation Models, Expert Systems and Information Technologies

A crop simulation model is an abstract, mathematical model that captures the behavior of the crop in response to the environment and management throughout the growing season. The model is converted to a computer program with equations that represent the response of the crop to management practices (e.g. planting density) and the environment (meteorological, soil). Therefore the model behaves similarly (and roughly) than the real crop, so we may perform virtual experiments that may help in crop management or genotype evaluation. The obvious advantage is that the model may be applied to a wide range of climates or soils thereby expanding the limited knowledge obtained from field experiments. However, models are always simplified representations of actual systems, so we have to be very careful in selecting the right model and test it against experimental data.

Crop simulation models may be classified according to different criteria:

(a) Empirical versus mechanistic: an empirical model relates yield to a set of environmental or management variables. For instance in arid and semi-arid areas yield may be calculated as a linear function of seasonal rainfall. On the other hand a mechanistic model is based on the biological, chemical and physical mechanisms related to plant growth, development and yield.

(b) Black-box versus comprehensive: This classification is parallel to the previous. A black-box model simply relates (empirically) the inputs and outputs of a system, without any information on how the system works. A comprehensive model represents the system (e.g. crop) by equations that explain the functioning of the organizational level below (e.g. plant, organ). Take for instance wheat production in a farm as affected by nitrogen. We could write a black-box model at the entry of the farm by simply recording the amount of fertilizer N that goes into the farm and the amount of wheat that goes out. Note that in this case we have no idea of what's going on in there but in the long run we may be able to predict wheat yields of the farm as a function of purchased N fertilizer. The comprehensive model would require entering the farm, collecting data (soil, weather, management) and setting up a model of wheat growth as affected by N and other factors. It is clear that a black-box model is cheap and easy to develop but is not valid for other systems.

(c) Specificity: Some crop models have been built for a single crop species (e.g. Oilcrop-Sun for sunflower) while others are valid for any species (e.g. Wofost). The former are more detailed and use parameters to characterize the different cultivars while the latter use different parameters for each species.

Most existing crop models have been built for annual species while only a few have been developed for fruit trees (e.g. OliveCan for olives) because of the lower importance, the larger complexity and the scarcity of good data sets for calibration and validation.

Crop simulation models are not only an alternative to field experiments but are the only choice for evaluating crop production under non existing conditions. For instance predictions of the impact of global change in agriculture are based on crop simulation models. Something similar happens with the evaluation of non-existing genotypes that may be tested using a model in order to identify characters that should be incorporated in breeding programs

Although primitive crop models may be traced to the 1960s with the work of de Wit in The Netherlands and Loomis in the USA, the first large scale attempt at developing general use crop models for the main crops species (wheat, maize) occurred in the USA during the late 1970s and was led by Ritchie, Kiniry and Jones. The primary interest for the USA was strategic, i.e. being able to predict crop yields of their main rivals at the time (USSR, China). Pretty soon this effort was abandoned and crop modelling became a very useful tool in agronomy around the world.

Crop models may be integrated in a decision support system (DSS), a software package including also other tools for input data management and output data analysis, such as in DSSAT (Decision Support System for Agrotechnology Transfer). A more sophisticated tool is an expert system which is a computer application with learning capacity intended to operate like a human expert. In general an expert system includes a data base and sometimes also a crop simulation model (e.g. model Gossym in expert system COMAX for cotton). Available information technologies (powerful cell phones, wireless sensors) will facilitate the development of very specific applications for crop management incorporation crop models, DSS and expert systems.

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Chapter 34
Cropping and Farming Systems

Helena Gómez-Macpherson, Francisco J. Villalobos, and Elias Fereres

Abstract Cropping systems can be based on a single crop (monoculture) or on many (polyculture), including intercrops and rotations. Intercrops are rarely used in western agriculture although they offer several advantages (better use of resources, improved nutrient cycling) that are quantified by the Land Equivalent Ratio (LER). Agroforestry systems are a case of intercrop in which trees provide protection to soil, improve the crop nutrient balance and can provide some additional useful products. Rotations involve crop diversification in time and have many advantages over monoculture (control of weeds, pests and diseases, improved nutrition, risk diversification). Farming systems have interlinked components of inputs and outputs through processes managed to achieve economic agricultural production in order to meet enterprise and/or household requirements.

34.1 Introduction

During the twentieth century agriculture generally evolved from low input agriculture to intensive systems with high inputs of energy, inorganic fertilizers and pesticides. During the 1960s and 1970s, the Green Revolution exported successfully this type of agriculture to less developed countries, mainly in the tropics. Despite its success questions have been raised on the sustainability of these agricultural systems that seek maximum yield, and alternative systems (more sustainable systems) have been proposed in which long-term yield stability is pursued with minimal impact on the environment. A sustainable system must have some of the characteristics of a mature ecosystem (e.g. diversity), but one

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must not forget that the agroecosystem exports nutrients that have to be returned in the form of inputs (fertilizers) to maintain long term soil fertility.

34.2 Types of Cropping Systems

Cropping system refers to the crops, their sequence and the management practices on a given field. One type of cropping system is continuous monocropping (or monoculture) in which the field is cultivated with the same species every year, which is characteristic of large areas of North and South America (e.g. the US Corn Belt) and sometimes are based on high inputs of energy and fertilizers. On the other extreme we find multiple (mixed) cropping systems that have in common the diversification of crops in time and/or space. The multiple cropping appears to be the oldest form of agriculture, and in fact it remains common practice in many areas of the tropics. In most developed countries, multiple cropping has almost disappeared and crop rotations, i.e. two or more crops grown sequentially in the same plot, are more common. In this case, the diversification is only performed over time.

Multiple-cropping variations are described by the number of crops per year and the degree of crop overlap. Double cropping or triple cropping signifies systems with two or three crops grown sequentially in a single year with no overlap in cycles. For example, in the Indogangetic Plains, farmers may cultivate two crops of rice in 1 year, the main one during monsoon season followed by another irrigated with a shorter cycle, or rice followed by wheat and then by berseem in 1 year. In this case, the production goal would be not so much to achieve high yields for any single crop but to maximize yields per unit time (from kg/ha to kg/ha/day). Intercropping indicates that two or more crops are grown with some overlap of their growing cycles. Relay cropping describes the planting of a second crop before the first crop is harvested. When a crop is allowed to regrow after harvest from the crowns or root systems, the term ratoon cropping is used. This is the case for cereals with this regrowth capacity (e.g. barley) or sugarcane.

34.3 Intercropping

Intercropping is the cultivation of two or more crops at the same time in the same field in order to use resources more efficiently and space out labor demand. Intercropping encourages biodiversity in the paddock and this tends to increase stability. In Europe, intercropping is present in pastures (mixtures of clover and grasses), in backyard vegetable gardens and in fruit orchards (alley cropping) but is rarely found in annual crops-based systems. The limited extent of intercropping can be explained, firstly, because the levels of soil fertility and the availability of inorganic fertilizers are high making it difficult to find a productive advantage. Secondly, intercropping hardly compensates for the additional management difficulties and therefore the production costs increase. On the other hand, organic production regulation in Europe is expected to increase interest in intercropping, including grain production for feeding purposes. This new interest should not mean necessarily returning to old systems but developing innovative technology-oriented new organic farming.

In developing countries in the tropics, intercropping is relatively common, generally combining a legume with a cereal. Legume crops are intercropped in low fertile soils because of their N fixation ability. In the Sahel, sorghum or millet is commonly sown with cowpea. The cereal grain is used for food, the straw for feeding and the cowpea leaves and grain can be used for both food and fodder. In wetter environments, maize may be combined with high value food legumes such as groundnuts or green gram. Other combinations are: deep- and shallow-rooted crops; tall and short crops, the last being able to grow in partial shade; climbing crop on a tall crop, e.g. beans around maize; alley cropping; fast- and slow-growing crops, so that the fast one is harvested before the slow one starts maturity.

Intercropping systems must be carefully designed in order to limit competition for light, water and nutrients. Intercropping also poses challenges to fulfil increased labor requirements or to mechanize operations, particularly harvesting. The following elements should be considered before establishing the crops in order to minimize competition and maximize complementarity during their cycles:

- Spatial arrangement
  - Mixed cropping: the plants of the different species are distributed randomly in the field, e.g. vetch-oat association as a forage crop.
  - Row intercropping: growing two or more crops together at the same time with at least one crop planted in rows. Includes alley cropping and strip intercropping (with strips wide enough to facilitate the use of machines but close enough to interact).
  - Relay intercropping: establish a second crop into a standing crop before the harvest time of the standing crop.
- Plant density: it should be reduced compared to single cropping but less in the most important crop.
- Crop cycle/sowing date: different cycles or sowing dates would result in different peak demands of nutrients, water and light to reduce competition between crops. A timely planting of each crop should be followed for an effective plan.
- Plant architecture: this is a key element when considering light competition and the possibility to use one crop as a structure for other climbing crops.
- Proper management, i.e. adequate fertilization at optimal times, localized if there is spatial arrangement in rows, effective weed and pest control, and efficient harvesting with minimum damage to later crops.

The potential benefits from intercropping are the following:

- Reducing the risk from pests, extreme weather events and price fluctuations. Apart from reducing risk by diversification, the population of natural biotic pest control agents (predators, parasites) is usually increased in intercropping.

- More efficient use of resources (light, water and nutrients) in time and space due to the different resource requirements of the components. For example, a complex architecture cover can enhance the interception of light. The intensive use of resources by the intercrop also reduces their availability to weeds.
- Improved nutrient cycling in the system: The combination of species with different temporal patterns of nutrient absorption reduces leaching losses. Moreover, crops with deep root systems absorb nutrients from deeper layers. Some of these nutrients then return to the soil surface after mineralization of the crop residues, and can then be used by other crops with shallow root systems.

Intercropping advantages regarding pests and diseases are not clear in all cases. The number of parasites and predators increases with the number of plant species, but also the number of species of potentially harmful insects and fungi may increase. The problem can be especially severe in the case of soil fungi. When the host plant is always present, the survival of pathogens is ensured.

The Land Equivalent Ratio (LER) is used to determine the effectiveness of intercropping systems. It is calculated as follows:

$$LER = \frac{Y_{I1}}{Y_{P1}} + \frac{Y_{I2}}{Y_{P2}} + \cdots + \frac{Y_{IK}}{Y_{PK}} = \sum_{1}^{K} \frac{Y_{Ii}}{Y_{Pi}} \tag{34.1}$$

where K is the number of crops and Y_{Ii} and Y_{Pi} are the yields as intercrop and pure stand, respectively, for crop i. There is an advantage in intercropping if the resulting LER is above 1, which typically occurs when the soil resources (water and/or nutrients) are limiting and the species differ in their pattern of root growth or when one species is a legume. There is a disadvantage in using intercropping if the LER value is below 1.

The advantage of intercropping depends on the relative importance of the different components. For example, in Table 34.1, yield and LER of vetch (legume) and oats (cereal) mixtures in the region of Castilla-La Mancha (Spain) are shown. In this case LER is only greater than 1 when the proportion of oats is 20 % or lower, because oats in small proportions serves to support vetch growth as it is a creeping

Table 34.1 Yield and LAR of intercrops of vetch and oats in the region of Castilla-La Mancha (Spain)

	Dry matter yield (t/ha)			LER
Percent of seeds vetch:oats	Vetch	Oats	Total	
100:0	3.1	0	3.1	–
90:10	3.2	1.0	4.2	1.19
80:20	2.9	1.8	4.2	1.13
70:30	2.2	1.8	4.0	0.97
60:40	1.7	2.6	4.2	0.95
0:100	0	6.6	6.6	–

Adapted from Caballero R, Garcia C (1996) Cultivo y utilizacion de la asociación veza-cereal en Castilla-La Mancha. CSIC, Madrid, Spain plant, so both species are benefited. However, when the proportion of oats is high, this species has a competitive advantage because of its greater height as compared to vetch.

Example 34.1 Yields of tropical rainfed corn and beans are 800 kg/ha and 600 kg/ha, respectively, when intercropped and 1,200 and 800 kg/ha as pure stands.

$$\mathrm{LER} = 800/1200 + 600/800 \ = 1.42$$

Example 34.2 Maize-bean-squash in Central America: beans climb up maize stalks while squash plants are established in between capturing the light that filters down through the canopy. When compared to pure stand crops in Mexico, intercropped maize yields were considerably higher while bean and squash yields suffered considerable yield reductions. Maize was the most important crop, and the beans and squash were a bonus. The LER for the whole mixture was considerably high (1.6).

Example 34.3 Maize and soybean were intercropped for silage in Canada. Intercrops were more cost effective than pure stands, although its success depended on seeding rate and spatial arrangement. The best performance was observed using 67 % of pure stand recommended planting rate in both crops. This system resulted in an LER of 1.14. Alternate rows of maize and soybean had higher yield (LER = 1.23) but with higher costs offsetting the yield increase.

Example 34.4 In USA, alternated strips of maize, soybean and spring wheat in a ridge-till system was tested. The strips width was adapted to the equipment widths and herbicides were applied with a ground sprayer. Strips were east-west oriented and followed a wheat–maize–soybean pattern, with soybeans on the north side of the maize. Wheat was harvested before maize had a chance to shade it. On the other hand, maize rows next to soybean strip profited of additional incident light.

Example 34.5 Backyard garden. When radish and carrot seeds are sown at the same time, radishes germinate and grow quickly and are harvested when carrots are just getting established. Lettuce plants tolerate shade and, therefore, are good to interplant among larger vegetables. Young tomato plants may be planted among declining pea vines to replace them on the trellis. Intercropping two vegetables with different architecture and nutritional value such as beet and okra or pepper and onion is being practiced in tropical Asia.

34.4 Agroforestry Systems

The practice of including trees in farming systems is very old and is still common in many parts of the world. Agroforestry systems are now receiving special attention, especially in tropical areas to increase sustainability. Agroforestry systems are forms of intercropping.

Overall, an agroforestry system is more stable than other cropping systems. Trees act as protectors of the soil and the crop from the direct effect of wind and rain and improve the nutrient balance of the system. If trees (e.g. *Acacia spp.*) or shrubs (e.g. *Leucaena spp.*) from the *Leguminosae* family are used, they contribute to nitrogen supply. Trees can also provide food (seeds) and firewood.

The need to conserve the soil in many agricultural systems worldwide will likely lead to a return to farming systems where trees and annuals that act as protective covers from erosion are associated. In Europe, the European Silvoarable Agroforestry For Europe (SAFE) project has described many different alley cropping or agroforestry systems in the region. The "dehesas" in Spain and "montados" in Portugal are good examples of agroforestry in which oaks trees, natural or introduced pastures, crops and livestock are included. Other examples include: cereals cropping between walnut, oak, olive or fig trees; grapevine rows planted with walnut or olive trees; vegetables in peach or dual purpose (fruit and timber) walnut groves; maize and soybean between rows of poplar trees; and fodder beet under cherry trees. Cover crops are also very common in orchards, particularly in areas prone to soil erosion.

In Kenya fruit trees are intercropped with all types of herbaceous crops such as beans, peas, potatoes, maize, millet, exotic and indigenous vegetables when they are still young as a way of attaining food security and income before the trees mature. Banana may be intercropped with sweet potato and beans to reduce the incidence of weevils and nematodes, and with *Grevillea robusta* for wood.

34.5 Crop Rotations

A crop rotation is a sequence of crops over time, repeated cyclically or not. The advantages of a crop rotation compared to monoculture are partly similar to intercropping:

- Better use of resources (water and nutrients) or improving fertility if legumes are included.
- Better control of weeds, pests and diseases.
- Risk diversification.
- Better distribution of the means of production in the farm.

The choice of crop rotation is to be based primarily on economic factors. This has led to monoculture in many agricultural areas. The species and their order in the rotation should be established based on the following criteria:

(a) Duration of the cycles and environmental requirements of the species: There is a huge variability among species and within species in the crop cycle duration and adaptability to climatic conditions. For temperate areas we can make the following classification in terms of planting dates for the different species:

   - Autumn-winter planting:

     Winter cereals: wheat, barley, rye, oats, triticale.
     Grain legumes: broad bean, pea, chickpea, lentil.
     Oilseeds: rapeseed, safflower, flax

   - Spring planting:

     Grains: maize, sorghum, rice.
     Oilseeds: soybean, sunflower.

   Some species may belong to different categories depending on the climatic characteristics of the area. Sugar beet is sown in autumn in mild winter areas (e.g. South of Spain) and in the spring in colder areas like in most European countries. Winter cereals with low vernalization requirements may also be sown in early spring in cold areas or in late autumn in the Mediterranean region.

   This classification should not be taken strictly as the trend over the last 20 years has been to advance the date of sowing of spring crops. For instance, when sunflower was introduced in Spain in the 1960s, it was regarded as a spring crop with planting in April or May, while today it is planted in many areas in February or March. Summer crops such as maize are planted in some areas of mild climates (California, Spain) 2 months earlier than 30 years ago. This is also due to the increased tolerance of this crop to suboptimal temperatures, as it is being increasingly grown in the cool environments of the higher latitudes. The adoption of other cultural techniques like plastic mulching may allow an advance on the planting date some of species (e.g. cotton in the Guadalquivir Valley in southern Spain).

(b) Time required for preparing the sowing of the following crop: After harvesting a crop a series of operations (residue management, primary tillage, seedbed preparation) can significantly delay the planting of the next crop. This time may be reduced by direct seeding the following crop (e.g. direct seeded wheat after rice harvest in South Asia).

(c) Ecological characteristics (e.g. rooting depth) and management of different crops. Traditionally it has been recommended to alternate closely sown (cereals) and row crops which help control weed populations. From the point of view of the control of pests and diseases we should avoid repeating the same (or similar) crop in the same field in consecutive years. Crop rotation is a good tool to reduce the incidence of pests and diseases, particularly soil borne pathogens, as the absence of the host plant causes a reduction in the inoculum in the soil. Some crop species (and weeds) of the *Cruciferae* family generate glucosinolates which have insecticide and fungicide effect, therefore providing a cleaning effect on the soil. In Australia, the introduction of canola in rotation with wheat has reduced the incidence of take-all in wheat crops in no-tilled systems

(d) Use and conservation of resources: the cropping system should help to prevent loss of water and soil nutrients. The current situation of European agriculture can promote the adoption of more conservative cropping systems. Some crop management practices can be very useful although a priori they are considered negative. For example, in rainy areas in which nitrogen is the limiting factor, keeping a clean fallow increases nitrate leaching. If weeds are left in the field, they will capture N in organic form and reduce soil water content, which reduces the amount of deep percolation and therefore N leaching. The same objective can be achieved through the use of catch crops to “capture” the N when nitrogen leaching risk is high.

The inclusion of clean fallow (uncultivated land free of weeds) for long periods is justified only in areas with very low rainfall, as leaving the soil bare increases the potential for soil erosion and N losses by leaching. In principle the rotation should contribute to keeping the soil protected by a crop canopy or by residues during the rainy period or when winds are strong.

The inclusion of legumes in the rotation improves N supply. The contribution is more important when the legume is incorporated into the soil as green manure which also helps to increase the organic matter content.

The effects of some crops over others in a rotation are sometimes unclear as even the rotation of different cultivars of the same species (for example maize) may have a positive effect. It is believed that an important part of the interaction is related to the maintenance of a large microbial biomass in the soil, capable of rapid mineralization.

34.6 Designing Crop Rotations

The primary concern for choosing crops in a rotation is farmer’s profit. That implies reducing costs and optimizing farm production means. In addition the rotation design should be flexible enough to accommodate possible changes and be suitable for the environmental and management (e.g. soil conservation) conditions. However, for increasing the sustainability of farming, several additional criteria should be considered:

(a) Conservation of resources (water, soil, nutrients)

  - Minimize the duration of periods without a crop
  - In periods without crops use crop residues to protect the soil surface
  - Include crops with deep rooting systems to use the N deep in the profile
  - Include legumes to improve the N supply
  - Maintain/increase levels of organic matter
  - Switch between species with different nutrient requirements

(b) Control of weeds, pests and aerial diseases

  - Alternate crops (the more they differ, the better) and avoid contiguity with the same or similar crops. When we talk about different crops we do not only mean in botanical terms but also in relation with management, like for instance, winter versus spring crops or wide versus narrow row spacing.

(c) Control of soil fungi

  - Increase the time between planting the same crop or similar (same type, same family)
  - Include cruciferous crops (containing glucosinolates which result in compounds having fungicidal, insecticidal and herbicide effects such as isothiocyanates)

34.7 Farming Systems

A farming system is defined as a population of farms that have similar resource bases, enterprise patterns, household livelihoods and constraints. Farming systems may be classified based on the following criteria:

- Available natural resource base, including water, land, grazing areas and forest; climate, of which altitude is one important determinant; landscape, including slope; farm size, tenure and organization; and,
- Dominant pattern of farm activities and household livelihoods, including field crops, livestock, trees, aquaculture, hunting and gathering, processing and off-farm activities; and taking into account the main technologies used, which determine the intensity of production and integration of crops, livestock and other activities.

In subsistence farming systems, farmers produce food for themselves and their family and there is no profit, e.g. rice production in Bangladesh or rainfed sorghum-cowpea in the Sahel, whereas in commercial farming, farmers would sell their crops and animals to make a profit as in most European farming systems. In general, intensive systems require high inputs of capital, labor or technology to achieve high outputs or yields per hectare; the farms are usually small, for example protected agriculture in Almeria or pig production in Denmark. Extensive systems are, however, characterized by low use of inputs, large areas of land and low outputs or yields per hectare, e.g. wheat-sunflower production in the rainfed areas of Andalusia, Spain. Arable is the growing of crops, pastoral is the keeping of animals and mixed is when farmers grow crops and rear animals. Sedentary is when the settlement is permanent and the landscape farmed every year whereas nomadic farmers move around looking for fresh pasture or new plots to cultivate. There are extensive subsistence systems, e.g. nomadic pastoralism in Africa and Central Asia, or intensive subsistence systems, e.g. rice-based farming systems in the Sahel. Among the most complex, there are rainfed systems in humid tropics of high resource potential, characterized by a crop activity (typically cereals, cassava, banana, coffee, etc. at small scale or in plantations, and commercial horticulture), often mixed with livestock production.

Farming system represents a resource management strategy to achieve economic and sustain agricultural production in order to meet some household requirements. Farming systems are not static as they have interlinked components of inputs and outputs through processes (Fig. 34.1). System management should give the crop its best chance of expressing its potential. For this, an understanding of the system is required. Firstly, the inputs, processes and outputs, then, the influence of natural (soil, slope, rain, temperature, sunshine, etc.) and human inputs (labor, machinery, energy, political, etc.) on the processes and outputs. Their combined effects on the

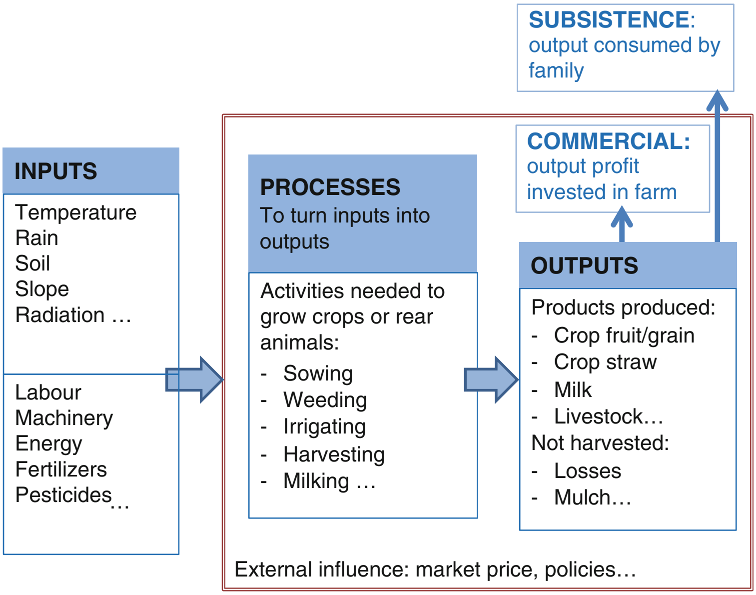

Fig. 34.1 Inputs, processes and outputs in a farming system

scale of production, methods of organization and the products should be understood for optimizing the system, also in the mid and long term.

Understanding farm household decision-making is essential for targeting research, fostering innovation and accelerating adoption of innovations. How to manipulate natural inputs for using them optimally and to avoid any waste? Could more of the inputs supporting diseases, weeds and pests be reallocated to grain? Are diseases building up, should a changed crop rotation be considered to control pests and diseases? Could the crop stubble be used to increase production of the next crops? Could water inputs be used more efficiently for producing grain? Is the management system environmentally sustainable or are soil and water resources being gradually downgraded or overused? Is current irrigation management progressively increasing soil salinity? Are the yield targets too high for the location? Would a lower yield target lead to a more efficient use of resources?

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Chapter 35
Agronomy and the Sustainability of Crop Production

Elias Fereres and Francisco J. Villalobos

Abstract Lessons learned since the discovery of agriculture suggest that good agronomy as an integrative science is essential for improving the sustainability of current agricultural systems. To meet the challenges of producing sufficient, nutritious food for a growing population, future agronomists will have to combine advances in plant breeding and biotechnology with new approaches to improve the efficiency of nutrient and water use in agricultural production. There is significant potential in many areas to increase yields by bridging the gap between potential and actual yields, but as average yields increase with time, such potential diminishes. The threats of soil degradation and water scarcity will require widespread adoption of conservation practices based on strong extension efforts and the use of new IT technologies. Global change will have positive and negative outcomes in the agriculture of different regions, but will introduce more uncertainty in defining the best strategies to cope with climate variability. The most likely path to the sustainable intensification of production would be through continuous, small productivity improvements rather than through a few revolutionary discoveries, at least in the medium term.

35.1 Introduction

Agriculture started with the domestication of cereals around 10,000 years ago (10,000 BP). Today the same species (wheat, rice, maize) constitute the basis for global food production. Much before 10,000 BP seeds from some grass species were collected and processed to increase digestibility, as part of a diverse diet that included fruits, animals and fish. Climate variations (colder, drier periods) probably led to a reduction in the availability of natural food sources, making it difficult to gather wild plants and to hunt animals in sufficient amounts. That explains why

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humans were forced to move up the trophic chain as herbivores have greater conversion efficiency than carnivores. It was found that productivity of natural grass populations increased with some management operations (e.g. weeding). While doing so these proto-farmers, unconsciously, started selecting plants with favorable characteristics (larger seeds, lack of dehiscence, absence of dormancy), and after harvest, some seeds were saved for planting subsequently in other fields. This process of domestication occurred independently at about the same time in several different areas of the world such as the Far East, Mesoamerica, and in the Near East where wheat and barley originated. Rice cultivation in China began 11,500 years ago, while squash was domesticated in Central America about 9000 years ago. That was the start, and very rapidly a few species of cereals and legumes achieved the desired agricultural characteristics. At the same time early farmers probably observed the advantage of concentrating useful plants in fields which could be protected from herbivores or neighbors and cleaned from other competing plants. This also allowed for a more efficient harvest.

Most hunter-gatherers had a very varied diet of wild plants and animals although in some cases they subsisted almost entirely on meat or on a few plant species. As agriculture developed, some wild species were selected under domestication for different purposes, leading to quite different crops. For instance, *Brassica oleracea* has been selected for its leaves (cabbage), stems (kohlrabi), flower shoots (cauliflower) and buds (Brussels sprouts).

With agriculture started the development of modern civilization whereby increases in food production led to technological development, because food surpluses could be used to feed full-time craftspeople and inventors, leading also to the diversification of human activities. It also led to social stratification, political centralization and militarization by feeding full-time aristocrats, bureaucrats and soldiers. These advantages enabled agricultural societies to eventually displace most hunter–gatherers around the world towards marginal environments.

Early agriculture was rainfed so it could only thrive in areas where enough rainfall could sustain grain production, which in the case of wheat and barley represents a minimum of 200–300 mm/year. In the arid zones, where precipitation was erratic and insufficient to sustain crop production, irrigated agriculture appeared first in 6000 BP in Egypt and Mesopotamia by merely diverting water from rivers to adjacent fields during periods of flood. This soon evolved into sophisticated systems of water distribution which required a strong social organization for operation and maintenance. Interestingly, lack of knowledge about the need to control salinity and excess water from irrigation through drainage led to the decline of some ancient civilizations in the arid areas of the Near East that expanded based on irrigated agriculture.

Continuous cropping of the same field soon showed declining yields due to the loss in soil fertility from extraction and cultivation. This led to shifting cultivation systems such as slash and burn agriculture, a primitive mode of rotation aimed at concentrating mineral nutrients after many years of forest growth and then releasing them by burning the vegetation, which allowed a few years of cultivation with sufficient production. This form of agriculture could be made sustainable if the turnaround time for burning the forest is long enough to allow for building back the natural soil fertility. However, population growth increased the pressure on land use and slash and burn expanded in many world areas and was in the end responsible for the deforestation and land degradation of many regions, when population pressure led to unsustainably low ratios of forest to cropped land.

The different agricultural techniques evolved in parallel. Tillage started using the ard which only cuts a small furrow (drill) in the soil and is therefore helpful for sowing but not for weed control, incorporation of residues or clearing new land. The ard appeared around 7000 BP in parallel with the domestication of cattle. In fact, the most primitive form of planting must have used a stick to drill a hole in the ground, place the seeds and covered them with soil, a practice that was used by most indigenous societies. Moldboard plows appeared much later and were designed to turn the soil for more effective weed control. The plow, pulled by man or animals, became popular in Europe around 1500 AD allowing a more complete and deeper soil disturbance, and the upturning of the soil which was the only way to control aggressive weed invasions. The Europeans exported the plow to America, Asia and Africa where it facilitated greatly the expansion of commercial agriculture with limited human labor inputs. In some areas, particularly within the tropics and subtropics, the use of the moldboard plow has become clearly unsustainable due to enhanced soil erosion and land degradation problems.

Animal husbandry also evolved in parallel with crop agriculture. Domesticated animals not only provided for food and clothing but contributed as draft power for tillage, allowed the exploitation as pastures of lands which were unsuitable for crop production, and contributed to nutrient cycling by redistributing nutrients within the agricultural systems. Other domesticated animals had a more specific role like cats as hunters of grain-eating rodents or dogs as guardians in rural areas. Production of animals and their products by grazing pasture and range lands in an extensive fashion is a practice that has ecological values such as contributing to the conservation of biodiversity.

Giant steps forward in agricultural science and technology have taken place in the last two centuries with the development of machinery, breeding of new cultivars, use of mineral fertilizers and pesticides, at an accelerated pace since the middle of the twentieth century. Modernization of agriculture has led to the separation of the different activities that once were all part of the life of farms, and has transformed human society. Prior to mechanization, the manual labor of most farming activities represented a physical effort that required large numbers of farm workers which had very low productivity. Additionally, life as a farm worker was not very pleasant and that was one of the incentives for introducing the mechanization of many farm operations. As technology improved, more specialization was required so that farmers could concentrate on fewer activities for which they had to develop the proper skills and afford the required machinery and infrastructure. Rural societies thus experienced a revolution that changed how farming was conducted and led to land consolidation, fewer farmers, and vast migration movements from rural areas to cities in search of a better life. Before mechanization, farmers exploited crops, pastures and forests using animals for different uses (food, draft, transportation). At that time, life of most of world population was based on agricultural activities, and even by 1950 more than 70 % of the population lived in rural areas. Since the 1950s, the challenge of feeding a population growing at unprecedented rates was more than met by an evolving agriculture in what is now considered one of the most remarkable success stories of mankind. In 1950, there were about 2500 million people in rural areas and about 750 million in the cities. By 2014, the total population had reached 7200 million with almost 4000 million in urban dwellings and yet, agriculture produces now 25 % more calories per capita than in 1950. There continues to be, however, serious limitations in food distribution and access, primarily in rural areas, as evidenced by the persistent existence of extreme poverty and hunger in hundreds of millions of persons in the Planet. Furthermore, there are concerns regarding the sustainability of present agricultural systems as to whether the recent productivity increases have been achieved at the cost of resource base degradation, with the ultimate consequence of a decline in productivity in the future.

Although there is wide diversity among the different agricultural systems currently in existence, commercial agriculture has now been transformed into a set of industries where crops or animals are grown that may provide inputs for each other but operate in isolation. This new specialized agriculture has been very successful in increasing productivity but its long term sustainability remains unclear. In this chapter we will discuss some important issues which represent future threats and challenges to agriculture and food production as it is presently carried out.

35.2 Climate, Soil and Water

Agriculture takes place outdoors and plants are primarily dependent on the weather around them for growth and development, and on the soil for nutrient and water supply. The climate of a location determines what species can be grown and, also, the level of risk that a farmer faces if he selects crops that may be sensitive to the anticipated climatic features. As the climate becomes more limiting, the risk of very low yields or even crop failures increases (risk being the product of probability and impact) and crop choice is reached as a compromise between profit expectations and risks. While agriculture has always been pushing at the margins by approaching the climatic limits of crop viability, farmers are risk avoiders and always try to balance profitability against risk. An additional factor that must be considered is the normal climate variability that agriculture must deal with every season. Some of the variability can be explained by regional phenomena such as the warming of ocean waters in the Pacific, an event called El Niño, which occurs with a periodicity of several years and causes excess rainfall in some regions and drought in others. In some areas such as Eastern Australia, predictive tools based on prior observations of El Niño events coupled with barometric pressure oscillations (El Niño-Southern Oscillation) have been developed to anticipate whether the upcoming season would be wetter or drier than normal. This information is critical to design seasonal strategies leading to the optimization of planting dates, and of investments in the application of fertilizers and other inputs. Seasonal predictions are still in their infancy in many world areas but improving their reliability is essential to greatly reduce the risk levels in farming.

35.2.1 Climate Change

Imbedded in the climate variability that agriculture has experienced since its invention, there is now a general consensus that the climate is currently warming as CO_2 concentration increases due to human activities (burning of fossil fuels, deforestation). The average temperature of the Earth has increased about 0.8 °C since 1880, while the magnitude of future warming is uncertain depending on the Global Circulation Model used and the future scenario of CO_2 emissions. One may expect a temperature increase of 1–4 °C with CO_2 concentrations between 500 and 700 ppm by the end of this century. The possible impact of this global change on agriculture has been studied mainly using simulation models (Chap. 33) that predict a general decrease in agricultural productivity. However most studies have not fully considered the positive effects of elevated CO_2 concentration on photosynthesis and assume that agricultural systems do not adapt to change. Nevertheless, crop management will adapt to and mitigate, at least partially, any possible effects of environmental change. On the other hand a higher CO_2 concentration leads to lower canopy conductance and will increase photosynthesis in C3 plants. Some of the main effects of global warming on crop performance include:

- Accelerated crop development with shortening of the growing cycle in annual species. This would reduce yields but may be offset by earlier plantings and/or by changing the cultivar (using longer cycle or responsive to photoperiod varieties).
- Increased evaporative demand: many studies have concluded that ET will increase with global change as reference ET (Chap. 10), which is calculated with meteorological data only, will increase as air temperature and vapor pressure deficit (VPD) increase. This is misleading as the increase in CO_2 concentration will increase canopy resistance, i.e. stomatal aperture will be reduced. In the end, the increase in VPD due to warming may be offset by partial stomatal closure, so ET probably will hardly change.
- While global warming should lead to a global increase in precipitation, it is not possible at this time to predict future changes in precipitation at the regional level with any degree of certainty. Many models predict an increase in the frequency of extreme events, droughts and floods, as the hydrologic cycle intensifies due to global change. However, such predictions have not been validated yet and should be taken with caution, although agriculture would be much more vulnerable to an increase in the frequency of extreme events than to a gradual change in temperature.

- Changes in biotic factors (changes in the incidence of insects, diseases, weeds) may occur but the actual outcome is hard to predict. Some pests would be more damaging than at present and others would be less, while new pests may emerge in locations where they did not exist now. For instance milder winters may favor survival of insects while warmer springs would promote growth of C4 weeds which compete favorably with C3 crops.

Agriculture has contributed in the past to global change primarily through the change in land use as agricultural lands greatly expanded since the 1800s until 1960. Since that time, the surface area devoted to crops has remained more or less constant and its contribution to greenhouse gas emissions has been modest relative to those from industry and transportation. While there are agricultural practices that contribute to mitigation (e.g. minimum tillage, Chap. 18), the capacity of agriculture to mitigate global warming by sequestering carbon is also modest relative to options derived from changes in the energy and transportation sectors. Emphasis should be placed on adapting agriculture to global change using the combination of breeding × agronomy × management that has been so successful until now, while at the same time, taking advantage of mitigation options that may also contribute to the sustainability of agriculture (see below).

35.2.2 Soil Degradation

Over the centuries, the conversion of lands for use in crop production has included the development of fragile areas which are prone to degradation. Exploitation of soils without maintaining their fertility by restoring nutrient extraction and their physical properties (Chap. 26) also leads to soil degradation. Exposure of bare soil surfaces to rainfall and tillage operations enhance the rate of natural soil loss or erosion of the surface layers which normally are the most fertile. A single soil erosion episode represents an amount of soil loss that exceeds by orders of magnitude the rate of soil formation. Despite the advances in methods of Earth observation, there are no good statistics of the degree of soil degradation around the world but estimates indicate that the problem is very relevant, requiring periodic monitoring to assess its severity in the different regions. Soil erosion will continue to be a major threat to sustainability of agricultural systems around the world. The expansion of conservation agriculture (Chap. 18) is helping in many areas to control erosion but it requires the adaptation of agricultural techniques (machinery, cultivars, pest control) to site specific conditions and cannot be used in all agricultural systems. There are soils that require periodic tillage to maintain some physical properties and in some regions, crop residues needed to protect the soil surface as part of conservation agriculture are used for animal feed and therefore are not available for soil protection. Intensification may lead to the production of enough crop residues to both uses. Soil salinization is another threat to sustainability that affects possibly up to 15–20 % of world irrigated area. Again new monitoring methods can reduce the risk and help to introduce salinity control measures to prevent the problem (Chap. 22).

The maintenance of soil fertility in the long term is essential to ensure the sustainability of agriculture. This is particularly important concerning phosphorus, as sources for P fertilizers are limited (Chap. 26). Efforts here should focus on P recycling and on increasing the availability of soil P to plants. In the case of N, the availability of N fertilizers will depend on energy prices so the inclusion of legumes in crop rotations would be a partial solution when needed. Nevertheless, the use of synthetic N fertilizers in agriculture is extremely efficient in energy terms. If N concentration in grain is around 2 %, each additional kilogram of N added to the crop will support a yield increase of 50 kg. The average energy required for producing the N fertilizer is 77 MJ/kg (Chapter 7) and since the energy content of grain is around 18 MJ/kg, the marginal efficiency would be $900/77 = 11.7$. Innovative approaches for improving the efficiency of N fertilizer use will reduce N fertilization rates and the consequent non-source pollution which affects surrounding ecosystems and water quality in many intensive production areas.

35.2.3 Water Scarcity

Irrigated agriculture expanded greatly in the second half of the twentieth century, increasing from 120 to about 300 million ha. In fact, given that the productivity of irrigated systems is about 2.75 times more than that of rainfed systems on a worldwide basis, today the production of sufficient food relies significantly on irrigated agriculture. Irrigation expansion has come at a cost from the environmental point of view. On the one hand, the construction of reservoirs for irrigation has changed the natural environment and had an impact on river ecology. On the other hand, the return flows from irrigated lands constitute a major source of non-point pollution, which is unavoidable to some extent if irrigated agriculture is to be sustainable. This is because the maintenance of salt balance through drainage is essential to prevent salinization of large irrigated areas. Additionally, irrigated area expansion and production intensification require large amounts of water, to the point that irrigation is the primary consumer of the water diverted by man for various uses. More of two thirds of diverted water is consumed in irrigation worldwide. Contrary to other uses (for example, domestic) where water used can be recovered and reused after appropriate treatment, much of the water used in irrigation is evaporated and thus leaves the basin. While a fraction of the irrigation water can be reused, as irrigation becomes more efficient, such fraction diminishes and the ET process dominates irrigation water use. With efficiency increases, due attention must be paid to the maintenance of salt balance in areas of low rainfall and/or where saline waters are used for irrigation.

An emerging problem that threatens the sustainability of irrigation in some areas is the excessive use of groundwater beyond the long-term supply. Groundwater usage may exceed aquifer recharge in droughty years provided that the excess extraction is eventually replenished in the long run. However, long-term decline in water table depth as it is occurring now in some regions of China and India, among others, is an indication of unsustainable use. In extreme cases, land subsidence can reduce aquifer capacity permanently or cause sea water intrusion in coastal areas with the permanent deterioration of water quality. Better assessment of groundwater resources combined with recharge programs and wise and strict resource management can bring solutions to this problem.

At present, irrigation is under scrutiny by the other sectors of society that perceive that its share of water usage is too high. This is particularly critical in areas or times of water scarcity, where competition with other uses becomes fierce and urban and other demands have higher priority. Thus, while there is a need to expand irrigation as one option for production intensification to meet future food demands, competition for scarce water with other sectors, including the environment, is going to restrict such expansion forcing irrigated agriculture to do more with less water. Although many advanced technologies are available for improving irrigation management, widespread dissemination has been limited so far. The time has come for many irrigated areas to promote on a large scale the adoption of efficient irrigation practices in order to meet both increased productivity needs and societal goals. Independent certification of efficient use of water in food production with appropriate indicators will be welcomed by consumers and the rest of the society.

Promoting the efficient use of water in rainfed agriculture is also a very promising goal for production intensification in the future. The approaches should focus on other factors co-limiting yields (such as nutrients) and on accepting more risks, abandoning the conservative approaches to rainfed farming that avoided risk but that had little reward on good years. Acceptance of more risk in rainfed farming requires new tools such as reliable seasonal forecasts, and advisory services that will assess risks quantitatively and will offer flexible options adapted to local conditions. In its simplest view, risk equals the product of probability by impact, and the avoidance of extreme events that could impact the viability of farming irreversibly causing famine has dominated past rainfed strategies. In this regard, the resilience of the agricultural system, that is its capacity to recover after a perturbation, is critical for the sustainability of the system. As new technologies and policies enhance the resilience of rainfed systems, accepting more risk will lead to productivity increases in the future.

35.3 The Role of Plant Breeding

The development of modern plant breeding technologies after 1950 has produced new cultivars which are highly productive and widely adapted. The major plant feature that has been improved in the major crops is its harvest index whereby current varieties have HI values that are 50 % greater than those of 50 years ago.

The success of the recent agricultural intensification has often been attributed to the new varieties without recognizing that varieties or agronomic inputs produce nothing in isolation. It was the combination of new varieties and new agronomy together with adequate management what has enhanced the productivity of agricultural systems until now.

Plant breeding techniques are nowadays more powerful and more efficient due to genetic engineering which has led to the production of new cultivars labeled 'transgenic' crops (Genetically Modified Organisms, GMO). Transgenic crops have been highly successful so far by addressing crop features than are related only to a few genes. For example, the quality of the seed may be improved (e.g. yellow rice) or the plant may acquire insecticidal properties (e.g. BT maize or cotton) or resistance to a given herbicide (e.g. resistance to Roundup in soybean). The primary goals were to reduce production costs (by applying less pesticides) and, by reducing/eliminating usage of some pesticides, to contribute to improved human health and to the environment. The improvements in farm profitability have been such that transgenic soybeans, maize and cotton have been widely adopted in less than 20 years, not only in the USA where more than 90 % of the three crops are now transgenic, but also in some developing countries, as India or China. Plant breeding efforts to produce transgenics are now being extended to other crops to address biotic stresses or crop quality problems.

By contrast, the promises of improving plants against abiotic stress (drought/salinity) using GMOs have not been fulfilled so far. This is firstly due to the complex nature of the problem. What is drought? Is the pattern of water deficit the same every year? Should we look for plants that are "water savers" or "water expenders"? The former would grow slowly thus allowing more soil evaporation to occur but would generally have more water for completing seed growth, thereby ensuring a high HI. On the contrary a "water expender" leads to higher biomass production and probably higher yield in good years at the expense of lower HI and yield in bad years. Thus, the best cultivar for rainfed conditions depends on local conditions (climate, soil) and changes from year to year. Furthermore, the tight relationship between assimilation and transpiration (Chap. 14) must be considered. Water use efficiency is mostly dependent on the evaporative demand (air VPD) so little can be achieved by breeding for high WUE under specific conditions. Breeding for high WUE could result in cactus-like cultivars that would keep their stomata closed most of the time! Breeding efforts should be directed instead at manipulating development to fit the most probable drought patterns and to tuning stomatal aperture to periods of low VPD.

Despite the success of the first transgenic crops, there are concerns on the use of this technology mostly related to perceived risks in food safety and the environment, and to the loss of autonomy of farmers for seed production. The risk for humans is unfounded and unfair as there are strict regulations regarding food safety and environmental impact assessment during the breeding process. Additionally, the improved GM varieties are allowing an important reduction in pesticide use thus reducing a potential toxic effect. The other concerns deal with broad social issues and intellectual property rights and is beyond the scope of this book. Is agricultural technology such as transgenic crops which are in the hands of a few private companies a real menace to small farmers around the world?

Plant breeding has been extremely effective not only in contributing to increased productivity, but in adapting crops to new environments. This will be even more important as global warming continues and crops will have to be adapted to warmer environments or to cold areas of the higher latitudes that until now have not been suitable for agriculture. Every major crop species has many thousands of different varieties offering wide adaptation that can be tested and adapted to specific environments through conventional and modern plant breeding combined with new agronomy and management, thus, as in the recent past, crop adaptation will be a very important target for the future of agriculture.

35.4 Alternative Agricultural Systems: Organic Farming

The intensification of agricultural production of recent decades with the extensive pesticide use and the episodes of environmental non-point pollution have given way to alternative movements that question mainstream agricultural practices, viewing them as unsustainable and unhealthy. As a result, other forms of agriculture have been proposed, some based on avoiding the use of synthetic chemical inputs and others that combine different practices using extensively traditional knowledge. These alternative movements have been met with positive views from some urban societies around the world that perceive ‘industrial’ agriculture as a threat to human well-being and to the environment.

The most popular alternative agriculture system is organic farming based on using only organic fertilizers such as manure and plant protection methods that forbid the use of synthetic pesticides and are founded on biological pest control. Eliminating pesticide use has been welcomed by consumers and reduces the environmental impact of agriculture but organic farming has also established a set of rules without scientific basis, particularly those related to soil fertility, which are solely based on the naïve idea that natural is good and synthetic is bad. Molecules such as nitrate, are exactly the same independent of the origin of the fertilizer, so they produce the same benefits to the crop or may lead to the same environmental problem (groundwater pollution). Thus when their systems are based on following a set of strict rules, organic farmers may be condemned to low yields/income if organic fertilizers are scarce and/or expensive. Often, additional land is needed to fix the N needed in the soil through the use of cover crops. While organic agriculture has been very successful in finding a market niche among the urbanites of affluent societies, the feasibility of expanding organic farming beyond a relatively small share of world agricultural production is highly questionable. Global N fertilizer production in 2010 was around 100 Mt N. If we eliminated completely synthetic fertilizers we would require legumes incorporated into the soil as green manure. Assuming an average input of 100 kg N/ha/year, that would take 10^9 ha which is clearly impossible to achieve as total arable land is only 1.5 10^9 ha. In other words, green fertilization would reduce current world productive arable land to one third of the current value.

35.5 Agriculture as an Energy Source

Primary production is an inexhaustible source of energy and therefore has been used by man since long ago. It was during the energy crisis of the late 1970s when agriculture was first considered as a potential source of energy, either through novel, energy crops or using some of the main crops for converting biomass and grain into fuels. Since that time, most of the energy crops have not fulfilled their initial promises (although newly tested C4 species such as *Miscanthus* might be a viable option) and the focus has shifted to ethanol production from sugarcane and maize, with some attention paid to converting edible oils into biodiesel. The contribution of fossil fuels to global warming and the high prices of oil in the recent past have fostered policies for promoting the use of biofuels produced in agricultural lands, particularly in South (sugarcane) and North America (maize). Globally, while the use of biofuels reduces greenhouse gas emissions, the competition between food and energy production is the subject of debate in ethical and environmental terms. For instance, the incentives for producing biofuels have contributed to the expansion of oil palm production at the expense of food crops or of the maintenance of tropical forests thus increasing deforestation. This debate is sided by proposals to use only crop residues as the energy source. This promise of "second generation" biofuels based on the use of residues by conversion of cellulose to sugars, which would then turn into alcohol has been achieved in technical terms, although production costs are still high relative to those of biofuels from sugarcane or maize. The claim that by using only crop residues there is no competition with food production is not valid for two reasons: first, crop residues do have an important role in soil conservation and in maintaining soil organic matter (Chap. 18), and as animal fodder in many agricultural systems and second, if sugars can be produced, then they could also be used for food production.

The relative capacity of agriculture as a potential energy producer may be quantified by comparing the energy contained in food products, against the energy burnt in fossil fuels. The total global consumption in 2010 of liquid fossil fuels (gasoline, refined fuel oils, etc) which is mostly used in transportation was around 70 million barrels/day which is equivalent to 135 10^{12} MJ/year. For the same year, global agricultural production was 3866 Mt of dry matter (Table 35.1) which corresponds to a total energy of 71 10^{12} MJ which is less than 50 % of the energy of liquid fuels. The EU has established the goal of supplying 10 % of fuel as biofuels by 2020. If that rule is applied globally it would require 13.5 10^{12} MJ which is equivalent to almost 20 % of agricultural production.

Table 35.1 Global crop production in 2012 classified by crop type and equivalent energy captured

Crop type	Crop production Mt dry matter	Energy content MJ/kg	Equivalent energy EJ
Grain	2276	17	38.70
Oil	450	27	12.15
Legumes	317	19	6.03
Sugar	307	17	5.22
Starch	230	17	3.91
Fruits	157	17	2.67
Vegs	74	17	1.27
Non food	38	17	0.65
Other	15	17	0.26
Total	3866		70.85

35.6 The Role of Research, Extension and Information/ Communication Technologies

The returns on past investments in agricultural research have been so high that some have termed agricultural research as the best business of the public sector ever. Modern agricultural research started in the last decades of the nineteenth century, primarily in Germany, USA and England. After the Second World War, in view of the need to produce more food for a growing population, there was an initiative led by private foundations and some countries to develop a system of international agricultural research which eventually became the Consultative Group of International Agricultural Research (CGIAR) with research centers located in developing countries. The CGIAR developed the first cultivars of dwarf wheat and rice that were more productive than existing tall cultivars, leading what was later called ‘the Green Revolution’. All countries have since developed their agricultural research systems which have contributed to the sustained increases in food production worldwide since 1950.

Along with agricultural research, some countries such as the USA developed in parallel a system for disseminating the new results among farmers to promote adoption of new techniques as they were developed by researchers. Agricultural extension has also been very successful and there are many examples of successful adoption of new techniques that were experimented locally and tested by extension. Many of the newly developed techniques require adaptation to local conditions as a prerequisite for adoption by farmers. Without a good extension system, farmers hesitate in adopting new ideas that have not been adapted and tested locally, and progress is slower. Also, being extension part of the public sector, they are independent of private corporations and free of biases towards certain varieties or products. Agricultural extension started in the USA before the end of the nineteenth century and has been largely responsible for the expansion and productivity increases of US agriculture. Other countries have created effective extension systems but many developing countries have not invested sufficiently in agricultural extension, and this is limiting the rate of adoption of effective solutions that increase productivity and sustainability. One limitation is the huge number of small farmers that exist in many countries which will require a very large extension force to carry out the work in the field, if extension is to be conducted in the way it has been until now (face to face). However, new communication technologies such as cell phones which are readily available in most areas could serve as innovative ways to reach the large populations of small farmers effectively.

In general, communication technologies have accelerated the access to vast amounts of information but cannot guarantee its quality. Information delivered by private companies is often biased towards the benefits of their products and sometimes it escapes regulations on false advertising. It is common to see web pages where companies mention "studies performed at different universities" (without more detail) to support their products. Public research/extension systems will be required to address the needs of farmers and the whole society in particular providing assessments concerning the long term or large scale effects on agricultural systems (e.g. soil erosion).

Given the predictions of increase in global population and economic development, it is estimated that 70 % more food will have to be produced by 2050 (see below). The magnitude of this challenge cannot be underestimated given the current productivity trends of the major crops. Agricultural research will play an important role in meeting this challenge as it has done in the past, provided that governments around the world realize the difficulties ahead and invest sufficient resources to tackle the research issues related to increasing production in a sustainable fashion. The associated extension efforts, which will be badly needed, will increasingly be based on the use of crop simulation models and the development of decision support systems tailored to the specific needs of the farmers and communicated through the web.

Box 35.1 Visualizing the Future

A farmer in 2050 is planning to sow wheat by November 1. By October 15 a sampling robot is sent to the different fields of the farm where it automatically samples the soil in different locations and produces maps of nutrient (nitrate, P, K) and soil water content, which the farmer checks against similar observations obtained 2 weeks ago from a satellite service that he subscribes. The robot also takes some samples that are packed and sent to the regional research center to test for soil pathogens or insects. On the same day, his drone flies over the farm and collects visual and NIR images to map the weed spots in the fields to be sown. Then the farmer looks at a DSS that shows the estimated soil water content in the different fields. With that data and the local rainfall forecast for the next 2 weeks, the system connects with the web sites of seed companies, collects information on the different cultivars available,

(continued)

Box 35.1 (continued)

runs a simulation model of the crop based on a reliable seasonal weather forecast and compares which are the best options, considering seed price, expected yields, product prices and local availability. The farmer buys online the seed required.

The same DSS builds also a map of recommended application of N, P, K and contact herbicide and calculates the quantities to be ordered by checking the actual stocks. The farmer compares online the prices and conditions of different suppliers and confirms the order. According to weather forecasts dry conditions are expected by October 22 and 23 with rainfall afterwards. These are appropriate for applying the N and the herbicide. By October 20 an email is received from the regional research center advising the use of an insecticide at a given rate along with the seed. The farmer confirms online the use of the insecticide which is registered on an external database of pesticide use.

On October 22 the robot fertilizer-sprayer goes to the fields and applies urea at variable rates depending on need. It also sprays herbicide only on the spots where weeds had been previously detected. After the job is done the farmer confirms online the amounts of N and herbicide used in each field. This information goes to the external databases for subsequent N fertilizer and pesticide use.

On November 1 the robot seed drill is sent to the fields to sow and to apply localized P and K fertilizers at variable rates. The planter will follow always the same path as all other machinery to avoid compaction due to traffic.

35.7 Food Security and Food Safety

Following a sharp increase in food prices in 2008, concerns for food security, understood as a situation where all humans will have access to sufficient and nutritious food, have increased around the world. Food security is now high in the agenda of many countries that are planning for an uncertain future where, at the same time that global food trade is reaching historical levels, food sovereignty issues related to the capacity of each country to be self-sufficient in food production are increasingly important given the current political climate. Food trade is balancing supply and demand in an effective manner and is the major instrument now to cope with instability in production caused by extreme weather events and by changes in food demand due to diet changes or other features of economic development.

Food safety refers to health issues from the standpoint of ensuring that marketable foods are both healthy and nutritious. Health-related problems in food productions appear periodically (for example, the mad cow disease caused by dubious animal feeding practices) and attract substantial attention from a society that is more and more distant from agriculture and food production processes.

Periodically, episodes of food contamination by chemical or biological agents occur in many countries and generate alarms regarding food safety. One important source of contamination is the use of untreated waste water for irrigation that still takes place in many world areas and that must be avoided by appropriate water treatment. Alarms due to food contamination cause great concern among consumers and this is rightly forcing more control and regulation of food production processes from farm to fork. Agronomists must ensure that products leaving the farm are always safe for consumption, the major issue being inadequate pesticide usage. Another important goal is to enhance the nutritional qualities of the food produced. Content in terms of protein, essential amino acids, vitamins, and other nutritional factors must be enhanced where possible by good agronomy. Other interesting aspect refers to the positive interactions between nutrition and health of certain agricultural products such as red wine, nuts, and olive oil among others, that have proven health-related benefits but where the content of the chemical products responsible for those benefits depends in part on the growing conditions. Finally, given the increasing importance of gastronomy in affluent societies, agronomists should focus more on issues related to ensuring product quality from the gastronomic viewpoint.

Although predictions vary, it is estimated that agricultural production should increase by 70 % to meet the demand of nine billion people expected in 2050. Is the world going to provide food security for all by 2050? First of all it is important to consider that not all agricultural products are used directly for food. Around 10 % is devoted to industrial crops including biofuels. The remaining 90 % is shared between food (65 %) and animal feed (35 %), which results in an overall efficiency of crop production for food of 0.65. This low efficiency is due to the low conversion efficiency of animals mainly for meat production. Here, there are ample differences in efficiencies among animals, chickens being the most efficient and cows the least (Table 35.2). However, ruminants exploit rangelands (which occupy more land that is used in agriculture) that otherwise would not be used for food production and this must be taken into consideration when addressing meat production in global food assessments. Calls have been made to reduce meat consumption in the developed

Table 35.2 Distribution of uses of edible crops and all crops circa 2012. The efficiency of conversion for energy is taken 1 for human as direct consumption. Using this Table a general efficiency of global crop production to food of 0.65 can be estimated as the weighted average of the efficiencies taken the fraction of use as weighing factors

	Edible crops	Total crops	Efficiency
	Fraction used	Fraction used	Fraction
Humans	0.65	0.5915	1
Pork	0.12	0.1092	0.1
Dairy	0.09	0.0819	0.4
Beef	0.05	0.0455	0.03
Chicken	0.05	0.0455	0.12
Eggs	0.04	0.0364	0.22

countries and this could have an impact on future food security. For instance if feed for meat production was reduced by half, the overall efficiency would increase from 0.65 to 0.74, a 14 % increase in calories available to humans. Such a drastic change would be difficult to achieve as it is doubtful that it would free as many calories for humans as computed above, as animal feed includes residues and other non-food components, in addition to the consumption of pastures. On the other hand there are clear health-related advantages of reducing the amount of animal products in human diets, particularly in countries of high consumption where obesity is a growing problem.

Another area where improvements will contribute to future food security is reducing food waste. It is estimated that up to one third of global food production is wasted before it can be consumed by humans. The nature of waste varies in different food chains but generally speaking, food waste in poor areas is primarily due to post-harvest losses caused by pests. By contrast, in the affluent countries the majority of food losses occur at the consumers' end of the chain. Although efforts are being made to reduce waste, much of it is related to social and cultural factors which, as in the meat consumption patterns, are difficult to change.

How can then agronomy contribute to food security in the future? We must make current agricultural systems more sustainable without losing sight of the need to intensify production in existing farmlands. The option of expanding agriculture has significant ecological limitations and is not going to be sustainable as most of the best lands have already been put in production. Thus, the sustainable intensification of production by introducing new techniques adapted to local conditions should continue that path of increased productivity. Ample opportunities exist around the world for increasing both agricultural productivity and sustainability by using good agronomy and appropriate crop management practices.

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Appendix

Practical Project for an Undergraduate Course on Principles of Agronomy for Sustainable Agriculture

Teaching the Course

The class of Principles of Agronomy for Sustainable Agriculture (PASA) may require between 6 and 9 credits according to the European system (1 credit = 25 h of student's work), depending on the actual background of students or the specific interests in some of the topics (e.g. irrigation chapters may be skipped in humid environments). This would be equivalent to between 60 and 90 classroom hours with basic lectures and practical work split 50 %. Apart from that, the students are grouped in couples that undertake a specific practical project that includes both individual and joint work. Each practical project has a specific location (with its climate characterized by a specific weather station) and a crop rotation (e.g. barley/maize) so that each student has a specific crop species assigned.

At the end of the course each group submits a written report on the project results that is evaluated by the teacher after each student gives an oral presentation (10 min plus 5 min for questions). At this time the teacher may ask specific questions to check the ability of the students to support their calculations. The quality of the presentation and the report and the answers to questions are major determinants of the final grade of the student.

An example of a proposed practical project used in the PASA course at the University of Cordoba is shown below.

F.J. Villalobos, E. Fereres (eds.), *Principles of Agronomy for Sustainable Agriculture*, DOI 10.1007/978-3-319-46116-8

Practical Project. Principles of Agronomy. 2015/2016 (Revised January 2016)

We will work in groups of two students. Each one will have a different crop and the two crops will make the crop rotation. Only one report will be presented by each group.

Weather station..
Year 2015
Crop species..
Soil of medium texture, 1 m depth

Irrigation is performed by sprinklers with 12 × 12 m spacing, discharge rate 0.3 l/s, and application efficiency 0.85. Irrigation water has a salinity of CE = 1.5 dS/m and the water is pumped from a small dam using a pump with diesel engine

1. **Climate**. Download the available weather data from the link shown in the web page in class. Take only complete years starting with 2015 and going backwards at least to the last 10 years.
   Calculate mean monthly values of:

   Maximum temperature
   Minimum temperature
   Solar radiation
   Vapor pressure deficit
   Wind speed
   Total rainfall
   Number of rainy days (consider only days with rainfall of 0.5 mm or more)

2. Calculate also for each month the mean values of:

   Daylength
   Maximum solar radiation (clear sky conditions)
   Net radiation over grass
   ET_0 using the Penman-Monteith-FAO equation
   ET_0 using the Hargreaves equation
   Effective rainfall (FAO method) (use monthly rainfall totals)

3. **Productivity**. Calculate for 2015 and the two crops:
   (a) Thermal time from sowing to harvest. Assume that crop duration is equal to that defined by the four stages of the FAO method of K_c.
   (b) Intercepted PAR: the fraction of intercepted PAR is calculated for each stage using:

       Stage A: $f = 0.1$
       Stages C and D: $f = K_c - 0.3$
       Stage B: Interpolate between the values of stages A and C

   (c) Potential yield. Compare this value with typical yields for this crop in this region.

4. **Fertilizer program**. Calculate:
    (a) Average fertilizer requirements of P and K for the crop rotation. All crop residues are left in the field. Assume that soil test levels for P and K are above the threshold levels and below maintenance levels, i.e. we need to apply fertilizers to compensate for nutrient exports. Assume that the average yield of your crop is 80 % of the value calculated in 3c.
    (b) Calculate the N fertilizer requirements for the two crops.
    (c) Calculate the total cost of the fertilizer program (not including the application cost).
5. **Irrigation Schedule**
   Calculate the irrigation programs for the two crops (dates and amounts) in 2015. Assume that the soil water deficit is zero at sowing.
6. **Salinity**: calculate the amount of irrigation that should be added to that calculated in step 5, to achieve maximum yields.
7. **Sowing**: Calculate the seed rates for the two crops.
8. **Frost**: Calculate the probability of frost after March 1.
9. **Crop calendar and energy requirements**.
   For the two crops establish the crop calendar. Choose a soil conservation system (tillage or no tillage) and indicate dates and operations to be performed (sowing, tillage, application of herbicides, harvest). Calculate the energy requirements of your farm with the current rotation.

Index

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