Remote sensing of canopy chemistry

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One of the major uncertainties in predicting climate change comes from a full accounting of carbon-cycle feedbacks, which roughly double physical feedbacks (1, 2). Most of this uncertainty is a result of the many pathways and time scales at which ecosystems interact with the climate system and how these will respond to change (3). The relationship between leaf nitrogen and the carbon cycle is key to many ecosystem processes because photosynthesis provides the energy and carbon-cycle molecules for growth and reproduction (4–7) and decomposition for nutrient cycling (7, 8). Ecologists have long recognized that nitrogen was the most limited nutrient for plant growth (9, 10). Quantifying changes in canopy nitrogen content provides direct information about ecosystem functioning and a method to detect and monitor changes in response to climate forcing (9, 10); thus, it has been a long-term objective for airborne and spaceborne imaging spectroscopy (11–13). Several papers have reported direct detection of canopy nitrogen from airborne imaging spectrometers (14–17). Ollinger (18) argues that selective pressure on plant competition for light, water, and nutrients should result in suites of biochemical and structural traits that integrate their functional strategies. Thus, structural traits affecting light scattering "over scales ranging from cells to canopies" (18) will be convergent with their biochemical traits. Knyazikhin et al. (19) explicitly test whether assumptions that canopy structure can be ignored in quantifying biochemical composition with a detailed analysis of the physical processes of photon scattering from leaves and plant canopies. Although there is recognition of the importance of multiple scattering (20), particularly in the near infrared, where plant compounds do not display strong absorption features (21–23), it has not been possible to quantify it at the canopy scale. The report by Knyazikhin et al. (19) is unique in being a full attempt at modeling spectral absorptions and scattering at both leaf and canopy scales (Fig. 1).

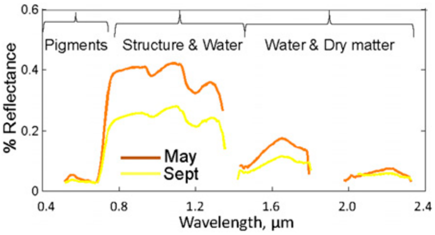

Fig. 1. AVIRIS spectra of mixed live-oak forest showing seasonal change. Wavelength region where significant plant absorptions occur are indicated. Multiple scattering dominates the near-infrared region between 0.7 and 1.5 μm.

Given understanding of ecophysiological controls on photosynthesis that demonstrate the significance of nitrogen on controlling productivity, it is not surprising that an early goal for imaging spectroscopy (24) recognized the importance of quantifying declining photosynthetic capacity. Identification of different plant materials, especially related to photosynthetic function, was an objective of airborne imaging spectrometry since its beginnings (11, 25, 26). Early laboratory studies on estimating nitrogen content with near infrared spectroscopy provided evidence that nitrogen could be quantified through spectroscopy, but measurements were restricted to ground dry foliage (27–29). Direct detection of canopy nitrogen from remote sensing observations have been reported by others since (12, 16, 29), but results have been questioned because spectral changes generally also corresponded to changes in land cover between conifer and broadleaf forests.

The first National Aeronautics and Space Administration (NASA) Airborne Imaging Spectrometer (AIS-1), flown from 1983 to 1986, included only the 0.9- to 2.1-μm reflected infrared spectrum and the AIS-2 measured from 0.8 to 2.4 μm (11), thus the emphasis for detecting chemistry shifted from pigments to canopy water and nitrogen because their absorption features occur in the reflected infrared. Lignin content was mapped from AIS-1 data over Blackhawk Island, WI, which allowed estimates of soil nitrogen availability by correlating nitrogen mineralization with foliage lignin content (12). These results were corroborated (28, 29), although different studies identified different spectral bands as significant in multiple linear regression predictions. At this time, NASA began to address the full costs of the Earth Observing System satellite program and the High Spectral Resolution Imaging Spectrometer (HIRIS), one of the original NASA facility instruments for the Terra platform, was being considered for deselection because of its cost and uncertainty of its scientific benefits to the climate mission. However, there were concerns that high atmospheric CO_2 concentrations could lead to increased C:N ratios and associated declining productivity because of higher lignin content in plant residues (30, 31). This concern about future soil nitrogen availability provided a unique climate role that only HIRIS, with its contiguous narrow spectral bands across the visible and shortwave infrared region, was capable of detecting. NASA established the Accelerated Canopy Chemistry Program (ACCP) in 1991–1992 to determine whether there was a sound theoretical and empirical basis for estimating nitrogen and lignin concentrations in ecosystem canopies from remote sensing data (13). Although NASA ultimately deselected HIRIS, this program led to numerous empirical studies over the past two decades (32) to identify nitrogen and lignin from airborne Advanced Visible Infrared Imaging Spectrometer (AVIRIS) data (e.g., refs. 13, 33, and 34). Despite concerns, the significance of structural contributions to measurements of lignin and nitrogen, predictions were never explicitly tested before Knyazikhin et al. (19).

Only a few leaf and canopy radiative transfer models have been developed. Only the LIBERTY (Leaf Incorporating Biochemistry Exhibiting Reflectance and Transmittance Yields) radiative transfer model, developed to estimate the optical properties of both dried and fresh conifer needles (35), specifically includes nitrogen, lignin, and cellulose. LEAFMOD, the Ganapol et al. (36) model, addressed internal leaf scattering, which they recognized must be fully modeled to define additional biochemical parameters. However, both LIBERTY and LEAFMOD have had limited distribution compared with the PROSPECT leaf optical properties model (37). After the ACCP program, nitrogen and lignin were introduced into the PROSPECT model (38, 39), but were later deleted for the more general "dry matter" because results were inconsistent (40, 41). More recently (42) the combined PROSPECT-SAIL (PROSAIL) leaf and canopy radiative transfer models have been used to predict canopy nitrogen by assuming a constant stoichiometry to chlorophyll. Bousquet et al. (43) modified PROSPECT to include the directional effects of leaf specular and diffuse reflectance, representing a start to address

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the 3D structure of actual canopies. Until the paper by Knyazikhin et al. (19), no one has made a thorough physically based analysis of the scattering effects of leaves and canopy structure. Such modeling efforts, combined with more rigorous measurements of the 3D structure of actual canopies, will test these models using small-footprint full-waveform light detection and ranging, and provide a path forward to achieve rigorous estimates of canopy chemistry. As Knyazikhin et al. (19) make clear, quantifying the retrieval of any biochemical information from remote sensing data is subject to leaf and canopy scattering processes, and these must be accounted for to achieve correct estimates. The paper by Knyazikhin et al. (19) quantifies the physical interactions, thus going a long way toward eventually solving these problems.

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