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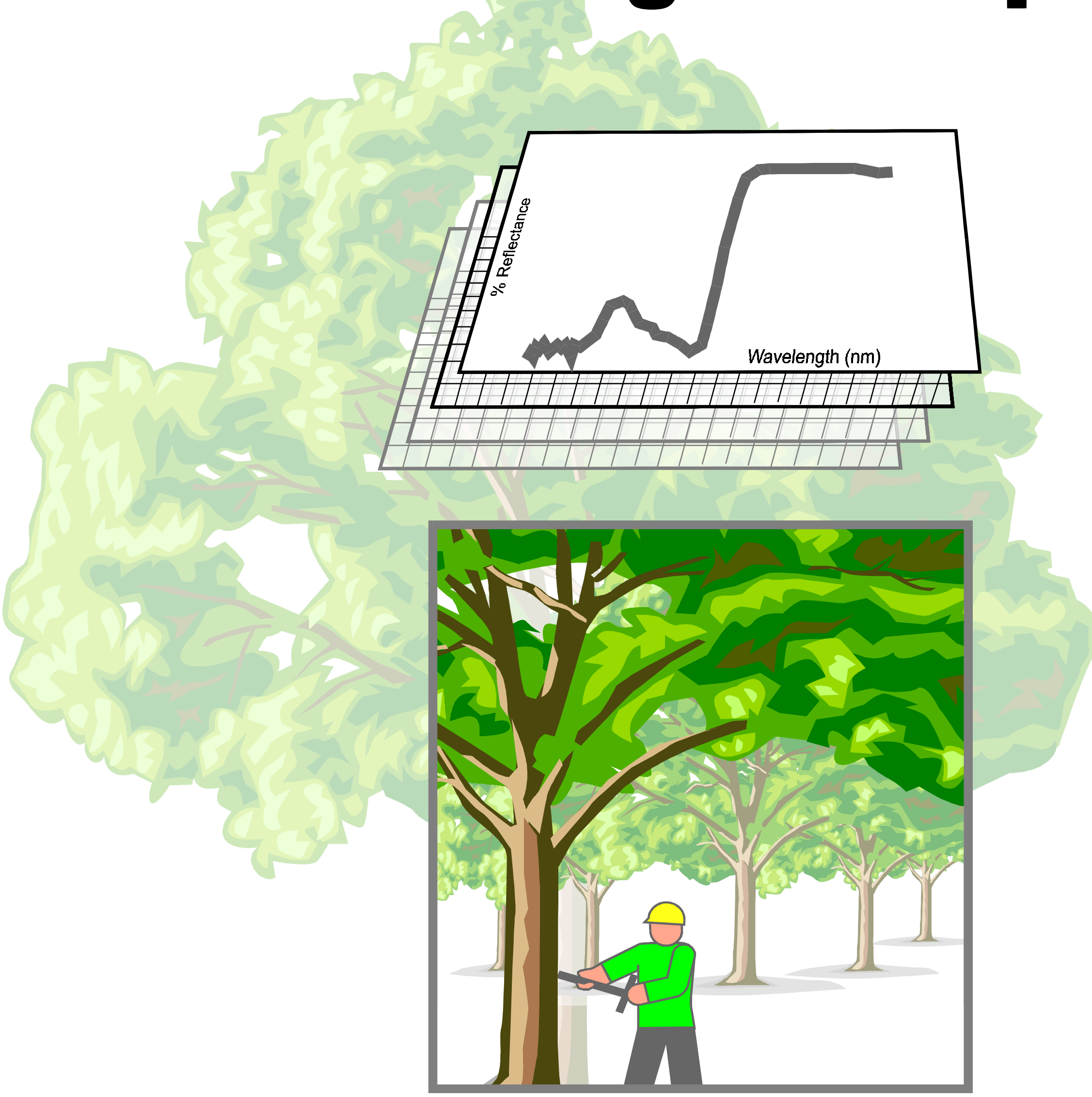
Bioindicators of Forest Sustainability
Progress Report



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Bioindicators of Forest Sustainability

Progress Report

by

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1998

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Abstract

Measurable indicators are needed to gauge the effects of management activities and natural phenomena on forest sustainability. To meet this need, the Bioindicators of Forest Sustainability Project is testing physiological approaches to develop a Forest Condition Rating (FCR) system. An FCR system would directly support provincial policy (e.g., Forest Resource Assessment Policy) and national initiatives (e.g., Criteria and Indicators) by providing an understanding of ecosystem condition. Furthermore, this project addresses a pressing need for indicators that can support operational forest management and possible concerns of sustainability at the local level. Development of an FCR system involves interpreting remotely sensed spectral information with the aid of ground-based assessments of structural and functional (i.e., physiological) aspects of forest condition. Analysis of this spectral information may reveal indicators of health across a wide range of tree species and ages. Current research activities include controlled laboratory studies, ground-based field assessments and acquisition of hyperspectral airborne data to develop gradients in key spectral features that correspond to actual differences in physiology. This report provides first-year progress results. Preliminary correlations in controlled experiments have been made between leaf-based spectral reflectance and physiological status. Compilation of a leaf-based spectral database has been initiated. The database shows the influence of species, leaf age, stress status, season and other factors on spectral features. Other physiological and structural measures, such as foliar biochemistry, stem electrical resistance, and leaf area index, have also been linked to forest decline status. Finally, a brief summary of collaborative projects and proposed research activities is provided.

Keywords: bioindicators, forest health, hyperspectral, remote sensing, physiology

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Introduction

The goal of the Bioindicators of Forest Sustainability Project is to develop a ***Forest Condition Rating (FCR)*** system based on physiological approaches to monitor forest health and stress. This rating system will advance our ability to quantitatively evaluate the functional status of our forests. Using remotely sensed spectral data and ground-based physiological measurements, the project seeks to classify forest stands on a scale from healthy to stressed relative to an established benchmark.

Development of an FCR system involves correlating remotely sensed spectral information to ground-based assessments of, for example, decline, productivity and physiology. In particular, analysis of the spectral information may reveal indicators of health across a range of tree species and ages, but this remains to be shown. Such indicators are known to exist in tree physiology and have been applied, for example, to assess the functional integrity of photosynthetic systems using chlorophyll fluorescence (Mohammed et al. 1995). By identifying these integrative measures of physiological condition, benchmarks or a range of forest stress conditions that define the FCR scale may be achieved.

The ability to provide indicators of stand physiological condition can support forest management decisions in areas such as:

- evaluating the effects of forest management practices,
- identifying areas in need of management action, and
- providing an early warning of declining productivity.

An FCR system could directly support provincial policy (e.g. Forest Resource Assessment Policy) and national initiatives (e.g. Criteria and Indicators) by providing a measure of certain aspects of forest ecosystem condition. Moreover, this project addresses a pressing need for indicators that can support operational forest management and concerns of sustainability at the local level.

To define our objectives in the development of an FCR system, a ***Project Strategy*** (Mohammed et al. 1997) was completed by a team of specialists in physiology and remote sensing. Supporting this project team is a technical advisory team and a host of cooperators. This report summarizes first-year accomplishments related to the project strategy. ***Accomplishments over the past year include:***

- conducting research to evaluate and establish spectral indices,
- measuring tree physiological and structural characteristics using ground-based methods,
- acquiring hyperspectral remote sensing data throughout the growing season for forests in the Algoma Region, and
- developing cooperative research and partnerships.

Hyperspectral Remote Sensing

The Project Team commissioned a report (Dendron Resource Surveys Inc. 1998) to assess the feasibility, operational applications and possible strategies to apply remote sensing for monitoring forest physiological condition. A conclusion of this review was that to discriminate changes in stress status at the canopy level reflectance at narrow bandwidths and within critical spectral regions is required. It is for this reason that remote sensing platforms with hyperspectral reflectance (i.e. several narrow spectral bands) capabilities were deemed necessary.

Hyperspectral data may provide a means to discern reflectance between "healthy" and "stressed" trees by evaluating changes in specific wavelengths of electromagnetic radiation. For this analysis, ratio-based indices are commonly applied to correlate spectral reflectance and corresponding changes in plant vigour. Hence, development of remotely sensed spectral indices involves relating spectral reflectance to forest conditions.

Relating spectral indices to forest condition requires an understanding of the effects of ecophysiological variables such as season, tree age, and species on spectral behaviour (reviewed in Treitz and Howarth 1996). These variables can confound the interpretation of data because they cause variability among assessments of the same site. Another aspect is the need to correlate spectral characteristics to other physiological features in healthy or stressed stands. Effects of common stresses such as drought, nutrient deficiency, physical damage and pests may be acute or chronic, and may be acting singly or in various combination. ***Investigating the factors affecting spectral indices of forest stands, as compared to ground-based assessments of decline, productivity, and physiology is, therefore, a focus of our current research efforts.***

Spectral Indices and Features

Current research activities include controlled laboratory studies, ground-based field assessments and acquisition of hyperspectral airborne data to develop gradients in key spectral features that might correspond to actual differences in physiology. The progress in each of these levels of investigation is provided in the following discussion.

Table 1. *Species included in the spectral database.*[1]

Evergreen Tree/Shrub	Deciduous Tree/Shrub	Herbaceous/Moss /Lichen	Wetland/Aquatic
Balsam fir	Basswood	Bracken fern	Broad-leaved arrowhead
Black spruce	Black walnut	Canada blue-joint grass	Fragrant white water lily
Eastern hemlock	Beech	Fireweed	Jewelweed
Eastern white pine	Cottonwood	Juniper haircap moss	Lakebank sedge
Jack pine	Green alder	Large-leaved aster	Marsh cinquefoil
Norway spruce	Paper birch	Monk's hood lichen	Meadowsweet
Pitch pine	Red maple	Reindeer lichen	Nodding bur-marigold
Red pine	Red oak	White clover	Northern bog violet
White cedar	Red raspberry		Sweet gale
White spruce	Silver maple		
	Striped maple		
	Sugar maple		
	Tamarack (larch)		
	Trembling aspen		
	Upland willow		
	White ash		
	Yellow birch		

[1] Common name nomenclature as per Newmaster et al. (1998).

Spectral library

Fundamental to understanding the spectral properties of forest canopies is the development of a spectral database for leaf-based reflectance. ***Spectral reflectance data have been collected for 44 Ontario plant species*** (Table 1). Spectral variations associated with foliar type, age, stage of development, season, and stress status have also been identified. Figure 1 illustrates typical spectra for healthy samples of a few species.

Leaf-based reflectance was measured with a UniSpec Spectral Analysis System / Reflectometer (PP Systems, Haverhill, MA, USA), operated with a palmtop PC. Leaves from at least 5 plants were individually sampled by placing into a leaf clip (adaxial side upwards) attached to a fibre-optic halogen light source and detector. Fifty scans per sample were integrated (integration time 10 ms). Reflectance measurements were preceded by a dark scan, and were compared to reflectance from a Spectralon (Labsphere Inc., North Sutton, NH, USA) white standard to obtain percent reflectance. From the reflectance data, various spectral indices and features were derived (Table 2).

Some general features have been found to distinguish plant functional groups, e.g., higher amplitude in the infrared reflectance region in angiosperm compared to gymnosperm species. However, simple features of leaf-based reflectance curves may be insufficient to satisfactorily distinguish individual species within a functional group. In other studies, analytical techniques for spectral curves, which utilize sophisticated algorithms, have shown more promise in distinguishing finer species.

Table 2. *Summary of spectral indices and features derived for species included in the spectral database.*

Spectral indices and features	Reference
R750/R550	Gitelson and Merzylak 1996, Lichtenthaler et al. 1996a
R694/R760	Carter et al. 1996
R750/R700	Gitelson and Merzylak 1996, Lichtenthaler et al. 1996a
(R800-R680)/(R800+R680)	Lichtenthaler et al. 1996a
(R734-R747)/(R715-R726)	Vogelmann et al. 1993
(R734-R747)/(R715-R720)	Vogelmann et al. 1993
(R531-R570)/(R531+R570)	Gamon et al. 1997
R440/R690	Lichtenthaler et al. 1996b (used fluorescence ratio)
R440/R740	Lichtenthaler et al. 1996b (used fluorescence ratio)
Avg. reflectance at 700 nm	Lichtenthaler et al. 1996a
Derivative at 690/700 nm (i.e. red edge region)	Horler et al. 1983, Gitelson et al. 1996
Integral at 400 to 700 nm	

Ground-based Assessments

The next level of investigation in correlating physiological condition to airborne reflectance data are ground-based assessments of forest condition. These assessments can be either structural or functional measures of condition. As summarized in Table 3, ***structural measures*** provide a direct evaluation of an individual characteristic or attribute, whereas functional measures reflect performance or vigour as an integrated effect of physiological condition. Changes in structural measures over time (e.g., height increment) can also reflect performance.

Seventeen study sites were selected in the Algoma Region of Ontario in 1997 to conduct on-ground-based assessments and to acquire hyperspectral imagery. Using existing plot networks (i.e., Growth and Yield and Hardwood Forest Health), sites were selected to represent a range of: i) productivity, ii) decline, and iii) species composition. In addition, controlled plantation studies at the Ontario Forest Research Institute (OFRI) arboretum were included in field and airborne assessments.

Biochemistry: Chlorophyll and total carotenoids

Chlorophyll production in the spring and its destruction in the fall are the only biochemical processes readily observed from outer space (Rudiger 1997). Remote sensing techniques have therefore been used to detect and correlate spectral reflectance changes to chlorophyll concentrations (Matson et al. 1994, Rudiger 1997). Of particular interest is the detection of decreased chlorophyll content when unfavourable environmental conditions result in plant physiological stress (Carter et al. 1996). Changes in leaf content of other pigments (e.g. carotenoids) also affect reflectance response and may indicate stress.

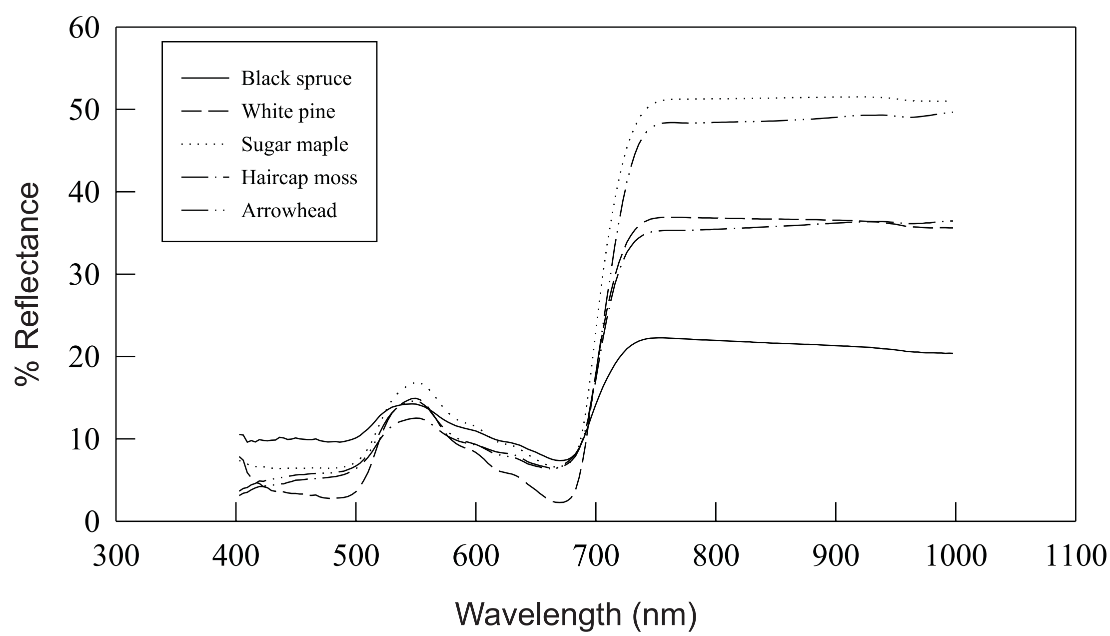


Figure 1. Examples of reflectance spectra for some Ontario plant species.

Maple decline study

A study was initiated to correlate remotely sensed leaf reflectance with leaf chlorophyll and carotenoid concentrations measured in the lab. For this investigation, samples from selected trees on a range of maple decline sites were collected just prior to the acquisition of canopy reflectance data.

Results:

- Moderate and severe maple decline plots had significantly lower chlorophyll and carotenoid concentrations than did the low decline plots (Table 4). No differences in chlorophyll a/b or total chlorophyll/ carotenoid ratios were found.

- Pigment reduction in the leaves of trees in maple stands classed as moderate or severe decline suggests that these trees were more stressed than the trees in the stand classed as low decline.

Implications:

- The analysis of hyperspectral remote sensing will focus on the potential reflectance changes observed at the leaf and at the canopy level. If both levels of investigation are significantly correlated then changes in reflectance may be an effective tool to identify and track maple decline and its progression.

Controlled treatments in a conifer plantation

Biochemical analyses of chlorophyll and carotenoids were performed on samples of black spruce (*Picea mariana* (Mill.) B.S.P.) eastern white pine (*Pinus strobus* L.) and jack pine (*Pinus banksiana* Lamb.) stocktypes planted in 1992. Controlled treatments (herbicide, root pruning, irrigation, and irrigation plus fertilization) were used to create stress or improve vigour.

Table 3. *Examples of structural and functional measures of tree condition (adapted from Ritchie 1984).*

Structural Measures	Information Acquired
• Mensurational	height, diameter, basal area and volume
• Chlorophyll & Pigment Concentrations	level of photosynthetic material
• Leaf Area Index	amount of leaf biomass
• Canopy Structure	size, shape and density of crown
Functional Measures	**Information Acquired**
• Spectral Reflectance	leaf pigment, biochemistry and structure
• Chlorophyll Fluorescence	photosynthetic capacity
• Stable Carbon Isotope	cumulative seasonal water stress
• Electrical Resistance	indirect measure of cambial layer width

Results:

- Herbicide and root pruning treatments caused significant reductions in pigment concentrations of the current and 1-year-old jack pine needles (Table 5 and Figure 2).

Implications:

- Stress caused by herbicide application was evident in the pigment concentrations, fluorescence, and spectral index values, and suggests that certain hyperspectral features may be worth focusing upon in the canopy-scale investigations.

- Results were similar for black spruce and white pine (data not shown).

Promising spectral indices that were identified that were well correlated to other physiological measures such as chlorophyll fluorescence and biochemistry. These are listed in Table 6 for the examples sugar maple and eastern white pine.

Stable Carbon Isotope

The use of **stable isotopes** is becoming a powerful tool in understanding ecosystem function. Isotopes of an element have the same number of protons but different atomic mass. Some isotopes are unstable and their breakdown produces radioactive energy (e.g., ^{14}C); others are stable and do not break down. The abundance of stable isotopes can in some instances be used to assess physiological status. The stable isotope of carbon, ^{13}C, is one that may be useful in determining stress in vegetation.

During photosynthesis CO_2 is absorbed by plants and converted into sugars. These sugars and the carbon atoms they contain are later converted into cellulose and numerous other carbon-containing compounds in plants. Most carbon atoms in CO_2 molecules contain 6 protons and 6 neutrons (^{12}C), however, 1 out of every 100 CO_2 molecules contains an additional neutron (^{13}C).

The ratio between ^{13}C and ^{12}C in plant tissues (expressed as d^{13}C) can be used to determine a stress history for plants. When stomata are open (non-stressed state) relatively more $^{12}CO_2$ than $^{13}CO_2$ enters leaves; $^{13}CO_2$ diffuses more slowly in air because it has a larger molecular weight. In addition, the biochemical conversion of ^{12}C into sugars is more efficient than that for ^{13}C. Therefore, when stomata are partially closed, the proportion of $^{13}CO_2$ converted to sugar rises. As a result of these differences in C absorption and conversion, the ratio of ^{13}C to ^{12}C in plant tissues such as cellulose can serve as a record of plant stress over time (McNulty and Swank 1995).

Table 4. *Mean (July and August) chlorophyll and total carotenoid concentrations of sugar maple (*Acer saccharum M.*) foliage from Hardwood Forest Health plots.*

Plot No.	Decline Status	Chlorophyll a&b[1]	Carotenoids[1]
35	moderate	3.37 b	0.66 b
37	severe	3.81 b	0.75 b
39	low	5.92 a	1.07 a

[1]Units = mg/g dry mass. Means (n = 3 trees x 2 dates) followed by different letters within a column are significantly different (P = 0.05).

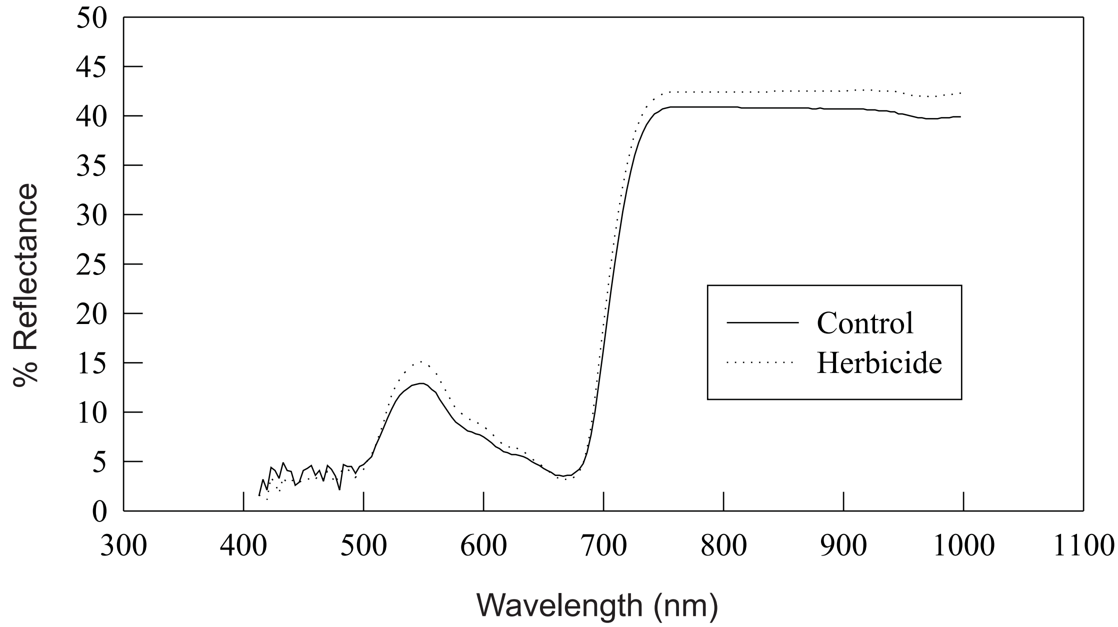


Figure 2. Herbicide effects on spectral reflectance in jack pine.

Table 5. *Effect of herbicide (glyphosate) on chlorophyll content, total carotenoids, chlorophyll fluorescence, spectral indices, and morphological features in jack pine.*[1]

Parameter	Control	Herbicide
Chlorophyll a&b[2]	2.35 a	1.22 b
Total carotenoids[2]	0.41 a	0.24 b
Fv/Fmax[3]	0.81 a	0.61 b
R750/R700	2.61 a	2.31 b
(R734-R747)/(R715-R720)	0.95 a	0.88 b
Tree height (cm)	259.6 a	251.6 a
Tree diameter (cm)	3.60 a	3.37 a
Foliar damage class[4]	1.00 b	2.95 a

[1] Herbicide was applied on July 16/97, physiology was evaluated on the current-season's needles in mid-August, and morphology was assessed on September 25/97. Note: (1) physiological measures were made on apparently healthy green foliage, and were used to test for previsual indicators of eventual foliar browning, (2) relatively small differences in the spectral index values were indicative of damage.

[2] All values are concentrations mg/g dry mass. Means (n=6) followed by the same letter within a column are not significantly different (P = 0.05).

[3] Ratio of variable to maximal chlorophyll fluorescence; a measure of photosynthetic efficiency.

[4] Damage classes: 1=0-25%, 2=26-50%, 3=51-75%, 4=76-100%

Table 6. *Summary of promising leaf-based spectral indices and their response to stress.*

Index	Sugar Maple	White Pine
R750/R550		Decrease
R694/R760	Increase	Increase
R750/R700	Decrease	Decrease
(R800-R680)/(R800+R680)		Decrease
(R734-R747) / (R715-R726)		Increase
(R531-R570) / (R531+R570)	Decrease	Decrease
Average R700	Increase	Increase
R440/R690		Increase

Wood cores were collected from 15 sugar maple trees at each of the 3 maple decline sites previously described as severe, moderate, or low decline. The cores have been examined under a dissecting microscope to measure the width of the annual ring, which will be used to reconstruct stem basal area growth. The increment cores will then be divided into annual wood increments for analysis of $d^{13}C$. High $d^{13}C$ values may indicate a relatively higher degree of stress. Based on $d^{13}C$ a stand stress condition and stress history can be reconstructed. This approach will allow us to illustrate seasonal stress condition of the forest going back over the life of the stand. Results of $d^{13}C$ analysis are not expected until late 1998.

Stem Electrical Resistance

The use of ***stem electrical resistance (SER) to indicate tree vigour*** has been the subject of numerous studies on a variety of tree species. Stem electrical resistance has been used as an indicator of stress in oak and of vigour in white pine. In sugar maple, SER has been used as a guide for thinning and to evaluate decline symptoms.

Stem electrical resistance is an attractive ground-based technique for assessing tree condition because it is rapid, the equipment is portable, and it measures a physiological property that has successfully been used to classify trees according to vigour. However, SER is affected by several factors that must be accounted for to properly interpret measurements. In preliminary studies, we examined several factors (stem diameter, radial growth rates, temperature, and electrode insertion depth) reported to affect SER. In a later study we measured stem electrical resistance of sugar maple from the same 15 trees sampled for stable carbon isotopes from each of 3 maple decline plots located in the Algoma Region. These studies are described below.

Assessment of Factors Affecting Stem Electrical Resistance

Stem electrical resistance was measured in October and November in a mature stand of sugar maple located near Maple, Ontario. A total of 29 trees were sampled. Trees were selected to sample a broad range of diameters, ranging from 11 to 45 cm (diameter at breast height). Resistance measurements were taken using a Shigometer). This instrument uses a pulsed DC current, and gives a reading in kiloohms. An impedance bridge with A C current was also tried; results were the same with the Shigometer. However, the Shigometer is smaller, lighter, and easier to operate than the impedance bridge.

To conduct a measurement the leads from the shigometer were attached to 2, 3-inch common nails inserted into the tree 2 cm apart, 1 nail above the other approximately 30 cm above the ground. The nails were inserted into a fissure in the bark and into the xylem of the tree at successively greater depths, 0.5 cm at a time, to a maximum depth of 5 cm. Resistance readings were taken at every 0.5 cm depth. Two sets of readings were taken for each tree, on different sides of the tree. Air, bark, and internal temperatures were recorded for each tree using a thermocouple thermometer.

Results

Stem electrical resistance of sugar maple was related to the depth of the electrodes (i.e., nails) in the stem, internal temperature, stem diameter, and average ring width of the tree. Resistance decreased exponentially with nail depth. Depths of 4 cm or more produced stable SER readings unaffected by insertion depth.

The SER measured using electrodes placed at a 5-cm depth was linearly related to temperature. Higher temperatures were associated with lower resistance values. Stem electrical resistance was also linearly related to tree diameter, with larger diameter trees having lower electrical resistance values.

Average ring width in the outer 5 cm of each tree was used as an indicator of the radial growth or vigour of the tree. Radial growth rate was linearly related to SER, with higher growth rates (larger ring widths) associated with lower SER values. Radial growth rate was also linearly related to diameter. In general, the larger, older trees had higher growth rates than the smaller, younger trees, indicating that the younger trees were being suppressed.

It seems that the radial growth of a tree has more of an effect on its electrical resistance than does diameter. Theoretically, in a population of uneven aged, dominant or co-dominant trees where suppression was not a factor, the oldest, largest trees would be less vigorous and have slower radial growth, resulting in higher electrical resistance values than the younger, more vigorous trees. The radial growth/SER relationship is probably a better method of accounting for variability in SER measurements than diameter. We conclude that electrical resistance is a reasonable indicator of the current growth rate of the tree, and is not directly affected by diameter.

Implications

- Correlations of various tree and environmental factors with SER can be used to adjust SER values to a common basis and improve the accuracy of SER as a measure of stand condition. The correlation of SER with radial growth rate suggests that this method may have value as an indicator of tree vigour.

Assessment of tree vigour in maple decline stands

Stem electrical resistance measurements were carried out in September on the same maple decline sites used for stable carbon isotope, biochemical analysis, and remote sensing. A total of 15 randomly selected trees were measured at each of the 3 test sites. To conduct a measurement, 2 vertically aligned nails approximately 2 cm apart were inserted to a depth of 4-5 cm. Resistance was measured using a LCD auto range digital multimeter (Micronta, model 22-163). Two readings were taken on opposite sides of the stem; data are the average of the 2 readings.

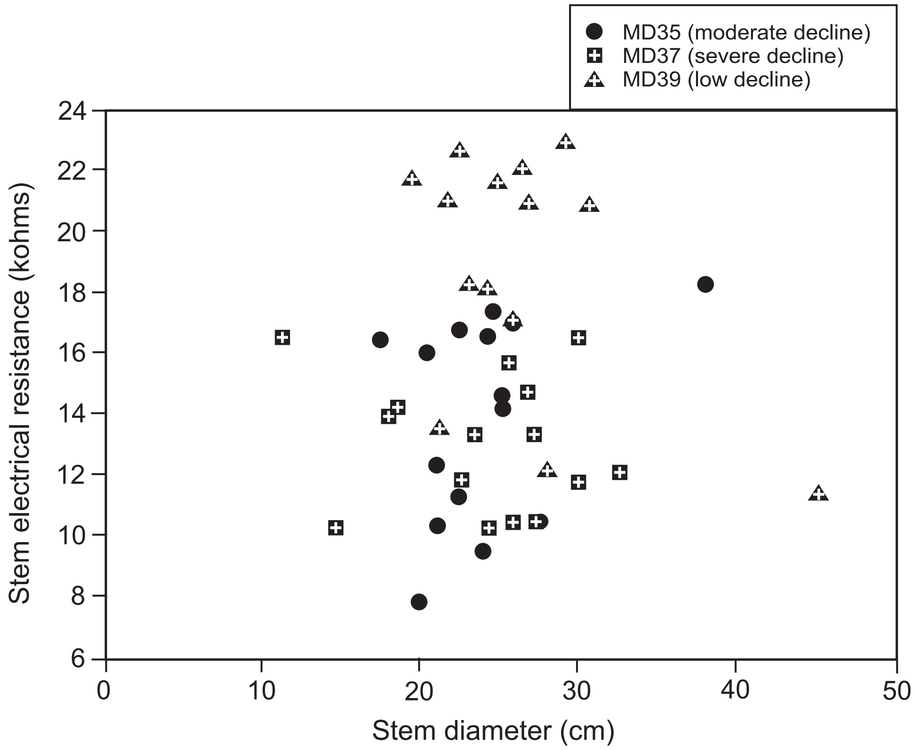


Figure 3. The relationship between stem electrical resistance and diameter of sugar maple trees in stands rated as low, moderate, or severe decline.

Results

Figure 3 shows individual tree SER measured at 3 maple decline sites. Unlike the previous study, this data does not show an obvious relationship between SER and diameter. There was, however, a relationship between stand decline status and SER: trees in the low decline stand at Maple Decline Plot 39 tended to have higher electrical resistance than those in the stands with moderate or high levels of decline. This is the reverse of what we anticipated, but may be attributable to cooler temperatures on the day of measurement at Plot 39.

The lack of obvious difference in SER between the moderate and high decline sites (Maple Decline Plots 35 and 37, respectively) suggests that these stands are of similar physiological status. The analysis of growth ring widths from increment cores will be completed later in 1998 and will provide a direct measure of vigour in these stands. These measurements will be used to evaluate and refine SER as a means of rating stand condition.

Implications

- The lack of difference in SER between the moderate and severe decline site matches the pigment analysis described previously. The relatively high SER obtained at the low decline site when temperatures were cold demonstrates the importance of taking measurements at comparable temperatures.

Leaf Area Index (LAI)

Throughout the literature, ***leaf area index (LAI)*** is identified as an important quantity controlling physical and biological processes of plant canopies (Chen et al. 1992). For example, LAI has been shown to be significantly correlated with nutrient and water availability in conifer and hardwood forests in Wisconsin (Fassnacht and Gower 1997). Estimates of LAI were obtained on all study sites to provide another measure of forest structure, which may prove valuable in relating spectral response to forest condition. Improved estimations of LAI also complements existing modeling systems such, as the Regional HydroEcological Simulation System, RHESSys (Band 1993a, b) that are used to simulate productivity and hydrology at a range of spatial scales. Such a modeling system may provide another means of deriving inferences of spectral response related to forest condition.

Estimation of LAI from remote sensing imagery has received considerable attention. In fact, Running et al. (1986) commented that LAI is "the single variable which may be derived from remote platforms that is of greatest importance for quantifying energy and mass exchange by plant canopies over landscapes". However, the measurement of LAI using remote sensing on open canopies is currently unresolved because of uncertainties around how to account for the effects of understory on canopy reflectance. Instead of relying on airborne or satellite platforms, the Plant Canopy Analyzer (PCA) (LAI-2000, Li-Cor, Inc. Lincoln, Nebraska) was used to provide a more direct measurement of LAI.

The PCA is a ground-based system that detects the penetrating diffuse light at five angles simultaneously, and hence measures the canopy gap fraction that is inverted to estimate LAI (Chen and Cihlar 1995). For conifers, recent studies by Chen et al. (1997) have shown the need to assess canopy "clumping" and shoot/needle ratios to optically derive LAI. This was not accounted for in the 5 pine study sites since a specialized instrument to estimate "clumping" was not available. For LAI assessments, 2 PCA instruments were used; one within the stand and another to acquire reference measurements in the open. The in-stand and reference measurements were merged together later using the PCA program c2000.exe to calculate the effective LAI. Given the limited number of pine plots (5) sampled, results will be restricted to the 12 maple sites that were assessed.

Results

- Significant differences in the effective LAI were present between the levels of productivity and decline. However, these differences were weakly correlated, with a coefficient of determination (r^2) of 0.64 and 0.58 for the productivity and decline sites, respectively.

- The level of variability in LAI (as measured by the coefficient of variability) was strongly correlated to levels of productivity and decline (r^2 =0.94 in both instances). Similarly, the level of variability tended to increase with lower values of LAI.

- The overall mean LAI for maple sites (n=12) was 4.11 ± 0.19 s.e. (max. 5.17 and min. 2.85), with the average LAI on the maple decline sites and Growth and Yield plots being 4.13 ± 0.23 s.e. and 4.10 ± 0.329 s.e., respectively.

Implications

- Understanding site differences in terms of LAI and associated levels of variability may provide greater insight into possible differences in spectral response. For example, severe decline sites and those characterized by low productivity have more variable LAI. The level of variability may, therefore, be an important aspect in discerning changes in forest condition. Applying this understanding to spectral response patterns may prove valuable in relating structural features to actual physiological function.

Canopy structure

Canopy structure is a central consideration in any description of plant-environment interactions. It is strongly coupled to the interception, scattering and emission of radiation (Welles 1990). In fact, canopy cover is considered the most important variable in determining canopy reflectance (Treitz and Howarth 1997). Any perceived differences in canopy cover and accompanying spectral reflectance would collectively provide strong indicators of forest condition; hence, meeting a critical project objective. In addition, estimates of crown transparency will support objectives identified by the Canadian Council of Forest Ministers (1995) to assess forest health.

To estimate canopy cover, two techniques were applied: i) a 24-grid ***spherical densiometer*** (Lemmon 1956), and ii) ***hemispherical or fisheye photography*** (Frazer et. al., 1997). The densiometer technique involves ocular estimates of canopy opening whereas, hemispherical photography applies an image analysis approach. More specifically, hemispherical photographs were written directly to compact disc, with percent visible sky (also referred to as diffuse non-interceptance) measured by a pre-determined intensity threshold using SigmaScan Pro (Jandel Scientific, San Rafael, CA) software. As in LAI estimation, all 17 field plots had measurements taken during full leaf expansion in August and early September. However,results will be confined to the 12 maple sites sampled.

Spherical Densiometer Results:

- Although significant structural differences were present across the range of site productivity, these findings were not correlated to productivity rankings. No significant differences were apparent among maple decline sites.

- When comparisons of average canopy opening were made with actual productivity measures (e.g. total height, diameter, and density), findings were significant (Table 7).

- Coefficient of variability for canopy openings tended to increase with LAI variability (r^2=0.69 and 0.78 in the productivity sites and maple decline sites, respectively)—as expected since the LAI measures used are based on gap fractions.

Table 7. *Summary of Pearson Product correlation coefficients between average canopy openings (%) and site productivity measures[1] (total height, diameter at breast height (DBH) and density) in 6 hard maple Growth & Yield plots. Probability values shown in parenthesis.*

	Total Height (m)	DBH (cm)	Merchantable Density	Regeneration (saplings/ha)
Average Canopy Opening[2] (%)	-0.9511 (-0.0035)	-0.7345 (0.0964)	-0.8728 (0.0232)	-0.7909 (0.0610)

Note: Correlations (p£0.05) were not significant for basal area or volume.

[1]Average productivity measures for primary working group in Growth and Yield permanent sample plots measured between 1992-94.
[2]Ocular estimates of overstory density from a 24-grid spherical densimeter measured at a height of 1.3 m (n=16).

- Overall mean canopy opening (%) for the maple sites (n=12) was 8.74 ± 0.911 s.e. (max. 14.05 and min. 4.53), with an average opening on the maple decline plots and Growth and Yield sites of 7.49 ± 0.25 s.e. and 9.98 ± 1.723 s.e., respectively.

Hemispherical Photography Results:

- Significant differences in percent canopy opening were present across the range of productivity sites and maple decline plots, but these findings were not significantly correlated to productivity or decline rankings.

- The measure of percent canopy opening for the Growth and Yield plots was significantly correlated to effective LAI (r^2=-0.79) and diffuse non-interceptance (r^2=0.89) parameters derived by the Li-Cor Plant Canopy Analyzer. However, the percent canopy opening on maple decline plots was only significantly correlated (r^2=-0.82) to the measure of diffuse non-interceptance.

- Unlike average canopy opening estimates derived by the spherical densiometer, significant correlation coefficients to actual productivity measures (e.g. total height, diameter, and density) were not evident for hemispherical photos.

- Overall mean canopy opening (%) for the maple sites (n=12) was 12.3 ± 0.11 s.e. (max. 23.05 and min. 7.53), with an average opening on the maple decline plots and Growth and Yield sites of 11.7 ± 0.141 s.e. and 13.0 ± 0.155 s.e., respectively.

Implications:

- The densiometer and hemispherical photography both provide estimates of forest canopy openings. However, the field of view is quite different between these two techniques (30^0 versus 180^0, respectively). Based on these design characteristics, the fraction of sky visible to the sensor differs, which explains the lack of correlation between the two techniques.

- Although the densiometer is technically simple and rapid, hemispherical photography provides a permanent record of canopy architecture and foliation. Changes in forest structural condition can be monitored over time. In addition, a digital image provides an objective estimate of forest conditions unlike the subjective densiometer measurements.

- Hemispherical photography may provide a relatively in-expensive alternative to the Li-Cor Plant Canopy Analyzer given the significant findings between hemispherical photography estimates of canopy opening and parameters, such as LAI and diffuse non-interceptance (a measure of canopy light absorption). These findings are consistent with the efforts of others (e.g., Frazer et al. 1997).

- Increased knowledge of canopy structure may prove valuable in relating spectral response patterns to forest conditions. For example, Table 7 illustrates the correlation between canopy structure and productivity, which may also relate to differences in spectral response. Particular attention in relating spectral and spatial attributes will, therefore, be made in developing an FCR system.

Airborne Hyperspectral Imagery

A hyperspectral airborne system, such as the ***Compact Airborne Spectrographic Imager (CASI)*** acquires high spatial and spectral resolution data. The CASI sensor is a push-broom imager that collects data in the visible and near-infrared wavelength regions (400-950 nm). It provides spectral dispersion of incoming optical signals over the spectral range, with a spatial resolution of 512 pixels across the 35° sensor field-of-view. The spatial resolution depends on aircraft altitude, but usually ranges from 0.5 to 10 m. The sensor spectral resolution is nominally 2.5 nm, with 288 spectral channels at 1.8 nm intervals (Anger et al. 1994). The sensor operates in a number of user-selectable modes, which sample the CCD in up to 288 spectral channels and 512 spatial positions or pixels. In *Spatial Mode*, imagery is obtained at full spatial resolution of 512 spatial pixels across the 35° swath. Channel wavelengths and bandwidths are operator programmable for up to 19 bands. In *Spectral Mode*, imagery is generated at a full spectral resolution of 288 channels for normally up to 39 look directions across the 35° swath.

Flight details

Data acquisition missions for the Bioindicators Project were:

1. ***Mapping Mission***. The CASI configuration for the study sites was Spatial Mode, Medium Resolution Imaging Spectrometer (i.e., a MERIS satellite sensor) bandset, with 512 cross-track pixels with 17-channel spectral resolution and 16-unsigned bits radiometric resolution. The altitude above ground level (AGL) was around 1800 m (depending on site elevation) with an integration time of 27 ms, giving a spatial resolution of 2 x 2 m. The sensor pitch was 0° (nadir) for the entire mission.

2. ***Bidirectional Reflectance Mission***. The CASI configuration for the study sites was the Spectral Mode Espec405 bandset, with 72 channels spectral resolution and 16-unsigned bits radiometric resolution. The AGL was about 2800 m (depending on the site elevation) with an integration time of 72 ms, giving a spatial resolution of 3 x 5 m. Sensor pitch was 0° (nadir) and 30° at each study site to provide a multi-angle study.

3. ***Transect Mission.*** A transect was flown across the Algoma Region (from Bright Lake to Wakomata Lake and westward to Turkey Lakes) using the Spectral Mode Espec 405 bandset with a configuration similar to that used for the Bidirectional Reflectance Mission.

In summary, 3 campaigns were undertaken in 1997 (i/ late July-early August, ii/ early-mid September and iii/ mid October) to acquire hyperspectral information for the project study sites using the CASI. In addition to obtaining data for each study site, a transect (50-100 km) was flown across the Algoma Region. A complete summary of imagery and flight details is available on the World Wide Web at: **http://terra.phys.yorku.ca/~bio**

Current Research Efforts

The degree to which field-derived spectral indices can be observed in the above-canopy reflectance imagery will need careful examination. As outlined by Zarco (1998), several physiological indices and derivative analysis indices extracted from spectral reflectance data will be tested in order to correlate with *in-situ* field measurements and laboratory studies. Examples of optical indices obtained using CASI imagery are shown in Figure 4.

An interpretation of spectral patterns shown in Figure 4 is not possible until further research is conducted. In particular, scientists at CRESTech and York University will be evaluating the potentially confounding effects

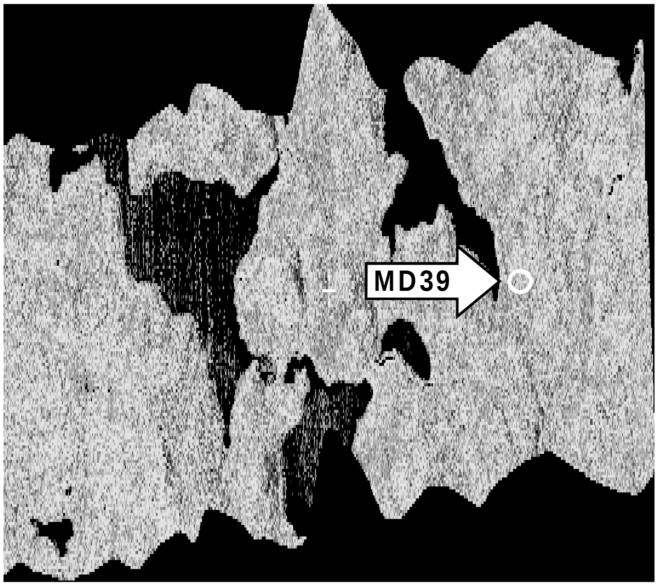
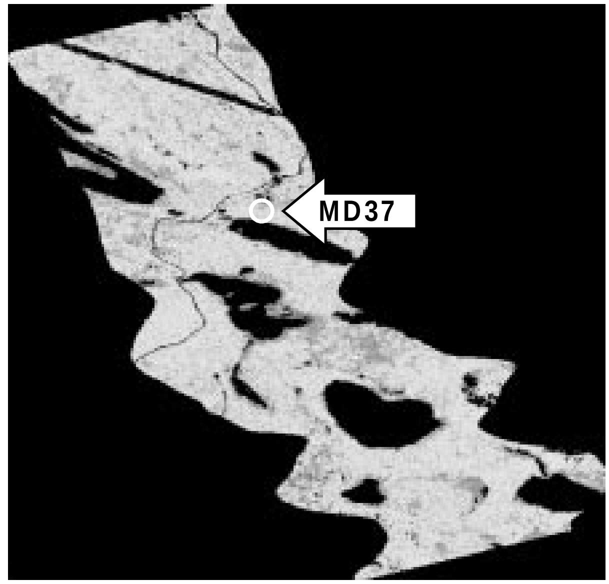


Image A: NDVI for Maple Decline Site 39 and the surrounding area



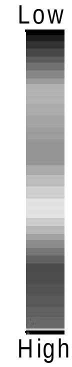


Image B: NDVI for Maple Decline Site 37 and the surrounding area

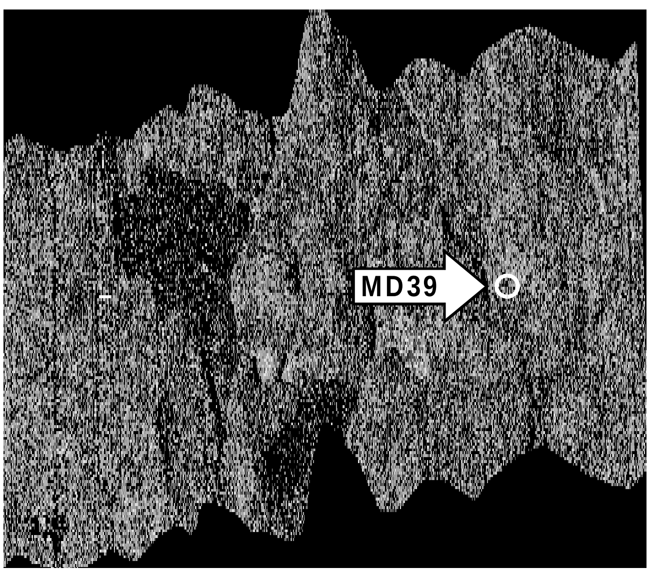
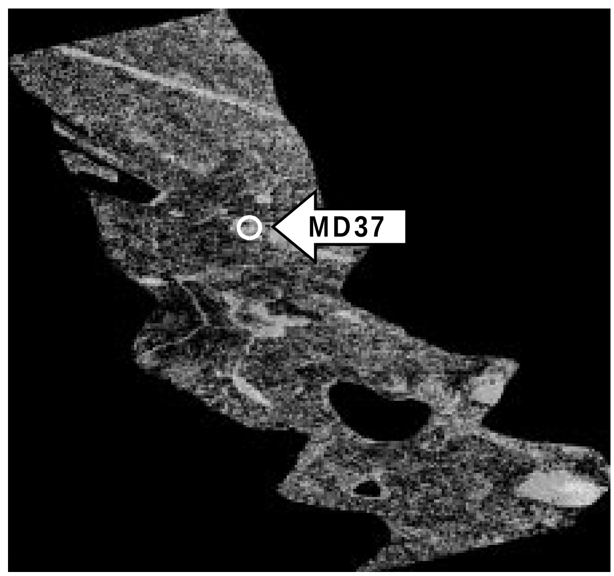


Image C: PRI for Maple Decline Site 39 and the surrounding area



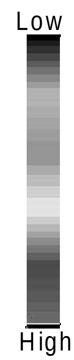


Image D: PRI for Maple Decline Site 37 and the surrounding area

Figure 4. Examples of spectral indices, which include the Normalized Difference Vegetation Index (NDVI (Rouse et al. 1974)) and the Photochemical Reflectance Index (PRI (Gamon et al. 1997)), currently being investigated. Imagery obtained July 30, 1997 using the Compact Airborne Spectrographic Imager (spectral mode Espec405 bandset, with 72 spectral channels and a 3 x 5 m resolution) for Maple Decline Sites 39 and 37 (rated as low and severe decline, respectively (McLaughlin and Kinch 1997)).

of bi-directional reflectance and understory reflectance. Subsequent research efforts will focus on developing remote sensing methods that permit operational use of spectral indices in airborne monitoring (50-100 km transect processing) and for satellite sensors. The vigourous testing of candidate bioindicators, and the corresponding spectral indices, for sensitivity to the effects of species, age, season, canopy closure and structural characteristics will also be investigated. Results of these research activities will be reported over the next 2 years.

Cooperative Research/ Partnerships

An overview of existing and proposed activities using remote sensing for forest health applications was the basis of a formal review by Dendron Resource Surveys (1998). Insight gained from this review was beneficial in devising a project strategy that would complement existing efforts and identify areas requiring research (Mohammed et al. 1997). Furthermore, the report identified expertise within Ontario that ultimately led to the formation of a collaborative research partnership between OFRI's physiology team and a group of remote sensing specialists at CRESTech. This collaboration has provided considerable benefits, including:

- the successful efforts of John Miller (CRESTech) to secure funding to develop spectral indices using above-canopy hyperspectral imagery; a critical objective in applying remote sensing to assess forest condition;
- successful project proposal submitted to NASA by John Miller (CRESTech) for analyzing airborne imagery to separate overstory and understory in boreal species using datasets acquired under the Boreal Ecosystem-Atmosphere Study (BOREAS) - a large-scale, international initiative, with direct relevance to this project and;
- participation in strategic planning, with the Canadian Space Agency, to develop hyperspectral space-borne technologies.

Supporting our collaborative efforts is a ***Technical Advisory Team and various cooperators*** whose expertise spans research, policy, and operations. The benefits of this broad-based support is demonstrated in the following.

- Dr. John Gamon, Research Scientist, California State University has a common interest in developing physiologically relevant indices, which has led to discussions of a graduate student conducting studies at OFRI. In addition, Dr. Gamon was awarded a BOREAS follow-on project by NASA in collaboration with John Miller (CRESTech) to integrate several remote sensing data sets and develop promising indices of forest condition that are relevant to our efforts in Ontario.
- Dr. Joan Luther, a remote sensing scientist with the Canadian Forest Service (CFS) in Newfoundland, will collaborate in a remote sensing study focusing on jack pine budworm in E. B. Eddy's holdings in Central Ontario. Mr. Brian Nicks, E. B. Eddy, will support this research by identifying suitable study sites and supplying jack pine budworm egg survey data. The results of this investigation will provide baseline data to develop an FCR system in jack pine and also, offer a means to assess the influence of forest management practices on jack pine budworm susceptibility.
- A project proposal by the Ecological Land Classification Program (OMNR) and the Bioindicators Project Team to address an expressed need by Ontario Parks to develop a monitoring and assessment system in parks.

Next Steps

To advance the project in coming years, the Project Strategy (Mohammed et al. 1997) outlines a schedule that includes the need for:

- testing physiologically based indicators; including those using remote sensing
- assessing indicators for healthy and stressed stands
- analyzing sampling approaches and spatial resolution
- acquiring ancillary data about site conditions, and
- incorporating certain emerging technologies (e.g. active systems) in remote sensing.

As previously mentioned, collaborative efforts and scientific advancements by others will further support these needs. It is also recognized that development of a forest condition rating system requires a continued effort in acquiring the baseline information necessary to evaluate natural and induced variation in selected indices over time. Implicit in these efforts is the need to transfer results to the science community, forest managers, and policy advisors.

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