HIGH RESOLUTION SPECTROMETRY OF LEAF AND CANOPY CHEMISTRY FOR BIOGEOCHEMICAL CYCLING

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ABSTRACT

High-resolution laboratory spectrophotometer and Airborne Imaging Spectrometer (AIS) data were used to analyze forest leaf and canopy chemistry. Fundamental stretching frequencies of organic bonds in the visible, near infrared and short-wave infrared are indicative of concentrations and total content of nitrogen, phosphorous, starch and sugar. Laboratory spectrophotometer measurements showed very strong negative correlations with nitrogen (measured using wet chemistry) in the visible wavelengths. Strong correlations with green wet canopy weight in the atmospheric water absorption windows were observed in the AIS data. A fairly strong negative correlation between the AIS data at 1500 nm and total nitrogen and nitrogen concentration was evident. This relationship corresponds very closely to protein absorption features near 1500 nm.

INTRODUCTION

Remote sensing data are being used to study and to model processes in the biogeochemical cycling of carbon, nitrogen, and phosphorus for forest ecosystems. Based on recent insights (Melillo and Gosz, 1983) regarding nutrient availability and its interaction with the biochemical content of the canopy, a process level model (Fownes and Aber, 1985, this volume) is being developed. This model predicts productivity, gas exchange, nutrient transformations and fluxes using information about climate and the biochemical content of the canopy. The three canopy variables under investigation using remote sensing are leaf area index (LAI), foliar biomass, and biochemical composition. This paper describes preliminary analysis using a laboratory spectrophotometer and the Airborne Imaging Spectrometer to determine leaf and canopy biochemical composition.

BACKGROUND

Various organic compounds present in foliage absorb infrared (IR) radiation in a manner analogous to the mineralogical features used in geology. The absorption features correspond to the fundamental stretching frequencies of organic bonds. The harmonics and overtones of these fundamentals are often found in the visible, near infrared and short — wave infrared. Unlike feature identification used for mineralogical discrimination, the same organic compounds are generally always present in all vegetation types, but in different concentrations and total contents. Thus, a primary goal of infrared spectroscopy for plants should be quantification of these contents rather than discrimination of specific features. These organic compounds are of equal importance to nutrient cycling because they are composed of the key nutrients (carbon, nitrogen, phosphorous, etc.) that are required for plant growth.

Nitrogen is bound up in leaves primarily in various proteins, enzymes, amino acids, cholorophylls, alkaloids, and cyanogenic compounds. The absorption features for the proteins and chlorophylls are shown in Figures 1-a and 1-b, respectively. Nitrogen concentration usually varies between 0.5 to 3 percent by weight. Phosphorus content is typically lower than nitrogen (less than one percent) and is bound up in phospholipids, ATP, and other organic molecules. Carbon is ubiquitous in organic material; the forms most important to nutrient cycling are structural carbon (lignin and cellulose) and mobile carbon (starches (Figure 1-d) and sugars). Important features for lignin occur at 1148 and 1685 nm, and for cellulose at 2100 nm. Water is abundant in leaves and its spectrum is shown in Figure 1-c. The role of other constituents of leaves (oils, carotenoids, cuticular waxes) may not be as significant for nutrient cycling, but the fact that they also absorb IR radiation and may not co-vary with the other compounds, means that they contribute to the overall - IR signature of the leaf and introduce variation in the reflected radiation.

Together with the multiple scattering properties of leaf structural interfaces, the biochemical constituents of leaves determine their infrared absorption characteristics in proportion to their concentration. Thus, at any one wavelength, the reflected radiation will be a composite dominated by the strength of the absorption feature of each compound so that multiple wavelengths are required to estimate any one constituent while accounting for the interference of other compounds. A goal of this research is to determine these predictive wavelength regions.
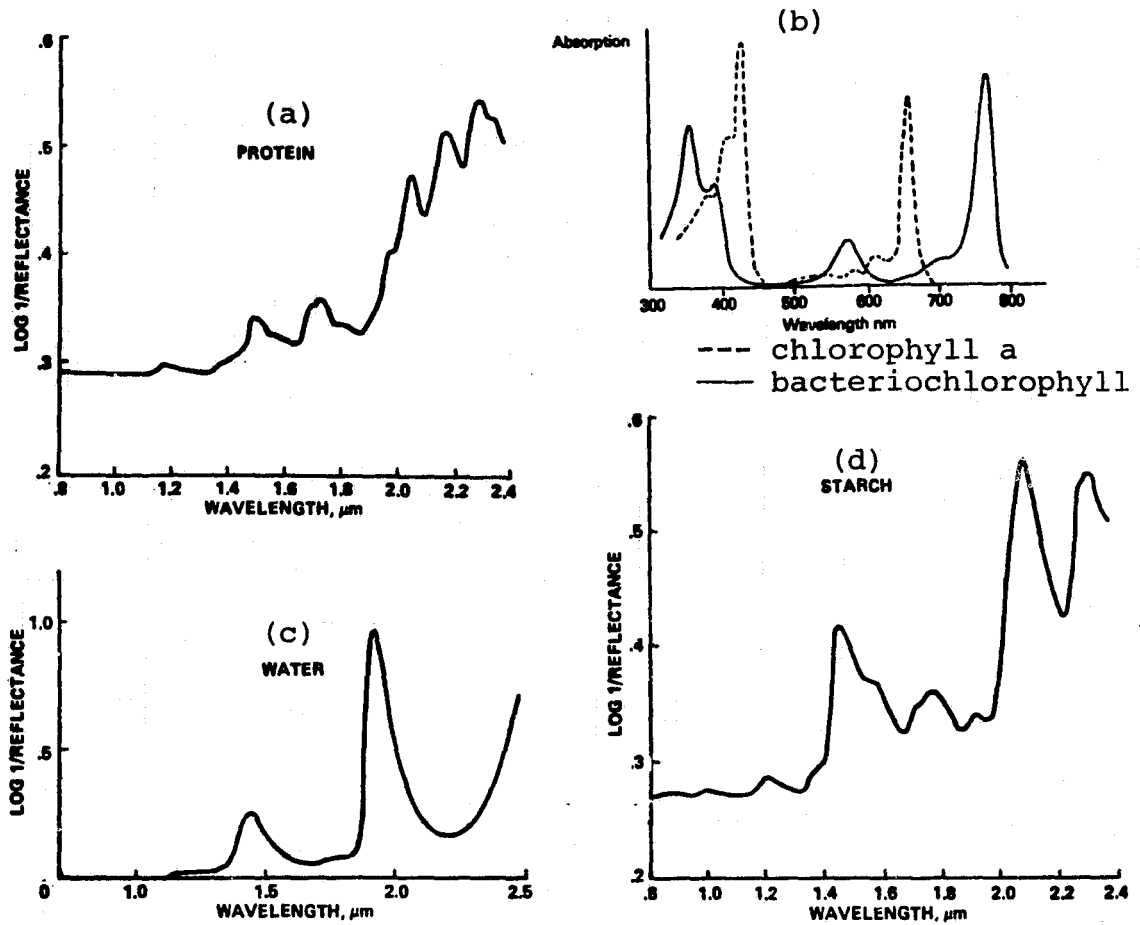
(a)
PROTEIN

(b)
Absorption

--- chlorophyll a
—— bacteriochlorophyll

(c)
WATER

(d)
STARCH

Figure 1. Absorption spectra for four organic
compounds in the visible and shortwave
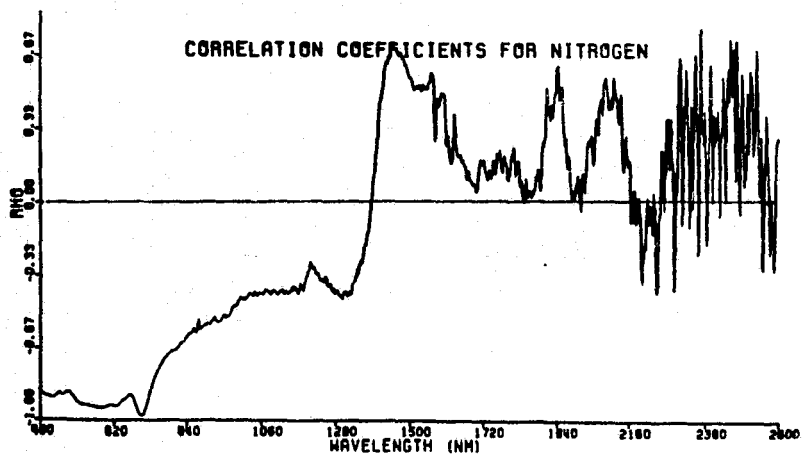radiation regions

CORRELATION COEFFICIENTS FOR NITROGEN

Figure 2. Correlogram for percent   nitrogen
versus total hemispherical reflectance
for ground needles from seedlings
of Tsuga mertensiana measured in a
laboratory spectrophotometer
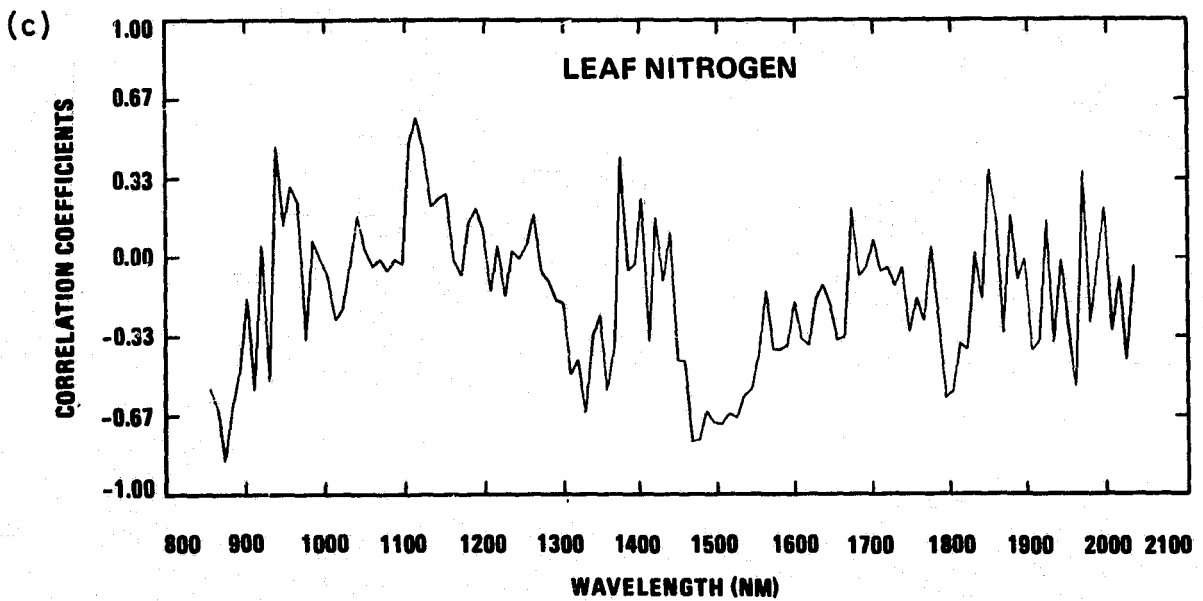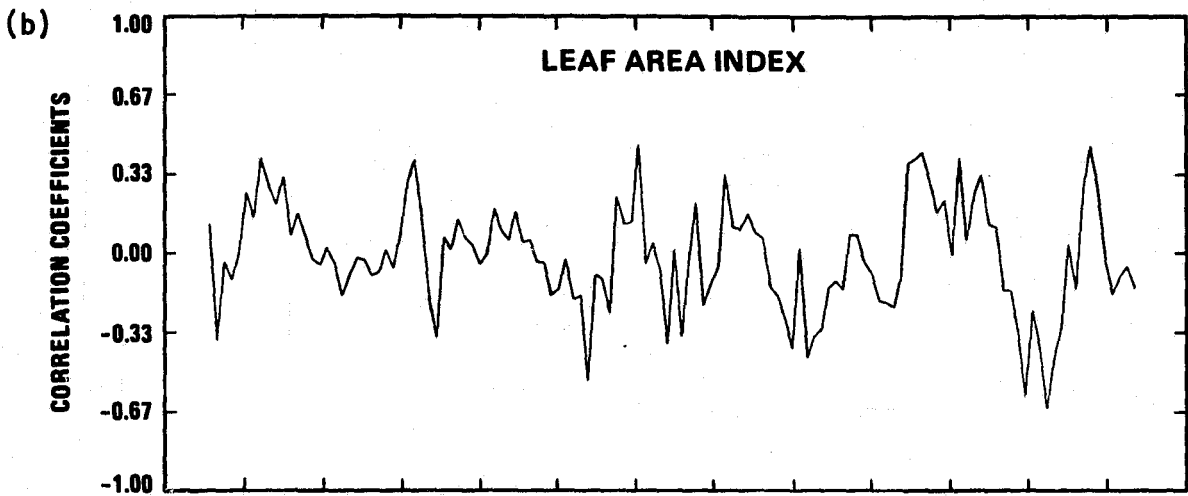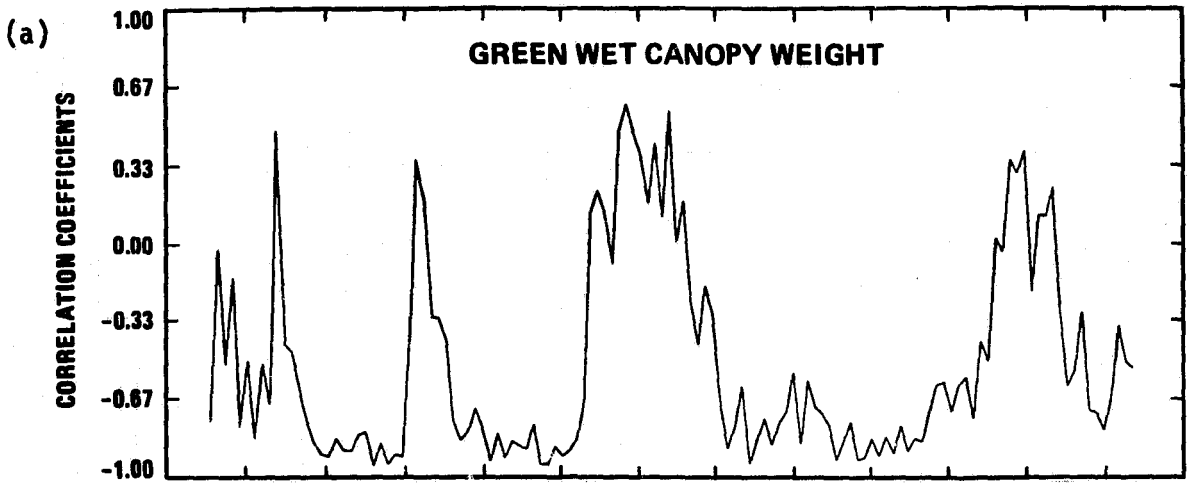
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LABORATORY TECHNIQUES AND RESULTS

Our research is attempting to understand spectra of forest leaves and canopies as we proceed from laboratory to field to airborne spectroscopic techniques. Presented here are laboratory analyses of seedlings of Mountain hemlock (Tsuga mertensiana) grown in a phytotron under several treatments to vary the canopy chemistry. The treatments were: a control; fertilized with N, P, S; sugar addition; and fertilized and shaded. These seedlings were part of research by Dr. Matson who provided freeze-dried, ground leaf samples from each treatment for spectral analysis. These samples were analyzed in a wet chemical lab to determine the nitrogen, phosphorus, starch, and sugar content to correlate with the spectra. The ten samples were spectrally measured in a Perkin-Elmer spectrophotometer for percent reflectance between 400 and 2600 nm.
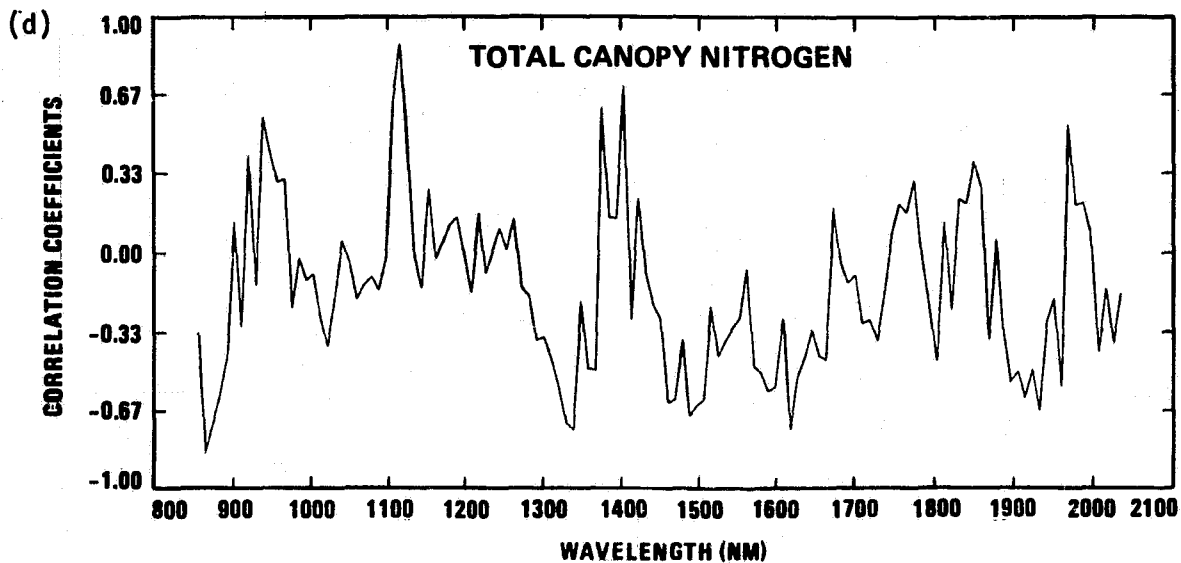
Correlation coefficients were calculated for each wavelength against the chemical analyses and are displayed as a correlogram. An example for percent nitrogen is shown in Figure 2. As expected, strong inverse correlations exist in the visible region due to the strong absorption effects of chlorophyll and associated proteins. Positive correlations are due most likely to other compounds which vary inversely with nitrogen (starch in this case) which corresponds to the correlation at about 2100 nm. Another absorption feature relating to protein begins to appear at about 2180 nm, but increasing instrument noise, small sample size, and small absolute differences in reflectance at these wavelengths may be obscuring this information.

We are in the process of investigating the use of smoothing fuctions and derivatives to identify and measure concentrations at specific spectral regions which may overcome some of these difficulties. The peak at about 1450 to 1500 nm is probably due to the presence of water reabsorbed by the samples during handling which masks the protein feature, thereby modifying the correlogram near 1500 nm and above. Similar correlograms were calculated (not shown) for phosphorous, starch and sugar, and indicate an inverse relationship between starch and nitrogen. The presence of a number of positive and negative peaks in the correlograms can be used to investigate multiple linear regressions for each constituent. This work is in progress and the present interpretations are still tentative due to the early stage of our investigations.

AIRBORNE IMAGING SPECTROMETER DATA ANALYSIS

The Airborne Imaging Spectrometer onboard a C-130 aircraft acquired imagery over Blackhawk Island, Wisconsin on September 9, 1984. The AIS data were acquired in grating positions 0-3 (vegetation mode), covering wavelengths from

(a) GREEN WET CANOPY WEIGHT

(b) LEAF AREA INDEX

(c) LEAF NITROGEN

CORRELATION COEFFICIENTS

WAVELENGTH (NM)

(d)

TOTAL CANOPY NITROGEN

Figures 3(a) to 3(d).   Correlograms for green wet canopy weight
(tons/hectare), leaf area index (one-sided),
nitrogen concentration (mg/cm^2) and total
nitrogen (kg/hectare) of the Blackhawk
Island plots measured by the Airborne
Imaging Spectrometer.

855 to 2036 nanometers. The spatial resolution of these data was approximately ten meters. No preprocessing algorithms were applied to the AIS data. There are four atmospheric water absorption regions within the vegetation grating position. Minor ones are centered at .94 nm and 1.13 nm, with major ones centered at 1.4 nm and 1.9 nm. The AIS data are of fairly good quality, with minor vertical striping in some bands.

Analysis of the AIS data was performed on a VAX 11-780 using IDIMS image processing software and software modified and developed specifically for the analysis of AIS data. The location of the six Deciduous Forest sites on Blackhawk Island (Fownes and Aber, 1985, this volume) were delineated on the AIS digital imagery using an interactive display. A two-by-two pixel region for each site was extracted and the mean and standard deviation for the 128 channels were calculated and plotted. A residual image was generated by defining a three-pixel wide transect along a fertility gradient across Blackhawk Island. The mean reflectance for each channel along the gradient was calculated and subtracted from the raw reflectance for the Blackhawk Island AIS scene. The residual reflectance was plotted for each of the six sites. Locations of low reflectance displayed negative residuals and areas of high reflectance had positive residuals. The residual plots allowed for improved discrimination of the six sites. A visual assessment of the fertility gradient was performed using the residual image.

The correlogram program calculated the correlation coefficients for each of the measured canopy parameters of the six sites at each independent AIS wavelength. The canopy parameters analyzed were green wet canopy weight (tons/hectare), total nitrogen (kg/hectare), nitrogen concentraton (mg/cm), and leaf area index (one-sided). The correlograms are presented in Figures 3a-3d.

AIS RESULTS AND DISCUSSION

Very strong correlation was observed between green wet canopy weight and AIS data at wavelengths other than the atmospheric absorption bands. Correlations exceeded .85 for many of these wavelengths, indicating the sensitivity of the AIS data to total mass (water and foliage) of the canopy. As expected, these relationships did not exist in the atmospheric water absorption bands. The correlation occurs across a broad range of wavelengths indicating relatively slowly varying absorption.

There were no wavelengths that displayed high correlations to leaf area index. This was not surprising because wavelengths on the AIS are not the same as those used for leaf area index estimation. Leaf area index estimations generally make use of ratios or transforms of

red (.63-.69μm) and near infrared (.76-.90μm) portions of the electromagnetic spectrum. The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) will provide spectral information in these shorter wave gths and should be of significant value for leaf area index determinations when these data become available and are analyzed as ratios.

Analysis of the total nitrogen and nitrogen concentration correlograms reveals that there are strong negative correlations near 1500 nm, corresponding to a strong protein absorption feature at that wavelength. This result is very encouraging and shows the promise of a high spectral resolution imaging spectrometer. Another important protein absorption feature exists at 2180 nm; unfortunately, this wavelength is out of the range of the vegetation mode grating position of the AIS instrument.

Another observation from the correlograms is that when comparing the green wet canopy weight correlogram with the leaf nitrogen plot, different information from each plot emerges. The AIS is sensitive to specific canopy parameters at different wavelengths, providing unique information at each wavelength. At wavelengths between 1500 and 1600 nm especially, the plots trend in opposite directions. These dissimilar trends can be used to investigate multiple linear regressions for each constituent.

We plan to expand our research efforts in Wisconsin next summer. We hope to obtain 20-25 plots with additional canopy information including canopy lignin. We are very encouraged by these preliminary results and we are excited about upcoming analyses of high spectral resolution remote sensing data.

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