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Chlorophyll Fluorescence Effects on Vegetation Apparent Reflectance: I. Leaf-Level Measurements and Model Simulation

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Results from a series of laboratory measurements of spectral reflectance and transmittance of individual leaves and from a modeling study are presented which demonstrate that effects of natural chlorophyll fluorescence (CF) are observable in the red edge spectral region. Measurements have been made with a Li-Cor Model 1800 integrating sphere apparatus coupled to an Ocean Optics Model ST1000 fiber spectrometer in which the same leaves are illuminated alternately with and without fluorescence-exciting radiation in order to separate the fluorescence emission component from the reflectance spectrum. The resulting difference spectrum is shown experimentally to be consistent with a fluorescence signature imposed on the inherent leaf reflectance signature. A study of the diurnal change in leaf reflectance spectra, combined with fluorescence measurements with the PAM-2000 Fluorometer, show that the difference spectra are consistent with observed diurnal changes in steady-state fluorescence. In addition, the time decay in the difference signature from repetitive leaf spectral reflectance measurements is seen to be consistent with the time decay of the leaf fluorescence signal (Kautsky effect) of dark-adapted leaves. The expected effects of chlorophyll fluorescence emission on the apparent spectral reflectance from a single leaf are also simulated theoretically using the doubling radiative transfer method. These modeling results demonstrate that the laboratory observations of a difference spectrum with broad peak at about 750 nm and a much smaller peak near 690 nm are in agreement with theory. Model simulation shows that chlorophyll pigment and fluorescence each affect indices that are being used in optical remote sensing to characterize pigment levels and stress in vegetation canopies. Implications for high spectral resolution remote sensing of forest canopies are presented in a companion paper.

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INTRODUCTION

Experimental evidence of a solar-induced fluorescence signal superimposed on leaf reflectance signatures remains speculative. As a result of laboratory studies with a reflection–absorption–fluorescence spectrometer (VIRAF-spectrometer) (Buschmann and Lichtenthaler, 1988) concluded only that the detection of the effects of a fluorescence signal in the red edge reflective region (680–800 nm) cannot be excluded. Subsequently additional suggestions of the effect of fluorescence in apparent reflectance have been reported (Peñuelas et al., 1998; Gamon et al., 1997; Peñuelas et al., 1997; 1995; Gitelson et al., 1998; Gamon and Surfus, 1999). However, to the best of our knowledge, a quantitative demonstration of the effect of the fluorescence signal on the apparent reflectance spectra of leaves has remained unproven to date. The challenge has been to separate the effects of scattering and absorption within the leaf from the self-emission fluorescence processes.

The research reported in this article was motivated by a field experiment involving data acquisition with the Compact Airborne Spectrographic Imager (CASI) over 12 test sites of *Acer saccharaum* M. (sugar maple) in which

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