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Landscape-scale prediction of forest productivity by hyperspectral remote sensing of canopy nitrogen

Marie-Louise Smith
University of New Hampshire, Durham

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Landscape-scale prediction of forest productivity by hyperspectral remote sensing of canopy nitrogen

Abstract
Foliar nitrogen concentration represents a direct and primary link between carbon and nitrogen cycling in terrestrial ecosystems. Although foliar N is used by many ecosystem models to predict leaf-level photosynthetic rates, it has rarely been examined as a direct scalar to stand-level carbon gain. Significant improvements in remote sensing detector technology in the last decade now allow for improved landscape-level estimation of the biochemical attributes of forest ecosystems.

In this study, relationships among forest growth (aboveground net primary productivity (ANPP) and aboveground woody biomass production (AWBP)), canopy chemistry and structure, and high resolution imaging spectrometry were examined for 88 long-term forest growth inventory plots maintained by the USDA Forest Service within the 300,000 ha White Mountain National Forest, New Hampshire.

Analysis of plot-level data demonstrates a highly predictive relationship between whole canopy nitrogen concentration (g/100 g) and aboveground forest productivity (ANPP: $R^2 = 0.81$, $p < 0.000$; AWBP: $R^2 = 0.86$, $p < 0.000$) within and among forest types. Forest productivity was more strongly related to mass-based foliar nitrogen concentration than with either total canopy N or canopy leaf area.

Empirical relationships were developed among spectral data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and field-measured canopy nitrogen concentration (mass basis). Results of this analysis suggest that hyperspectral remote sensing can be used to accurately predict foliar nitrogen concentration, by mean of a full-spectrum partial least squares calibration method, both within a single scene ($R^2 = 0.84$, SECV = 0.23) and across a large number of contiguous images ($R^2 = 82$, SECV = 0.25), as well as between image dates ($R^2 = 0.69$, SECV = 0.25).

Forest productivity coverages for the White Mountain National Forest were developed by estimating whole canopy foliar N concentration from AVIRIS spectral response. Image spatial patterns broadly reflect the distribution of functional types, while fine scale spatial variation results from a variety of natural and anthropogenic factors. This approach provides the potential to increase the accuracy of forest growth and carbon gain estimates at the landscape level by providing information at the fine spatial scale over which environmental characteristics and human land use vary.

Keywords
Biology, Ecology, Agriculture, Forestry and Wildlife

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LANDSCAPE-SCALE PREDICTION OF
FOREST PRODUCTIVITY BY
HYPERSPECTRAL REMOTE SENSING OF
CANOPY NITROGEN

BY

Marie-Louise Smith
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DISSERTATION

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Doctor of Philosophy
in
Natural Resources

May, 2000
This dissertation has been examined and approved.

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ABSTRACT

LANDSCAPE-SCALE PREDICTION OF FOREST PRODUCTIVITY BY HYPERSPECTRAL REMOTE SENSING OF CANOPY NITROGEN

by

Marie-Louise Smith
University of New Hampshire, May, 2000

Foliar nitrogen concentration represents a direct and primary link between carbon and nitrogen cycling in terrestrial ecosystems. Although foliar N is used by many ecosystem models to predict leaf-level photosynthetic rates, it has rarely been examined as a direct scalar to stand-level carbon gain. Significant improvements in remote sensing detector technology in the last decade now allow for improved landscape-level estimation of the biochemical attributes of forest ecosystems.

In this study, relationships among forest growth (aboveground net primary productivity (ANPP) and aboveground woody biomass production (AWBP)), canopy chemistry and structure, and high resolution imaging spectrometry were examined for 88 long-term forest growth inventory plots maintained by the USDA Forest Service within the 300,000 ha White Mountain National Forest, New Hampshire.

Analysis of plot-level data demonstrates a highly predictive relationship between whole canopy nitrogen concentration (g /100 g) and aboveground forest productivity
Within and among forest types. Forest productivity was more strongly related to mass-based foliar nitrogen concentration than with either total canopy N or canopy leaf area.

Empirical relationships were developed among spectral data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and field-measured canopy nitrogen concentration (mass basis). Results of this analysis suggest that hyperspectral remote sensing can be used to accurately predict foliar nitrogen concentration, by means of a full-spectrum partial least squares calibration method, both within a single scene ($R^2 = 0.84$, SECV = 0.23) and across a large number of contiguous images ($R^2 = 0.82$, SECV = 0.25), as well as between image dates ($R^2 = 0.69$, SECV = 0.25).

Forest productivity coverages for the White Mountain National Forest were developed by estimating whole canopy foliar N concentration from AVIRIS spectral response. Image spatial patterns broadly reflect the distribution of functional types, while fine scale spatial variation results from a variety of natural and anthropogenic factors. This approach provides the potential to increase the accuracy of forest growth and carbon gain estimates at the landscape level by providing information at the fine spatial scale over which environmental characteristics and human land use vary.
Chapter I

RELATIONSHIPS AMONG FOREST PRODUCTIVITY, FOLIAR CHEMISTRY AND CANOPY STRUCTURE IN THE WHITE MOUNTAINS, NEW HAMPSHIRE

Introduction

Foliar chemical concentrations and structural traits (i.e. specific leaf area (SLA), leaf area index (LAI)) reflect growth potential and are strongly correlated to whole plant and ecosystem processes. Foliar nitrogen concentrations have been shown to be strongly related to the maximum photosynthetic rate across a range of species and biomes (Field and Mooney 1986; Reich et al. 1999a). As simple, direct scalars of productivity, both nitrogen content and concentration have been shown to be correlated with aboveground net primary productivity (ANPP) across a number of forest types, primarily coniferous (Comeau and Kimmins 1985; Matson et al. 1994). Similarly, a number of studies have demonstrated a close relationship among foliar chemical concentrations, particularly nitrogen and lignin, and the rate of litter decomposition and hence nutrient cycling (McClaugerty and Berg 1987; Mellilo et al. 1982; Scott and Binkley 1997). Canopy structure and indices of canopy structure, particularly LAI, have also been shown to be positively related to forest productivity, particularly for coniferous forests of the western U.S. (Gholz 1982). LAI, in turn, has been shown to be closely related to canopy SLA and leaf N concentration (Pierce
et al. 1994). Similar relationships have been demonstrated for deciduous and mixed forests of the eastern U.S. (Fassnacht et al. 1997; Jose and Gillespie 1997).

Such observations strongly suggest that both foliar chemistry and structure are closely linked to a variety of important ecosystem processes and may provide, either directly as simple scalars, or mechanistically through process models, powerful indicators of forest ecosystem productivity and function. Although measurement of foliar chemistry and structure is difficult for scales at and beyond that of the forest stand, significant improvements in remote sensing detector technology in the last decade (evolving from panchromatic and broadband, multi-spectral scanners to imaging spectrometry) now allow for improved landscape- to region-level estimation of both the biochemical and biophysical attributes of forest ecosystems (Asner 1998; Martin and Aber 1997; Martin et al. 1998).

As there have been relatively few attempts in northeastern forests types to simultaneously examine relationships among productivity and canopy chemical and structural traits at the stand level, the primary objective of the study reported here was to examine relationships among forest growth (aboveground net primary productivity (ANPP) and aboveground woody biomass production (AWBP)), leaf area, and canopy chemistry across a variety of species and site types at the Bartlett Experimental Forest, located in the central White Mountains, New Hampshire. This research was conducted as part of the White Mountain MAPBGC project (Mapping and Analysis of Productivity and Biogeochemical Cycles) (Ollinger et al. in prep.) which is directed at application of hyperspectral remote sensing to analysis of canopy chemistry and forest ecosystem function at stand to landscape scales. In this study, emphasis was placed on the extent to which forest productivity could be related to leaf traits that are potentially detectable via remote sensing.
**Methods**

**Study Area**

The study was conducted on the Bartlett Experimental Forest (BEF) which lies within the White Mountain National Forest in north central New Hampshire (Fig. 1.1). Established in 1932 by the USDA Forest Service as a forest management experimental and demonstration forest, the BEF is a 1052 ha tract of secondary successional deciduous and coniferous forest types—northern hardwood [e.g. sugar maple (*Acer saccharum* Marsh), beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britton)], red spruce-balsam fir (*Picea rubens* Sarg. - *Abies balsamea* (L.) Miller), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and red oak-white pine (*Quercus rubra* L. - *Pinus strobus* L.). Soils are derived from granitic drift and tend to be coarse textured ranging from weathered shallow bedrock, outwash, and compact sediments to basal tills and washed ablational tills (Leak 1982). Elevations on the BEF range from 200 m to 850 m. The climate of the southeastern White Mountains is characterized by a relatively short growing season (frost free period of about 100 days) and long, cold winters. Air temperatures at the BEF average −12° and 19° C in January and July, respectively (BEF, unpublished data). Precipitation is generally evenly distributed throughout the year and averages 100-120 cm, with about half in the form of snow.
The BEF has a wide range and long history of active forest manipulation that is reflected in a range of successional sequences, forest patch sizes, and structural distributions (Leak and Smith 1996). Forest manipulations that include clear-cutting, group and individual tree selection, and shelter-wood cutting comprise 50% of the forest. Forest ages in manipulated stands range from more than 60 to less than 5 years old. The remaining half of the forest is unmanipulated. Age of this portion of the forest ranges upwards of 100 years and is characterized by natural forest disturbance regimes. In 1931-32 approximately 500 0.1ha (32 x 32 m) permanent plots, spaced about 200 by 100 m apart were established over the extent of the forest. After an initial measurement of all woody stems larger than 3.8 cm diameter at breast height (DBH), a majority of these plots (444) have been re-measured by 1-inch (2.54 cm) diameter classes and species in at least three periods, most recently in 1991-92. For this study, forty-four of these established permanent plots were selected for both re-measurement and intensive sampling of canopy composition and chemistry. Plots were chosen subjectively with the aim of sampling the widest possible range in productivity and foliar chemistry. The chosen plots reflect the range in species composition, soil/habitat types (Leak 1982), and elevation found on the BEF.

**Aboveground Net Primary Productivity (ANPP)**

**Wood Production.**

In order to make use of data collected in previous inventories of the BEF, all stems greater than 3.8 cm DBH were measured in 2.54 cm size classes by species on each study plot after the 1998 growing season. Woody biomass for each recorded stem was calculated from species specific allometric equations based on DBH. Only equations developed in the northeastern region and only those that included algorithms for both stem and branch biomass were used (Hocker and Early 1983; Tritton and Hornbeck 1981). Woody biomass
(g m⁻²) for each plot was calculated by summing individual tree values over the entire plot and dividing by the plot area. Plot level AWBP (g m⁻² yr⁻¹) was calculated as the difference between woody biomass determined from the 1991-1992 BEF forest inventory and 1998 woody biomass divided by the growing season interval.

**Foliar Production.**
Litterfall was collected on 17 of the 44 study plots. Eight litterbaskets (0.23 m²) were randomly placed in each plot during the late summer of 1996. Litter was collected every two to three weeks in the fall, once in the spring, and once at the end of the summer of 1997; these samples were composited into a single sample per litter basket prior to sorting. Litter from each basket was air dried and sorted into leaf and non-leaf litter. Leaf litter was sorted by species and then oven-dried at 70° C for 48 h and weighed. Annual foliar production (g m⁻² yr⁻¹) was calculated as the sum of litterbasket foliar mass divided by litter basket area. For hardwoods foliar mass equals foliar production. For conifers, foliar mass (g m⁻²) was calculated by multiplying the weight of samples for each litterbasket by average leaf longevity to account for leaves retained by the trees.

ANPP (g m⁻² yr⁻¹) was calculated as the sum of AWBP for each plot and annual litterfall biomass production.

**Foliage Sampling and Analysis**

**Green Leaf Collection.**
Green leaf samples were collected on each of the 44 study plots over a two day period in July, 1995. Samples were collected in conjunction with the overflight of NASA’s Airborne Visible/Infrared Imaging Spectrometer (AVIRIS).

On each plot, all dominant and co-dominant species were identified and between two and seven trees per species were selected for green leaf collection. Leaves were collected by shooting small branches from the canopy with a shotgun. Each sample
consisted of leaves collected from several heights in the canopy. For needle-leaved species, no separation was made among needles of different ages. The samples were sealed in ziplock bags and weighed within several hours of collection. The fresh and dry weights were used to determine water content. After air-drying, the samples were then oven-dried at 70°C for 48 h and re-weighed. After drying, the leaves were ground with a Wiley mill to pass through a 1-mm mesh screen.

**Specific Leaf Weight and Area Determination.**

Additional leaf samples were collected from the top of the canopy for each dominant or co-dominant species on each plot in order to make a determination of specific leaf weight (SLW; weight to area ratio) and its inverse, specific leaf area (SLA) for species found on the BEF. The samples were sealed in ziplock bags and transported to the lab. Disks of known area (2.035 cm²) were taken from deciduous leaves by means of a sharpened metal punch. Five to seven disks per leaf were taken from 3 to 5 leaves per species per sample. For conifers, projected leaf area was determined by optical planimetry. Fifty to eighty needles per sample were scanned using a high resolution black and white optical scanner. Image processing software was used to determine needle perimeter based on change in digital number (DN) value across the projected perimeter of each needle. DN counts below the perimeter threshold based on the scanner resolution (dots per centimeter) yield the projected leaf area. All area-based measures were calculated for single-sided projected leaf area. All leaf samples were dried at 70°C for 48 hours and then weighed to the nearest 0.1 mg.

**Leaf Area Index.**

Leaf area (single-sided) was estimated as the product of species dry foliar mass from litterfall collection and SLA. Leaf area index (LAI) for each plot was calculated as the mean ratio of litterbasket leaf area and litterbasket ground area (m² m⁻²).
Foliar Chemistry.

A visible-near infrared spectrophotometer (NIRSystems 6500 monochromator) was used to determine foliar nitrogen concentration of oven dried, ground foliage according to the methods described by McLellan et al. (1991) and Bolster et al. (1996). This method uses partial least squares regression equations derived from a calibration data set in which both dried, ground leaf spectra and wet chemistry measurements were available for each sample. It has been demonstrated that the biochemical signals that exist in the spectra of ground, dried leaf material and the standard error of analysis from near infrared spectrometry for lignin and nitrogen for these materials are the same or better as for well-understood laboratory wet chemistry (Aber 1994; Martin 1994).

Canopy Chemistry.

Plot-level canopy nitrogen concentrations were calculated as the mean of foliar N concentrations for individual species, weighted by fraction of canopy foliar mass per species. Determination of canopy species fraction by mass was accomplished by two methods. For the first method, on all 44 study plots, a camera point-quadrat sampling technique was applied to determine canopy fraction of leaf area by height and by species. This method has been demonstrated to be an accurate means of determining the relative distribution or fraction of leaf area by height in a forested canopy (Aber 1979a; Aber 1979b). In each sample plot, 15 grid point observations at nine sample points (plot center and each of the four cardinal and off cardinal directions at 15 m from plot center) for a total of 135 observations per plot were taken. The sampling device is a 35-mm camera with a telephoto lens used as a range finder (calibrated to distance in meters) and having a grid of 15 points marked on the view-finder. Species and height to lowest leaf covering each grid point was recorded. Fractional species composition by leaf area by height was determined from foliage height profiles as described by Aber (1979a) and species distribution by height data.
Fraction of species by leaf area was converted to fraction by weight using specific leaf weights for each species.

For the second method, canopy species composition was calculated directly using litterfall data for the 17 plots where litterfall data was collected. A comparison of the methodologies was undertaken to evaluate the accuracy of the camera point method to estimate foliar constituent concentrations on a mass basis.

Canopy-level nitrogen concentrations were multiplied by total foliar mass and litterfall mass to determine canopy nitrogen content (g m\(^{-2}\)) on a total canopy mass and a canopy annual production (litterfall) basis, respectively.

**Statistical Analysis**

All statistical analyses were performed using SYSTAT 7.0 (SPSS, Inc. 1997). Simple and multiple linear regression analyses were used to examine relationships among canopy nitrogen, productivity (AWBP and ANPP), and LAI. The coefficient of determination (R\(^2\)), residual plots, and regression p-values (p < 0.05) were used to identify the best regression models. Analyses of variance were made in which stand type and soil/habitat types were included as nominal effects along with continuous variables and their interactions. Coincident regression analyses and equal slopes analyses were used to test for slope and intercept differences of regression relationships among nominal variable groupings of continuous variables (Klienbaum et al. 1988).
Results

Foliar Chemistry

Species Nitrogen Concentration.
Total nitrogen concentration in foliage of species ranged from 1.08 for red spruce to 2.97 for mountain ash, with %N for needle-leaved evergreen conifers ranging from 1.08 to 1.57 and for broad-leaved deciduous species from 1.80 to 2.97. Values for species mean nitrogen concentration are consistent with those reported in an extensive survey by Bolster et al. (1996) (Table 1.1). There is clear difference among mean values for some species at BEF versus the Bolster et al. (1996) data set, however, the majority of BEF values fall within the range of variance of nitrogen concentration for the species reported by Bolster et al. (1996).

Canopy-Level Nitrogen Concentration.
Comparison of N concentrations derived using the camera point versus litterfall methods of calculating canopy species composition demonstrate nearly identical prediction of mass-based nitrogen concentration among sample plots (Fig. 1.2; $R^2=0.98, p < 0.000$). Canopy-level nitrogen concentration for the sample plots at BEF, based on the camera point method, ranged from 0.88 for a red spruce stand to 2.48 for a beech-dominated northern hardwood stand (Table 1.2).

Nitrogen concentration differed significantly among forest types, primarily between stands dominated by conifer species and those dominated by hardwood species. After controlling for forest type effects, no significant differences

Figure 1.2. Correlation among camera point and litterfall mass based canopy-level nitrogen concentration for sample plots at the Bartlett Experimental Forest.
Table 1.1. Mean (and standard deviation) nitrogen concentration in foliage of common northeastern woody species found at the Bartlett Experimental Forest and as reported in the literature.

<table>
<thead>
<tr>
<th>Species</th>
<th>N</th>
<th>Mean</th>
<th>N</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartlett Experimental Forest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acer pennsylvanicum</td>
<td>1</td>
<td>2.24</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Acer rubrum</td>
<td>33</td>
<td>1.80 (0.29)</td>
<td>94</td>
<td>1.63 (0.31)</td>
</tr>
<tr>
<td>Acer saccharum</td>
<td>37</td>
<td>1.82 (0.17)</td>
<td>30</td>
<td>2.08 (0.40)</td>
</tr>
<tr>
<td>Betula allegehaniensis</td>
<td>15</td>
<td>2.37 (0.26)</td>
<td>7</td>
<td>2.30 (0.19)</td>
</tr>
<tr>
<td>Betula papyrifera</td>
<td>22</td>
<td>2.26 (0.22)</td>
<td>30</td>
<td>1.95 (0.43)</td>
</tr>
<tr>
<td>Fagus grandifolia</td>
<td>41</td>
<td>2.33 (0.28)</td>
<td>14</td>
<td>2.00 (0.46)</td>
</tr>
<tr>
<td>Fraxinus americana</td>
<td>10</td>
<td>2.11 (0.15)</td>
<td>10</td>
<td>2.15 (0.26)</td>
</tr>
<tr>
<td>Populus grandidentata</td>
<td>5</td>
<td>2.32 (0.22)</td>
<td>17</td>
<td>2.19</td>
</tr>
<tr>
<td>Prunus pennsylvanica</td>
<td>10</td>
<td>2.93 (0.25)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Quercus rubra</td>
<td>13</td>
<td>2.34 (0.10)</td>
<td>94</td>
<td>2.39 (0.42)</td>
</tr>
<tr>
<td>Sorbus americana</td>
<td>3</td>
<td>2.97 (0.28)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Viburnum alnifolium</td>
<td>1</td>
<td>2.00</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Abies balsamea</td>
<td>13</td>
<td>1.56 (0.10)</td>
<td>3</td>
<td>1.19 (0.27)</td>
</tr>
<tr>
<td>Picea rubens</td>
<td>35</td>
<td>1.08 (0.16)</td>
<td>50</td>
<td>0.93 (0.09)</td>
</tr>
<tr>
<td>Pinus strobus</td>
<td>10</td>
<td>1.57 (0.14)</td>
<td>40</td>
<td>1.54 (0.29)</td>
</tr>
<tr>
<td>Tsuga canadensis</td>
<td>30</td>
<td>1.19 (0.20)</td>
<td>46</td>
<td>1.08 (0.26)</td>
</tr>
</tbody>
</table>

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were observed among soil/habitat types. However, a significant interaction effect of forest type and soil/habitat type on canopy-level nitrogen concentration was observed. Stands on deeper and/or finer textured soils (e.g. washed and fine tills and enriched sites) generally had higher relative canopy-level nitrogen concentration than stands of similar species composition on shallow, compacted and/or coarse textured soils (e.g. shallow to bedrock or compact till and outwash).

**Productivity and LAI**

AWBP varied by a factor of 8 across study sites, ranging from 66 g m\(^{-2}\) yr\(^{-1}\) for a red spruce stand to 502 g m\(^{-2}\) yr\(^{-1}\) for an early successional northern hardwood stand dominated by paper birch (Table 1.2). AWBP differed significantly among forest types. Likewise, as for nitrogen concentration, a significant interaction effect between soil/habitat type and forest type was observed.

ANPP values varied by nearly as much, and ranged from 120 g m\(^{-2}\) yr\(^{-1}\) (red spruce) to 752 g m\(^{-2}\) yr\(^{-1}\) (northern hardwood-paper birch) differing significantly only between red spruce and hemlock forest types and all others types. Litterfall comprised between 32% and 45% of ANPP except for red spruce stands (18%), with slightly higher proportions in stands dominated by deciduous forest types.

LAI ranged from 0.74 (red spruce) to 3.61 (white pine - hardwood). With the exception of stands dominated by red spruce, values of LAI and litterfall were not significantly different among forest types.
Table 1.2. Productivity, LAI and canopy-level nitrogen concentration (and standard deviations) by sample plot, forest type and soil/habitat type at the Bartlett Experimental Forest.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Species (Bark)</th>
<th>ANPP (g m⁻² yr⁻¹)</th>
<th>LAI</th>
<th>Nitrogen %</th>
<th>Habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wood</td>
<td>Litterfall</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>6N</td>
<td>Red Spruce</td>
<td>165</td>
<td>59</td>
<td>224</td>
<td>1.82</td>
</tr>
<tr>
<td>10T</td>
<td>Red Spruce</td>
<td>229</td>
<td>51</td>
<td>280</td>
<td>1.80</td>
</tr>
<tr>
<td>7N</td>
<td>Red Spruce</td>
<td>217</td>
<td>70</td>
<td>287</td>
<td>1.90</td>
</tr>
<tr>
<td>6P</td>
<td>Red Spruce</td>
<td>252</td>
<td>1</td>
<td>253</td>
<td>1.21</td>
</tr>
<tr>
<td>7V</td>
<td>Red Spruce</td>
<td>220</td>
<td>54</td>
<td>120</td>
<td>0.74</td>
</tr>
<tr>
<td>30AE</td>
<td>Red Spruce (P.Birch)</td>
<td>283</td>
<td>54</td>
<td>337</td>
<td>2.58</td>
</tr>
<tr>
<td></td>
<td>Hemlock</td>
<td>238</td>
<td>1</td>
<td>239</td>
<td>1.20</td>
</tr>
<tr>
<td>24I</td>
<td>Hemlock</td>
<td>226</td>
<td>76</td>
<td>302</td>
<td>3.09</td>
</tr>
<tr>
<td>32P</td>
<td>Hemlock</td>
<td>309</td>
<td>1</td>
<td>310</td>
<td>1.28</td>
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<td>40G</td>
<td>Hemlock</td>
<td>294</td>
<td>1</td>
<td>295</td>
<td>1.35</td>
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<tr>
<td>14L</td>
<td>Hemlock (Beech)</td>
<td>357</td>
<td>149</td>
<td>406</td>
<td>2.78</td>
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<tr>
<td>34K</td>
<td>Hemlock (R.Spruce)</td>
<td>248</td>
<td>149</td>
<td>397</td>
<td>1.09</td>
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<tr>
<td>32AF</td>
<td>White Pine (Hardwood)</td>
<td>286</td>
<td>256</td>
<td>542</td>
<td>3.46</td>
</tr>
<tr>
<td>32AH</td>
<td>White Pine (Hardwood)</td>
<td>348</td>
<td>267</td>
<td>615</td>
<td>3.61</td>
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<td>30G</td>
<td>Paper Birch (Beech)</td>
<td>502</td>
<td>1</td>
<td>503</td>
<td>2.26</td>
</tr>
<tr>
<td>30T</td>
<td>Paper Birch (Beech)</td>
<td>501</td>
<td>251</td>
<td>752</td>
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<tr>
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<td>Red Maple</td>
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<td>361</td>
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<td>349</td>
<td>2.07</td>
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<td>228</td>
<td>603</td>
<td>3.35</td>
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<td>329</td>
<td>1.91</td>
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<tr>
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<td>332</td>
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<tr>
<td>26V</td>
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<td>1</td>
<td>287</td>
<td>1.70</td>
</tr>
<tr>
<td>28AE</td>
<td>Red Maple (W.Pine)</td>
<td>401</td>
<td>1</td>
<td>402</td>
<td>1.96</td>
</tr>
<tr>
<td>24T</td>
<td>Beech (R.Maple)</td>
<td>386</td>
<td>1</td>
<td>387</td>
<td>2.12</td>
</tr>
<tr>
<td>38U</td>
<td>Beech (Hemlock)</td>
<td>304</td>
<td>1</td>
<td>305</td>
<td>1.61</td>
</tr>
<tr>
<td>38Q</td>
<td>Beech</td>
<td>341</td>
<td>190</td>
<td>531</td>
<td>3.04</td>
</tr>
<tr>
<td>42J</td>
<td>Beech</td>
<td>421</td>
<td>1</td>
<td>422</td>
<td>2.08</td>
</tr>
<tr>
<td>36Z</td>
<td>Beech</td>
<td>416</td>
<td>239</td>
<td>655</td>
<td>3.49</td>
</tr>
<tr>
<td>9J</td>
<td>Beech</td>
<td>400</td>
<td>1</td>
<td>401</td>
<td>2.15</td>
</tr>
<tr>
<td>16L</td>
<td>Beech</td>
<td>462</td>
<td>1</td>
<td>463</td>
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</tr>
<tr>
<td>18T</td>
<td>Beech</td>
<td>470</td>
<td>1</td>
<td>471</td>
<td>2.21</td>
</tr>
<tr>
<td>14J</td>
<td>Beech</td>
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<td>1</td>
<td>489</td>
<td>2.48</td>
</tr>
<tr>
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<td>Beech (Red Oak)</td>
<td>445</td>
<td>1</td>
<td>446</td>
<td>2.05</td>
</tr>
<tr>
<td>13J</td>
<td>Beech (Red Oak)</td>
<td>404</td>
<td>191</td>
<td>595</td>
<td>3.33</td>
</tr>
<tr>
<td></td>
<td>Beech</td>
<td>405</td>
<td>207</td>
<td>612</td>
<td>3.29</td>
</tr>
<tr>
<td>10N</td>
<td>Sugar Maple (Beech)</td>
<td>445</td>
<td>1</td>
<td>446</td>
<td>2.03</td>
</tr>
<tr>
<td>12H</td>
<td>Sugar Maple (Beech)</td>
<td>462</td>
<td>213</td>
<td>675</td>
<td>3.34</td>
</tr>
<tr>
<td>43J</td>
<td>Sugar Maple (Beech)</td>
<td>435</td>
<td>1</td>
<td>436</td>
<td>1.98</td>
</tr>
<tr>
<td>14Z</td>
<td>Sugar Maple (Beech)</td>
<td>396</td>
<td>1</td>
<td>397</td>
<td>1.98</td>
</tr>
<tr>
<td>9D</td>
<td>Sugar Maple (Beech)</td>
<td>368</td>
<td>197</td>
<td>565</td>
<td>3.52</td>
</tr>
<tr>
<td>6D</td>
<td>Sugar Maple (Beech)</td>
<td>424</td>
<td>1</td>
<td>425</td>
<td>2.11</td>
</tr>
<tr>
<td>5D</td>
<td>Sugar Maple (Beech)</td>
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<td>1</td>
<td>482</td>
<td>2.21</td>
</tr>
<tr>
<td>24P</td>
<td>Sugar Maple (Ash)</td>
<td>383</td>
<td>224</td>
<td>607</td>
<td>3.47</td>
</tr>
<tr>
<td></td>
<td>Sugar Maple</td>
<td>424</td>
<td>211</td>
<td>635</td>
<td>3.44</td>
</tr>
<tr>
<td>9L</td>
<td>Yellow Birch (Beech)</td>
<td>319</td>
<td>1</td>
<td>320</td>
<td>1.98</td>
</tr>
<tr>
<td>36G</td>
<td>Yellow Birch (Beech)</td>
<td>465</td>
<td>1</td>
<td>466</td>
<td>2.39</td>
</tr>
</tbody>
</table>

*For forest type means, values without letters in common differed significantly (p<0.05) using post hoc Tukey pairwise comparisons.

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**Relationships Among Productivity, Foliar Chemistry, and LAI**

Among canopy variables measured, plot-level nitrogen concentration was the strongest predictor for both ANPP and AWBP (ANPP: \( n=17 \) \( R^2 = 0.91, p < 0.000 \); AWBP: \( n=44 \) \( R^2 = 0.86, p < 0.000 \)) (Fig. 1.3, Table 1.3). The relationship was significant for both conifer and hardwood forest types. Coincident regression analyses show no significant differences between regressions among forest types.

Relationships between ANPP and AWBP with LAI, foliar mass, and canopy N content differ in both slope and intercept among forest types. Among conifer forest types, ANPP and AWBP show strong linear correlations with LAI (ANPP: \( R^2 = 0.88, p < 0.000 \); AWBP: \( R^2 = 0.63, p < 0.011 \)), foliar mass (ANPP: \( R^2 = 0.87, p < 0.000 \); AWBP: \( R^2 = 0.59, p < 0.011 \)), and canopy N content (ANPP: \( R^2 = 0.88, p < 0.000 \); AWBP: \( R^2 = 0.62, p < 0.011 \)).

Among deciduous types, ANPP and AWBP are most strongly related to canopy N content (ANPP: \( R^2 = 0.88, p < 0.001 \); AWBP: \( R^2 = 0.69, p < 0.011 \)) and are more poorly related to both canopy mass (NS) and LAI (NS).

**Discussion**

**Productivity**

Average annual woody biomass production and leaf biomass production estimates for BEF hardwood and conifer sites are comparable to those reported for similar study sites in the region. Whittaker et al. (1974) reported for deciduous and mixed stands at the Hubbard Brook Experimental Forest woody biomass production (wood+branch) ranging from 318 - 538 g m\(^{-2}\) yr\(^{-1}\) and foliar production from 273 - 293 g m\(^{-2}\) yr\(^{-1}\) (as compared to 317 - 502 g m\(^{-2}\) yr\(^{-1}\) and 216 - 267 g m\(^{-2}\) yr\(^{-1}\) for woody and foliar biomass production, respectively, found in this study). More recent productivity data from the Cone Pond, NH
Figure 1.3. Relationships among forest productivity (ANPP and AWBP) and whole canopy nitrogen concentration (g/100 g), LAI (m² m⁻²), canopy N content (g m⁻²), and foliar mass (g m⁻²) for coniferous (△) and deciduous (■) stands at the Bartlett Experimental Forest, NH.
Table 1.3. Statistics for regressions of ANPP and AWBP for selected canopy variables.

### Aboveground Net Primary Productivity (ANPP)

<table>
<thead>
<tr>
<th></th>
<th>R²</th>
<th>Regression p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Conifer</td>
</tr>
<tr>
<td>Canopy %N (g / 100 g)</td>
<td>0.91</td>
<td>0.82</td>
</tr>
<tr>
<td>LAI (m² m⁻²)</td>
<td>--</td>
<td>0.88</td>
</tr>
<tr>
<td>Canopy N content (g m⁻²)</td>
<td>--</td>
<td>0.88</td>
</tr>
<tr>
<td>Foliar Mass (g m⁻²)</td>
<td>--</td>
<td>0.87</td>
</tr>
</tbody>
</table>

### Aboveground Woody Biomass Production (AWBP)

<table>
<thead>
<tr>
<th></th>
<th>R²</th>
<th>Regression p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Conifer</td>
</tr>
<tr>
<td>Canopy %N (g / 100 g)</td>
<td>0.86</td>
<td>0.71</td>
</tr>
<tr>
<td>LAI (m² m⁻²)</td>
<td>--</td>
<td>0.63</td>
</tr>
<tr>
<td>Canopy N content (g m⁻²)</td>
<td>--</td>
<td>0.62</td>
</tr>
<tr>
<td>Foliar Mass (g m⁻²)</td>
<td>--</td>
<td>0.59</td>
</tr>
</tbody>
</table>
watershed study (J. Hornbeck, unpublished data) for spruce-dominated conifer forest types are likewise similar. Woody biomass production values for conifer stands at Cone Pond range from 102 – 187 g m$^{-2}$ yr$^{-1}$ and leaf biomass production values range from 63 – 109 g m$^{-2}$ yr$^{-1}$ (as compared to 66 – 252 g m$^{-2}$ yr$^{-1}$ for woody biomass production and 51 – 176 g m$^{-2}$ yr$^{-1}$ for leaf biomass production for similar forest types at the BEF). The lower range in productivity values at Cone Pond versus the BEF data set may be due to the historic effect of a severe fire that burned portions of the Cone Pond watershed in 1820 and whose legacy in reduced N mineralization and availability are still evident today (Hornbeck and Lawrence 1996, Aber and Driscoll 1997). In short, the BEF can be characterized in terms of productivity as an aggrading secondary successional forest comparable to other well studied second-growth temperate forest sites in the region.

**Canopy Nitrogen Content and Concentration**

Relationships between canopy chemistry and productivity indicate distinct differences between deciduous hardwood and evergreen coniferous growth strategies. Lower growth rates among conifers for a given canopy biomass and canopy N content likely reflect lower photosynthetic rates per unit leaf N. In both forest types (broad-leaved deciduous and needle-leaved, evergreen) ANPP and AWBP were significantly correlated with canopy N concentration. Although needle-leaved evergreen forest types had consistently lower canopy nitrogen concentration and productivity than broad-leaved deciduous forest types, the nature of the relationship did not differ between them and so suggests that conifers and hardwoods experience N limitation in this region to an equal extent. Moreover the relative strength of the productivity-canopy N concentration relationship, as compared to that with canopy N content, suggests that leaf-level N
concentration is more important than the total amount of N in the canopy (Reich et al. 1999a).

A significant interaction effect among forest type and soil/habitat type related to both AWBP and whole canopy nitrogen concentration suggests potential feedbacks among soil processes, mediated by soil/parent material type, and plant productivity. For example, in an extensive survey and synthesis of productivity and N cycling data from 50 diverse conifer and deciduous stands in the midwestern U.S., Reich et al. (1997) found that intrinsic soil properties, particularly soil texture as it influences water availability (and which is highly related to parent material type in glaciated regions), exerts a large influence over N mineralization rates and that N availability, in turn, strongly controls productivity. To the extent that whole canopy nitrogen concentration reflects N availability across soil/parent material types, this same relationship may also be true of forested stands at the BEF.

**Canopy Structure**

Of the canopy structural traits measured, ANPP and AWBP were most highly related to foliar biomass production and to LAI. These relationships were much stronger for conifer than for hardwood types and/or for stands of lower LAI, foliar biomass, and foliar production (mostly conifer stands in this study). It has been generally observed that, within ecosystem types, once a certain level of canopy cover is attained, increases in productivity reach an asymptote in relation to either LAI or canopy mass (Reich et al. 1999b). As canopies get denser, self-shading increases and, consequently, light interception efficiency decreases resulting in a reduction in production efficiency relative to canopy mass and LAI. The use of LAI as a strong linear correlate and hence a potential estimator of ANPP has been most effectively demonstrated across steep gradients in LAI (Pierce et al. 1994, Fassnacht and Gower 1997, White et al. 1997) such as are found between biomes and...
functional types. In contrast, leaf and whole canopy traits such as SLA and nitrogen concentration on a mass basis have been shown to scale positively and at a high level of generality with photosynthetic rate, growth, and productivity at scales from the leaf to the ecosystem both within and across biomes (Reich et al. 1999a). In this study whole canopy nitrogen concentration scaled more strongly with productivity than did LAI across forest types. Sites with higher LAI had higher whole canopy N concentrations than sites with low LAI, but this relationship becomes non-linear reaching an asymptote at LAI values of about 3.5 (Fig. 1.4). These results suggest that both among functional groups and at relatively fine spatial scales, variation in whole canopy leaf traits such as N concentration are more sensitive scalars of site to site variation in ecosystem productivity than either LAI, foliar mass, or canopy N content.

**Conclusions**

Results of this study provide strong evidence that whole canopy leaf traits, particularly foliar nitrogen concentration, are powerful correlates of forest ecosystem productivity. Such leaf traits are relatively straightforward to measure in the field and can be efficiently extrapolated to the whole plot/canopy scale.

Because production efficiency is directly related to foliar nitrogen concentrations, efforts to develop the capacity for broad-scale detection of canopy chemistry are warranted. A number of recent studies carried out in conjunction with NASA’s Accelerated Canopy

---

Fig. 1.4. Relationship between whole canopy nitrogen concentration (g/100g) and leaf area index (LAI) for conifer and deciduous stands at the Bartlett Experimental Forest.

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Chemistry Program (Aber 1994) have demonstrated that hyperspectral remote sensing can be used to accurately estimate foliar chemistry, particularly nitrogen concentration, for scales at and beyond that of the forest stand (Martin and Aber 1997; Wessman et al. 1988). Continuing advances in detector technology, and the likelihood that both moderate- and hyper-spectral sensors will become operational from space-based platforms in the near term (e.g., MODIS (EOS-Terra), HYPERION (New Millenium Program EO-1)), suggest that this technology coupled with these relationships, either directly or through ecosystem models, may provide the foundation for an efficient means to make near real-time spatially explicit estimates of forest ecosystem function. Such estimates, particularly at landscape scales, \((10^2 \, \text{km}^2)\), are essential to developing understanding of both the temporal and spatial patterns of variation in ecosystem processes as a function of environmental gradients, land cover, and land-use history and to establish baselines of forest ecosystem function in order to monitor change over time.
Chapter II

HIGH SPECTRAL RESOLUTION REMOTE SENSING OF
FOREST CANOPY CHEMISTRY IN AN AREA OF
COMPLEX TERRAIN

Introduction

Imaging spectrometry is a unique type of optical remote sensing because surface radiance is measured in contiguous, narrow spectral bands allowing analysis of surface elements by absorption features (i.e., the shape of the reflectance continuum) (Asner 1998). The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an instrument designed to acquire such radiance spectra as images in 10 nm bandwidths over the solar reflected spectrum from approximately 400 nm to 2500 nm.

Canopy biochemical constituents (e.g. leaf water, chlorophyll, ancillary pigments, cellulose, lignin) in conjunction with leaf and canopy structure combine to produce the reflectance of vegetation as measured by AVIRIS (Green et al. 1998). Based on absorption features correlated with canopy biochemical and structural attributes, AVIRIS spectral images of terrestrial ecosystems have been used successfully to estimate forest canopy chemistry (Curran et al. 1997; Martin and Aber 1997), to determine patterns of use and productivity in vegetated regions (Wessman et al. 1997; Roberts et al. 1997; Martin and Aber 1997), and to identify vegetation types and species (Martin et al. 1998; Roberts et al. 1998).

Most of these applications rely on empirical-statistical relationships among AVIRIS spectral data and terrestrial ecosystem properties. An inherent limitation of such an image
analytical approach is that empirically derived relationships can be confounded by factors that cause variation in reflectance that are either unrelated to intrinsic surface reflectance or which are scene dependent.

Radiometric distortion in hyperspectral data, as well as in other types of sensor data, arise from a variety of sources some of which are sensor-induced (e.g. detector calibration, platform stability, instrument stability, etc.) and others which are scene related (e.g. topography, atmosphere, view angle, sun azimuth, reflectance properties of earth elements) and whose influence varies with wavelength (Teillet 1986; Schowengerdt 1997). Calibration or normalization is often required to minimize distortions and to derive, as accurately as possible, intrinsic surface reflectance.

Sensor induced radiometric distortion in AVIRIS data is minimized by spectral, radiometric, and spatial calibration of the instrument in the laboratory before and after each flight season and periodically in flight (during the flight season) onboard the NASA ER-2 aircraft. In-flight calibration experiments show that average absolute agreement between predicted and AVIRIS measured incident radiance is now better than 96% with an average radiometric precision (signal to noise ratio) of better than 700 in most spectral regions (Green et al. 1998).

In addition to distortions of surface reflectance caused by atmospheric molecular and aerosol scattering and atmospheric gaseous absorption, an important source of both within-scene radiometric distortion and scene-to-scene variance in reflectance arises from variation in sun-sensor-target geometry. This is particularly significant in areas of rugged topography where variable illumination angles and reflection geometry produced by different and often extreme slope angles and orientations cause surfaces to receive differing levels of irradiance (Fig. 2.1). Surfaces having the same cover type but of differing slope and aspect often have
different radiance values, which is problematic for image classification. Multi-temporal studies are also made more difficult in areas of complex terrain as this effect varies with both solar elevation and azimuth.

Although reflectance from most natural surfaces can be approximated by a Lambertian or isotropic reflectance distribution within a limited range of view angles, typically between 20 - 40° (Schowengerdt 1997), as sun and sensor geometry approach or exceed this range most materials show quite unequal, or anisotropic, reflectance in different directions. Dependence of observed reflectance on sun and sensor geometry is termed bi-directional reflectance distribution function (BRDF). The BRDF of vegetation has been shown generally to be strongly anisotropic and results from differences in structure at both the canopy-level (leaf area and angle, foliage clumping) and the landscape-level (canopy shape, tree density, season of year) (Asner et al. 1998). The strength and structural level
dependence of vegetation BRDF is a function of vegetation type, illumination conditions, and image pixel size (Gu and Gillespie 1997; Asner et al. 1998).

In short, radiometric effects arising from sun-sensor-target geometry may affect many analyses of AVIRIS imagery. Any technique that assumes variation in spectral response is unrelated to within scene pixel position and illumination is likely to be affected by these distortions, particularly those that are focused on vegetation and those that include areas of complex topography. Variation in image sun-sensor-target geometry is also likely to confound multi-image and multi-image date comparisons.

The objectives of the study presented here were to determine empirical relationships among AVIRIS spectral data and field-measured canopy chemical composition for a wide array of forest types typical of northeastern temperate forests (deciduous hardwood, evergreen conifer and mixed conifer-hardwood forest types), in an area of complex topography, and among multiple scene dates. The study is part of a larger remote sensing and field sampling project in the White Mountain National Forest, New Hampshire aimed at the development of multi-temporal, spatially explicit, estimates of forest productivity and biogeochemical cycling at landscape scales (Ollinger et al. in prep.). The emphasis of the work presented here is to evaluate the influence of sun-sensor-target geometry on our ability to remotely sense foliar chemistry (a critical component of forest ecosystem growth and function), and the suitability of several radiometric correction strategies to minimize radiometric distortion both within scenes and across image dates. In addition, I present a comparison of two near infrared reflectance spectroscopy based regression methods for the calibration of AVIRIS spectral response to forest canopy chemistry, multiple linear regression (MLR) and partial least squares regression (PLS).
Methods

Study Site

The data used in this study were collected at the Bartlett Experimental Forest (BEF), Bartlett, New Hampshire which lies within the White Mountain National Forest (WMNF) in north central New Hampshire (Fig 2.2). The BEF was established in 1932 by the USDA Forest Service as a forest management experimental and demonstration forest and is a 1052 ha tract of secondary successional deciduous and coniferous forest types—northern hardwood [e.g. sugar maple (Acer saccharum Marsh), beech (Fagus grandifolia Ehrh.), yellow birch (Betula alleghaniensis Britton), red spruce-balsam fir (Picea rubens Sarg. - Abies balsamea (L.) Miller), eastern hemlock (Tsuga canadensis (L.) Carr.), and red oak-white pine (Quercus rubra L. - Pinus strobus L.). The BEF is mountainous in its topography with elevations ranging from 200 m to more than 850 m. In 1931-32 approximately 500 0.1 ha permanent plots were established, spaced about 200 by 100 m apart, covering the full extent of the forest. For this study, 48 of these established permanent plots were selected for both re-measurement and intensive sampling of canopy composition and chemistry. Plots were chosen subjectively with the aim of sampling the widest possible range in foliar chemistry and to reflect the range in species composition, stand age, soil/habitat types (Leak 1982), and elevation found on the BEF.

Figure 2.2. Location of the Bartlett Experimental Forest, White Mountain National Forest, New Hampshire.
Field Data Collection

Green Leaf Collections.

In order to determine the chemistry of each species on sample plots in each time period, green leaf samples were collected from 48 study plots over a three day period in 1995 (July 5-7, 1995) and on a 17 plot subset in 1997 (August 16-17, 1997). Green leaf collections occurred within 5 days of overflight of the AVIRIS instrument.

On each plot, all dominant and co-dominant species were identified and between two and seven trees per species were selected for green leaf collection. Leaves were collected by shooting small branches from the canopy with a shotgun. Each sample consisted of leaves collected from several heights in the canopy. For needle-leaved species, no separation was made among needles of different ages. The samples were sealed in ziplock bags and weighed within several hours of collection. The fresh and dry weights were used to determine water content. After air-drying, the samples were then oven-dried at 70°C for 48 h and re-weighed. After drying, the leaves were ground with a Wiley mill to pass through a 1-mm mesh screen.

As a part of the foliage sampling collection, additional leaves were collected at the top of the canopy from each of dominant or co-dominant species on each plot in order to make a determination of specific leaf weight (SLW; weight to area ratio (g cm⁻²)) for each species. SLW is necessary for calculation of canopy nitrogen concentration on a mass basis. Samples were sealed in ziplock bags and transported to the lab. Disks of known area (2.035 cm²) were taken from all deciduous leaves by means of a sharpened metal punch. Five to seven disks per leaf were taken from 3 to 5 leaves per species per sample. For coniferous species, projected leaf area was determined by optical planimetry. Fifty to eighty needles per species per sample were scanned using a high resolution optical scanner. Image processing
software was used to determine needle perimeter based on change in digital number (DN) value across the projected perimeter of each needle. DN counts below the perimeter threshold based on the scanner resolution yield the projected leaf area. All area-based measures were calculated for single-sided projected leaf area. All leaf samples were dried at 70°C for 48 hours and then weighed to the nearest 0.1 mg.

**Foliar Chemistry.**

A visible and near infrared spectrophotometer (NIRSystems 6500 monochromator) was used to determine nitrogen, lignin, and cellulose concentrations of oven dried, ground foliage according to the methods described by McLellan et al. (1991) and Bolster et al. (1996). The method uses partial least squares regression equations derived from a calibration data set in which both dried, ground leaf spectra and wet chemistry measurements were available for each sample. It has been demonstrated that the biochemical signals that exist in the spectra of ground, dried leaf material and the standard error of analysis from near infrared spectrometry for lignin and nitrogen for these materials are the same or better as those for well-understood laboratory wet chemistry methods (Martin 1994; Aber 1994).

**Canopy Chemistry.**

Canopy level nitrogen concentration for each foliage plot was calculated as a mean concentration per species (green leaf collection) weighted by fraction of canopy foliar mass per species (Table 2.1).

Determination of canopy species fraction by mass was accomplished by means of a camera point-quadrat sampling technique (Aber 1979a) combined with SLW measurements. The camera point-quadrat method has been demonstrated to be an accurate means of determining the relative distribution or fraction of leaf area by height in a forested canopy (Aber 1979a; Aber 1979b). In each sample plot, 15 grid point observations at nine sample points (plot center and each of the four cardinal and off cardinal directions at 15 m from
Table 2.1. Whole canopy nitrogen, lignin, and cellulose, concentrations for Bartlett Experimental Forest plots. Dominant species are listed for each plot. Values for nitrogen, lignin, and cellulose are percentages of foliage dry mass as calculated from the green leaf and camera point derived canopy fraction by mass data for each plot.

<table>
<thead>
<tr>
<th>Plot</th>
<th>Dominant Species</th>
<th>Nitrogen (%)</th>
<th>Lignin (%)</th>
<th>Cellulose (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24I</td>
<td>Hemlock</td>
<td>1.20</td>
<td>-</td>
<td>15.19</td>
</tr>
<tr>
<td>32V</td>
<td>Hemlock</td>
<td>1.28</td>
<td>-</td>
<td>15.81</td>
</tr>
<tr>
<td>14L</td>
<td>Hemlock, Beech</td>
<td>1.69</td>
<td>-</td>
<td>16.08</td>
</tr>
<tr>
<td>34K</td>
<td>Hemlock, Red Spruce</td>
<td>1.09</td>
<td>1.22</td>
<td>17.98</td>
</tr>
<tr>
<td>32P</td>
<td>Hemlock, Yellow Birch</td>
<td>1.20</td>
<td>1.22</td>
<td>16.83</td>
</tr>
<tr>
<td>40G</td>
<td>Hemlock, Yellow Birch</td>
<td>1.35</td>
<td>-</td>
<td>16.27</td>
</tr>
<tr>
<td>5N</td>
<td>Red Spruce</td>
<td>1.11</td>
<td>1.10</td>
<td>24.13</td>
</tr>
<tr>
<td>7N</td>
<td>Red Spruce</td>
<td>1.17</td>
<td>1.02</td>
<td>-</td>
</tr>
<tr>
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<td>Red Spruce, Hemlock</td>
<td>0.91</td>
<td>0.88</td>
<td>24.17</td>
</tr>
<tr>
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<td>1.05</td>
<td>21.19</td>
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<td>-</td>
<td>23.70</td>
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<td>Red Spruce, Paper Birch</td>
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<td>1.29</td>
<td>22.20</td>
</tr>
<tr>
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<td>White Pine</td>
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<td>1.75</td>
<td>-</td>
</tr>
<tr>
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<td>1.74</td>
<td>1.64</td>
<td>23.49</td>
</tr>
<tr>
<td>14J</td>
<td>Beech</td>
<td>2.48</td>
<td>-</td>
<td>23.07</td>
</tr>
<tr>
<td>16L</td>
<td>Beech</td>
<td>2.21</td>
<td>-</td>
<td>22.39</td>
</tr>
<tr>
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<td>Beech</td>
<td>2.21</td>
<td>-</td>
<td>22.79</td>
</tr>
<tr>
<td>38Q</td>
<td>Beech</td>
<td>1.87</td>
<td>1.87</td>
<td>21.04</td>
</tr>
<tr>
<td>42J</td>
<td>Beech</td>
<td>2.08</td>
<td>-</td>
<td>23.64</td>
</tr>
<tr>
<td>9J</td>
<td>Beech</td>
<td>2.15</td>
<td>-</td>
<td>23.14</td>
</tr>
<tr>
<td>24G</td>
<td>Beech, Hemlock</td>
<td>1.55</td>
<td>-</td>
<td>17.57</td>
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<tr>
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<td>Beech, Hemlock</td>
<td>1.61</td>
<td>-</td>
<td>18.10</td>
</tr>
<tr>
<td>24T</td>
<td>Beech, Red Maple</td>
<td>2.12</td>
<td>-</td>
<td>21.99</td>
</tr>
<tr>
<td>36Z</td>
<td>Beech, Red Maple</td>
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<td>1.85</td>
<td>21.92</td>
</tr>
<tr>
<td>12J</td>
<td>Beech, Red Oak</td>
<td>2.05</td>
<td>-</td>
<td>21.64</td>
</tr>
<tr>
<td>13J</td>
<td>Beech, Red Oak</td>
<td>2.14</td>
<td>2.24</td>
<td>22.43</td>
</tr>
<tr>
<td>32G</td>
<td>Paper Birch, Beech</td>
<td>1.97</td>
<td>-</td>
<td>18.34</td>
</tr>
<tr>
<td>30G</td>
<td>Paper Birch, Beech</td>
<td>2.26</td>
<td>-</td>
<td>20.59</td>
</tr>
<tr>
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<td>1.90</td>
<td>-</td>
<td>22.10</td>
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<td>Paper Birch, Yellow Birch</td>
<td>2.34</td>
<td>2.30</td>
<td>21.87</td>
</tr>
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<td>28AF</td>
<td>Red Maple</td>
<td>1.96</td>
<td>-</td>
<td>22.24</td>
</tr>
<tr>
<td>30V</td>
<td>Red Maple, Beech</td>
<td>1.91</td>
<td>-</td>
<td>20.37</td>
</tr>
<tr>
<td>30Y</td>
<td>Red Maple, Beech</td>
<td>1.86</td>
<td>1.76</td>
<td>19.43</td>
</tr>
<tr>
<td>26V</td>
<td>Red Maple, Paper Birch</td>
<td>1.70</td>
<td>-</td>
<td>22.13</td>
</tr>
<tr>
<td>28AB</td>
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<td>-</td>
<td>22.68</td>
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<td>2.07</td>
<td>-</td>
<td>20.27</td>
</tr>
<tr>
<td>28AE</td>
<td>Red Maple, White Pine</td>
<td>1.96</td>
<td>-</td>
<td>24.95</td>
</tr>
<tr>
<td>9D</td>
<td>Sugar Maple, Beech</td>
<td>1.99</td>
<td>1.83</td>
<td>19.04</td>
</tr>
<tr>
<td>10N</td>
<td>Sugar Maple, Beech</td>
<td>2.03</td>
<td>-</td>
<td>19.77</td>
</tr>
<tr>
<td>12H</td>
<td>Sugar Maple, Beech</td>
<td>2.12</td>
<td>2.18</td>
<td>21.15</td>
</tr>
<tr>
<td>14Z</td>
<td>Sugar Maple, Beech</td>
<td>1.98</td>
<td>-</td>
<td>20.14</td>
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<td>5D</td>
<td>Sugar Maple, Beech</td>
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<td>-</td>
<td>20.37</td>
</tr>
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<td>6D</td>
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<td>-</td>
<td>20.76</td>
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<tr>
<td>43J</td>
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<td>1.98</td>
<td>-</td>
<td>17.27</td>
</tr>
<tr>
<td>24P</td>
<td>White Ash, Sugar Maple</td>
<td>2.01</td>
<td>2.03</td>
<td>17.72</td>
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<tr>
<td>36G</td>
<td>Yellow Birch, Beech</td>
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<td>-</td>
<td>22.87</td>
</tr>
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<td>9L</td>
<td>Yellow Birch, Beech</td>
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<td>-</td>
<td>20.20</td>
</tr>
<tr>
<td>9V</td>
<td>Yellow Birch, Beech</td>
<td>2.28</td>
<td>-</td>
<td>22.50</td>
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</table>
plot center) for a total of 135 observations/plot were taken. The sampling device is a 35-mm camera with a telephoto lens used as a range finder (calibrated to distance in meters) and having a grid of 15 points marked on the viewfinder. Species and height to lowest leaf covering each grid point was recorded. Fraction of leaf area by height and by species was determined from foliage height profiles and species distribution by height data. Fraction of species by leaf area was converted to fraction by weight by multiplying area fraction by specific leaf weight of each species and deriving a new fraction by weight for each species on sample plots. A comparison of the camera-based method and the more conventional litterfall mass based calculations of canopy-level nitrogen concentration demonstrate nearly identical prediction of mass-based nitrogen concentration among sample plots (see Chpt. 1).

**Remote Sensing Data**

**AVIRIS Data.**

AVIRIS, built and operated by NASA's Jet Propulsion Laboratory (JPL) and in operation since 1983, was used to collect hyperspectral image data for the BEF (Fig 2.3). Flying aboard a NASA ER-2 aircraft at an altitude of 20,000 m, AVIRIS measures upwelling radiance from the solar reflected spectrum in 224 contiguous channels from 400 nm to 2500 nm with a spectral resolution of ~10 nm (Green et al. 1998). Spatial images of radiance spectra are collected by a cross-track scanning mechanism (15° maximum view angle from nadir) and the forward motion of the aircraft. Images are 11 km in width and up to 800 km in length with a spatial resolution of ~20 m (Green et al. 1998). AVIRIS data are received from JPL with at sensor radiometric correction applied. This correction converts raw AVIRIS DN values to radiance values for each pixel in units of μW cm⁻² nm⁻¹ sr⁻¹. AVIRIS data were acquired for the Bartlett Experimental Forest, a roughly 5 km x 5 km area, on 3 July 1995 and 12 August 1997.
Geometric Registration.

Georeferencing of image data was accomplished by registering 20 m AVIRIS data to geo-coded (NH state plane) 10 m SPOT Panchromatic coverage of the study area. Features common to both images (e.g. road intersections, distinctive topographic features, etc.) were used as ground control points in order to generate a coordinate transformation matrix that enabled the mapping of NH state plane coordinates, using a nearest neighbor re-sampling algorithm, to image pixel locations. The root mean square error of registration (meters) for each image is summarized in Table 2.2, and for both image dates is less than one nominal AVIRIS pixel.

Table 2.2. Root mean square (RMS) error (meters), for AVIRIS image dates for the Bartlett Experimental Forest, NH.

<table>
<thead>
<tr>
<th>Image Date</th>
<th>RMS X</th>
<th>RMS Y</th>
<th>Total RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>10.3</td>
<td>9.0</td>
<td>13.7</td>
</tr>
<tr>
<td>1997</td>
<td>12.4</td>
<td>10.7</td>
<td>16.4</td>
</tr>
</tbody>
</table>
Radiometric Distortion: View-Angle Correction.

View-angle effects in AVIRIS imagery are manifest as brightness gradients corresponding to the cross-track dimension of the image and can be a significant distortion in AVIRIS imagery of forested surface types (Kennedy et al. 1997). This effect arises from AVIRIS scan angle and direction, flight path orientation, and solar azimuth (Fig 2.4).

Brightness gradients were modeled and corrected empirically for each image, prior to image registration, by calculating mean radiance by view angle and fitting a quadratic curve to the means (Kennedy et al. 1997). As view-angle effects are zero at nadir, compensation factors were calculated to normalize each view-angle, on a pixel-by-pixel basis, to the nadir view.

The topographic illumination compensation methods tested in this study are based on nadir-view spectral response.

Figure 2.4. AVIRIS image (12 August 1997, wavelength 0.65 µm) of the Bartlett Experimental Forest, Bartlett, NH showing view-angle dependent brightness gradient (image on left). This effect arises from (1) instrument scan angle (15° maximum from nadir) and direction (EW), (2) flight path orientation (NS), and (3) solar azimuth (145.93°). Brightness correction (image on right) follows Kennedy et al. (1997).
Radiometric Distortion: Topographic Correction.

Incident solar radiation reflected from a surface is a function of (1) the optical properties of the surface, (2) the incidence angle of solar radiation, \( \cos i \) (the angle between the normal to the surface and the light source) as in Eq. 1,

\[
\cos i = \cos \theta_s \cos \theta_s + \sin \theta_s \sin \theta_s \cos (\phi_s - \phi_s)
\]

where,

- \( \theta_s \) = slope of the terrain surface,
- \( \theta_s \) = solar zenith angle,
- \( \phi_s \) = solar azimuth angle, and
- \( \phi_s \) = aspect of the slope angle

and, (3) the exit angle, \( \cos e \) (the angle between the normal to the surface and the sensor or the slope of the terrain surface (\( \beta \))) (Colby 1991).

In this study we evaluated the effects of two photometric topographic normalization models upon the normalization of scene radiance and upon the prediction of forest canopy chemistry: the Lambertian or cosine correction model (Holben and Justice 1980) and the Minnaert correction model (Colby 1991).

The cosine correction as shown in Eq. 2:

\[
L_{H} = \frac{L_T}{\cos i}
\]

where, \( L_H \) is radiance observed for a horizontal surface and \( L_T \) is radiance observed over sloped terrain, is a trigonometric approach which takes into account the portion of incident radiance on the inclined surface element (pixel) and in which objects are regarded as pure lambertian reflectors (i.e. perfectly diffuse), thus compensating only for differences in illumination caused by the surface orientation.

The Minnaert correction as shown in Eq. 3:

\[
L_{H} = \frac{(L_T \times \cos e)}{(\cos k \times \cos k \times e)}
\]
is a variation of the cosine correction by introduction of the Minnaert (1941) constant, $k$, simulating the dependence, or bi-directional distribution function (BRDF), of observed reflectance on sun-terrain-sensor geometry as well as on surface roughness. The Minnaert constant is found empirically by regressing observed radiance over sloped terrain with known incidence and exitance values. When $k = 1$ it is a normal cosine correction.

As variation in BRDF of vegetation is strongly related to canopy structural characteristics and is also strongly wavelength dependent, individual $k$ constants for each wavelength in each image were calculated independently for deciduous and coniferous pixels. Corrections based on variation in canopy structure due to age and stand density within forest types were not considered. Non-forest image pixels were excluded from the analysis.

An RGB clustering algorithm was applied to each AVIRIS image to derive a simple deciduous, coniferous, and non-forest classification. A 3 band false-color composite image (1.21 μm, 2.27 μm, 0.57μm) of high visual contrast between conifer, deciduous, and non-forest pixels was used to group image pixels in three-dimensional feature space for each image date (ERDAS Inc. 1997). Histograms of each band were used to specify the number of R, G, and B sections in each dimension. Histogram sections were used to define clusters of pixels in the resulting single-band thematic images. Pixel clusters were then classified as non-forest, coniferous, or deciduous based on comparison with AVIRIS false color composite images, high-resolution aerial photography of the BEF (leaf-off, CIR), and knowledge of the study area. Image masks for each forest type for each image date were generated and used to extract pixels by cover type for calculation of Minnaert constants.

Slope, aspect, and elevation data used in calculation of $\cos i$ and $\cos e$ were extracted from USGS 30m digital elevation data for the study area. DEM data were re-sampled to 20 m pixels to geometrically match the AVIRIS imagery. Slope and aspect were calculated in
ERDAS Imagine (ERDAS Inc. 1997) using a 3x3 pixel window around each pixel to calculate its slope and aspect. \( \cos i \) parameters for sun angle and elevation for each AVIRIS image date were calculated according to Gronbeck (1999).

**Radiometric Distortion: Atmospheric Correction.**

After correction of scene radiance for scan angle and topographic effects, the ATmospheric REMoval program (ATREM) was used to transform AVIRIS radiance to apparent surface reflectance (Gao et al. 1992; Gao et al. 1993). ATREM uses a radiative transfer approach to remove the effects of molecular and aerosol scattering and atmospheric water and gases from AVIRIS reflectance spectra. ATREM is parameterized for each pixel in the image by using absorption features in each AVIRIS radiance spectrum to calculate water vapor.

**Spectral Feature Extraction.**

Sample plot coordinates for use in spectral feature extraction were collected with the use of a global positioning system (GPS). A Trimble Pathfinder Professional GPS receiver was used to determine the coordinates of study plots across the BEF. GPS data, collected as latitude/longitude coordinates, were differentially corrected (+/- 3-5 m) using base station data collected at the NH Department of Transportation located in Concord, NH (~ 100 km from the Bartlett Experimental Forest) and then re-projected to NH state plane coordinates (GRS 1980, Zone 4676, NAD 1983).

In order to minimize errors due to pixel/plot mis-registration on correlations of AVIRIS image spectra with forest canopy chemistry data, average spectral values for each sample plot were extracted from 2 x 2 pixel windows centered on each plot location from each image or image transform of interest.
Correlating AVIRIS Data With Canopy Chemistry Data

AVIRIS measured signals are analyzed each flight season to determine the spectral positions, response functions, and uncertainties of the 224 AVIRIS spectral channels (bands) (Green et al. 1998). As a result, spectral channel wavelength centers and bandwidths vary from year to year. In order to compare the predictive potential of AVIRIS derived canopy chemistry calibration equations from year to year, 1995 AVIRIS wavelength centers were interpolated to 1997 AVIRIS wavelength centers for each band. A simple linear interpolation algorithm was applied to the 1995 AVIRIS data using Eq. 4:

\[
X_{2\text{AV}}(i) = \frac{((X_{1\text{AV}}(i + 1) - X_{1\text{AV}}(i - 1)) \times (X_{2\text{AV}}(i) - X_{1\text{AV}}(i - 1)))}{(X_{1\text{AV}}(i + 1) - X_{1\text{AV}}(i - 1))} + X_{1\text{REF}}(i - 1)
\]

where, \(X_{1\text{AV}}\) and \(X_{1\text{REF}}\) are the original spectral data (wavelength center and reflectance, respectively) and \(X_{2\text{AV}}\) is the desired output wavelength center. \(X_{2\text{REF}}\) is the reflectance at that location interpolated from the original spectra. The output reflectance is the fractional change in reflectance between the bracketing wavelengths of the input spectra multiplied by the actual change in wavelength between the current output wavelength and the lower bracketing wavelength added to the reflectance at the lower wavelength.

In order to linearize spectral response to chemical constituent concentration, AVIRIS reflectance (\(R\)) data were then converted to absorbance (\(A\)) prior to calibration using Eq. 5:

\[
A = \log(1/R)
\]

Data analysis was conducted using the ISI software system (Shenk and Westerhaus 1991b) and PLSplus/IQ software system (Galactic Industries 1999). Relationships between AVIRIS data and field-measured foliar chemical concentrations were investigated using both multiple linear regression (MLR) and partial least squares regression (PLS). Calibrations

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were performed on a several AVIRIS data transformations including an ATREM + Brightness corrected data set (ATREM+Bright), an ATREM+Brightness+Cosine corrected data set (Cosine), and an ATREM+Brightness+Minnaert (Minnaert) corrected data set.

A first difference transformation was applied to all AVTRIS absorbance data as shown in Eq. 6:

\[ A'(\lambda) = A(\lambda - 20 \text{ nm}) - A(\lambda - 20 \text{ nm}) \]  

where \( A(\lambda) \) is the mean absorbance value centered as \( \lambda \), for an average of three AVIRIS bands (\( \approx 30 \) nm). Values of inflection points are reported at the center point of the smoothed 40 nm segment. The derivative spectrum is simply a measure of the slope of the spectral curve at every point and results in a spectrum in which peaks and valleys correspond with inflection points in the absorbance spectra and from which baseline offsets and low frequency variation have been removed. The full set of AVIRIS bands were included in these calculations but excluded the large water absorption features centered at approximately 1450 nm and 1950 nm, respectively.

Regression equations in the form of Eq. 7 were developed using absorption bands selected by stepwise MLR or PLS:

\[ \text{Concentration(\%)} = b_0 + \sum_{i=1}^{n} b_i A'(\lambda_i) \]  

where \( A'(\lambda) \) is the first difference approximation absorbance value centered at \( \lambda \), and \( b_i \) is the regression-fitting coefficient for that term. To avoid over-fitting, the number of terms used in the MLR solutions were set to a maximum of four according to the criteria of Hruschka (1987) where between five and ten samples are required for each regression constant and for each varied parameter (i.e., wavelength). For the PLS solutions, the prediction residual error sum of squares (PRESS statistic) was calculated for each factor based on an iterative cross
validation prediction of each sample. The number of factors at which the additive prediction errors (PRESS) are minimized indicates the appropriate number of factors to include in the PLS model to avoid both overfitting and underfitting.

**Results and Discussion**

**Illumination Effects and Topographic Normalization**

In order to directly examine the spectral effect of topography in both coniferous and deciduous forest types, spectral data for each radiometric image correction (Bright, Bright+Cosine, and Bright+Minnaert) were extracted from the 12 August 1997 BEF AVIRIS image. Radiance values at each wavelength from 115 pixels (57 conifer, 58 deciduous) with slopes of 0° to 30° over the range of aspects were extracted from each corrected image. Linear correlations between both topographically uncorrected (Bright) and topographically corrected (Cosine, Minnaert) AVIRIS radiance and cosine of incidence angle for each of three wavelengths spanning the AVIRIS spectral range are summarized in Table 2.3. Graphical representations are presented in Fig. 2.5.

Nadir-view only corrected AVIRIS data (Bright) displays a clearly identifiable response in radiance to an increasing cosine of incidence angle, where \( \cos i = 0 \) corresponds to the angle of incidence at which slopes of northern aspect become shadowed and \( \cos i = 1 \) corresponds to southern slopes perpendicular to the sun. This effect is stronger at shorter NIR wavelengths and stronger for dominantly coniferous forest types across all wavelengths. Although scene radiance in these data exhibit a highly significant relationship with topography in most cases, the overall correlations are relatively low indicating that only a limited part of the variability of the data is related to varying incidence angle. Such a result is not surprising given both the high solar altitude of the image date (and hence relatively low effective incidence angles) and the comparatively moderate topography of the study area (as
Table 2.3. Correlation coefficients (R²), F-ratios, and p-values expressing the level of dependence of AVIRIS radiance (µW cm⁻² nm⁻¹ sr⁻¹), from 12 August 1997 Bartlett Experimental Forest image, on cosine of incidence angle (terrain effect) at three wavelengths after treatment by each of three radiometric correction approaches. Radiance values from 115 pixel locations with slopes of 0 to 35° over the range of aspects were included. Results are reported for the whole scene (All) and for two generalized forest types (Coniferous, Deciduous).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wavelength (nm)</th>
<th>0.56</th>
<th></th>
<th>1.28</th>
<th></th>
<th>2.07</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²</td>
<td>F-ratio</td>
<td>P-value</td>
<td>R²</td>
<td>F-ratio</td>
<td>P-value</td>
<td>R²</td>
</tr>
<tr>
<td>Bright</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>0.20</td>
<td>29.786</td>
<td>0.000</td>
<td>0.23</td>
<td>34.582</td>
<td>0.000</td>
<td>0.12</td>
</tr>
<tr>
<td>Coniferous</td>
<td>0.25</td>
<td>22.718</td>
<td>0.000</td>
<td>0.28</td>
<td>22.487</td>
<td>0.000</td>
<td>0.14</td>
</tr>
<tr>
<td>Deciduous</td>
<td>0.12</td>
<td>7.542</td>
<td>0.008</td>
<td>0.18</td>
<td>11.804</td>
<td>0.001</td>
<td>0.09</td>
</tr>
<tr>
<td>Bright+Minnaert</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>0.02</td>
<td>2.529</td>
<td>0.115</td>
<td>0.02</td>
<td>1.966</td>
<td>0.164</td>
<td>0.01</td>
</tr>
<tr>
<td>Coniferous</td>
<td>0.01</td>
<td>0.236</td>
<td>0.610</td>
<td>0.03</td>
<td>2.038</td>
<td>0.159</td>
<td>0.02</td>
</tr>
<tr>
<td>Deciduous</td>
<td>0.09</td>
<td>5.765</td>
<td>0.020</td>
<td>0.00</td>
<td>0.003</td>
<td>0.960</td>
<td>0.00</td>
</tr>
<tr>
<td>Bright+Cosine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>0.76</td>
<td>362.81</td>
<td>0.000</td>
<td>0.13</td>
<td>17.329</td>
<td>0.000</td>
<td>0.16</td>
</tr>
<tr>
<td>Coniferous</td>
<td>0.75</td>
<td>170.648</td>
<td>0.000</td>
<td>0.09</td>
<td>5.289</td>
<td>0.025</td>
<td>0.11</td>
</tr>
<tr>
<td>Deciduous</td>
<td>0.80</td>
<td>219.392</td>
<td>0.000</td>
<td>0.27</td>
<td>19.440</td>
<td>0.000</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Figure 2.5. AVIRIS radiance (\( \mu W \cdot cm^{-2} \cdot nm^{-1} \cdot sr^{-1} \)) from 12 August 1997 Bartlett Experimental Forest image, versus cosine of incidence angle for three radiometric correction treatments (Bright, Bright+Minnaert, Bright+Cosine) at three wavelengths. One hundred and fifteen pixel locations with slopes of 0 to 35° over the range of aspects and representing both deciduous (o) and coniferous (.) forest types are included. Level of dependence of radiance on incidence angle by forest types based on linear regression is summarized in Table 2.1. A cosine of incidence angle of 0.83 represents horizontal terrain.
compared to the wider White Mountain region. Illumination at lower solar angles or of steeper topography or both will likely increase the magnitude of the spectral effect of topography.

Topographically dependent scene radiance was more effectively reduced by a correction function employing the empirically derived Minnaert constant than by the Lambertian (Cosine) correction function. As has similarly been found for multi-spectral data (Smith et al. 1980; Teillet et al. 1982; Itten and Meyer 1993; Ekstrand 1996), the Lambertian correction function resulted in an over-correction of AVIRIS radiance values for northern slopes ($\cos i < 0.83$) at all wavelengths, but especially at shorter wavelengths and in particular for deciduous forest types, resulting in a reversed topographic effect stronger than in the uncorrected data. Except for well-illuminated terrain ($\cos i > 0.83$) where the Lambertian correction gave similar results as the Minnaert correction for both generalized forest types, the Lambertian correction effected an overall increase in scene variance with incidence angle across wavelengths rather than a reduction (Table 2.3, Fig. 2.5). In contrast, the Minnaert correction effectively removed the spectral effect of topography on scene radiance across wavelengths and incidence angles for both forest types. Statistically this is reflected in a reduction in correlation coefficients and in the magnitude of the F-statistics and in an increase in the magnitude of the p-values (Table 2.3). Empirically derived estimates of the Minnaert constant, $k$, for both coniferous and deciduous forest types vary with wavelength and are highly class specific, particularly in the NIR (Fig 2.6). At all wavelengths and for both generalized forest types values of $k$ are considerably less than one indicating that neither generalized forest type at any wavelength functions as a Lambertian reflector. However, as demonstrated by Ekstrand (1996) for Norway spruce, values of $k$ may approach unity (equivalent to a Lambertian correction) at high values of $\cos i$ if the Minnaert constant
is also computed by varied incidence angle for each wavelength.

Although the more general wavelength approach was employed in this study, the similarity of correction of pixel radiance at high values of \( \cos i \) for both the Lambertian and Minnaert correction functions evaluated here would also suggest that more precise correction might be achieved by calculating the correction factor for different values of \( \cos i \) at each wavelength.

This analysis suggests:

- The spectral effect of topography is likely to be present in even relatively well illuminated remote sensing data of forest cover in areas of complex terrain, even in areas characterized by relatively gentle to moderate topography.

- As has been observed by others in the analysis of multi-spectral data, it is likewise observed that the spectral effect of topography in hyperspectral data varies both by wavelength and incidence angle, and is class specific. Only correction approaches that take into account these dependencies are likely to be effective in reducing this effect.

- Lambertian correction functions applied to remote sensing images of areas of even moderate terrain complexity are likely to introduce greater spectral variance, dependent both on incidence angle and wavelength, than is present in an uncorrected image.

Figure 2.6. Empirically derived Minnaert constants, \( k \), by wavelength (excluding wavelengths dominated by water absorption) and generalized forest types for 12 August 1997 AVIRIS image of the Bartlett Experimental Forest.
**Topographic Normalization and the Prediction of Canopy Chemistry**

**Derivative Spectra.**

The remote sensing of forest canopy chemistry is based on the empirical correlation of both visible and near-infrared spectral absorbance features with field-measured foliar chemistry (Wessman et al. 1988; Matson et al. 1994; Martin and Aber 1997). Such analysis using full spectrum or hyperspectral data typically involves the application of first- or second-order derivatives to absorbance spectra prior to calibration. The efficacy of spectral derivatives in such analysis stems from two effects: the resolution of overlapping spectral peaks and the removal of both linear and, with derivatives of second-order or higher, curvilinear baselines (Hruschka 1987). Thus, spectral derivatives should be relatively insensitive to variations in illumination caused by changes in sun-sensor-target geometry that result in primarily linear (first-order) or curvilinear (second-order) effects.

A graphical comparison of absorbance spectra and first order derivatives by both relative topographic illumination (shaded \(\cos i = 0.62\), neutral \(\cos i = 0.83\), and bright \(\cos i = 0.95\) conifer dominated pixels) and topographic illumination compensation treatment (Uncorrected, Cosine, Minnaert) for a topographically shaded conifer site \(\cos i = 0.62\) from the 12 August 1997 AVIRIS image of the BEF is presented in Fig. 2.7. Differences in topographic illumination are manifest primarily as differences in the magnitude, rather than shape of the spectral response. Spectral shape differences may be attributed to compositional differences (white pine-hardwood, red spruce-hemlock, red spruce-balsam fir, respectively) among the selected conifer dominated pixels. Similarly, topographic illumination normalization by both the Minnaert and Cosine correction approaches has the effect of “brightening” the shaded spectra relative to its original response (i.e. increasing reflectance and hence decreasing absorption) resulting in an overall baseline shift in the
Figure 2.7. Absorbance spectra and first order derivative for (a) topographically shaded (cos $i = 0.62$), neutral (cos $i = 0.83$) and bright (cos $i = 0.95$) conifer pixels and (b) by topographic normalization treatment (Uncorrected, Cosine, Minnaert) for a topographically shaded site (cos $i = 0.62$) from the 12 August 1997 AVIRIS image of the BEF.

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spectra. Cosine corrected spectra demonstrate not only a baseline shift in brightness but a strong wavelength dependency in the visible spectral range, indicated by a change in the shape of the spectra. Similar but much lower magnitude wavelength dependency is also apparent in the infra-red (>2220 nm) between the uncorrected and corrected spectra.

First-order spectral derivatives illustrate the removal of the baseline shift due to difference in topographic illumination among shaded, neutral and bright pixels and between the uncorrected and corrected data, but do so only partially for Cosine corrected visible spectral wavelengths. As the 1st derivative of a spectrum is simply a measure of the slope of the spectral curve at every point, the slope of the curve is not affected by baseline offsets in the spectrum.

Although demonstrably an artifact of the illumination compensation method, non-linear spectral offsets in the visible wavelengths of the Cosine corrected data are likely to be removed by a second-order derivative. The 2nd derivative is a measure of the change in the slope of the curve. In addition to removing the offset, it is not affected by curvilinear trends that may exist in the data, and is therefore a very effective method for removing both the baseline offset and slope from a spectrum. However, caution must be used in applying higher-order derivatives to hyperspectral remote sensing data. Even in laboratory spectroscopy where illumination, viewing geometry, and target can be highly controlled, higher order derivatives have been found to be more sensitive to noise and are thus apt to generate more spectral artifacts than the lower-order derivatives, as well as having more difficult interpretation (Hruschka 1987). Such effects are likely to be exacerbated when using hyperspectral remote sensing data of lower spectral resolution and which relies on the natural illumination, through a varying atmosphere, of mostly non-homogeneous pixels of coarse spatial resolution (often of tens to several tens of meters).
Spectral Calibration of Canopy Chemistry: Effect of Illumination Correction.

First-order derivative absorbance spectra for each illumination correction treatment from each image date were correlated with plot-level canopy chemistry for each site using two common multivariate NIR calibration methods. Only results for prediction of nitrogen concentration are presented here.

Because of the high level of correlation between plot-level nitrogen concentration between years ($R^2 = 0.95, p < 0.000$) and the potential sensitivity of the MLR calibration method to between year sample size differences, nitrogen concentration data from 1995 plots that were not also sampled for foliar chemistry in 1997 (Table 2.1) was used to augment the 1997 foliar chemistry data set for this analysis. Whole canopy foliar chemistry from 48 plots was used in analysis of spectral data from each year.

As might be expected based on examination of first-order derivative absorbance spectra, differences in prediction accuracy between topographic illumination corrected and uncorrected data were not substantial (Table 2.3). Cosine corrected spectra gave the poorest calibration both between years and between calibration approaches having in all cases the lowest correlation coefficients ($R^2$) and highest standard errors of calibration (SEC) and cross-validation (SECV). Based on wavelength selection from the MLR calibration approach for the Cosine corrected spectra, predominant wavelengths are in the 730 nm and 650 nm regions of the spectrum. This region represents segments most highly correlated with foliar chlorophyll concentration (Gates et al. 1965; Curran 1989; Martin and Aber 1997) and, hence, total nitrogen content, and most susceptible to spectral artifacts introduced by the Cosine correction approach. Wavelength selection between uncorrected and Minnaert corrected spectra are much more similar, but not identical. Main differences arise from the number of significant terms selected by the calibration approach (1995 image) and
Table 2.4. AVIRIS calibration equations for nitrogen, derived from 12 August 1997 and 3 July 1995 imagery of the Bartlett Experimental Forest using data from 48 plots, by calibration method and illumination correction type.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Year</th>
<th>Terms</th>
<th>Wavelength (nm)</th>
<th>( R^2 )</th>
<th>SEC(^\dagger )</th>
<th>SECV(^\ddagger )</th>
<th>CV(^* )</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>1995</td>
<td>3</td>
<td>731, 1144, 1038</td>
<td>0.78</td>
<td>0.19</td>
<td>0.21</td>
<td>0.11</td>
<td>1.83</td>
<td>0.93-2.48</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>732, 1154, 807</td>
<td>0.79</td>
<td>0.19</td>
<td>0.21</td>
<td>0.12</td>
<td>1.81</td>
<td>0.88-2.48</td>
</tr>
<tr>
<td>Minnaert</td>
<td>1995</td>
<td>2</td>
<td>730, 1144</td>
<td>0.74</td>
<td>0.20</td>
<td>0.21</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>656, 1144, 2059</td>
<td>0.80</td>
<td>0.19</td>
<td>0.20</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosine</td>
<td>1995</td>
<td>1</td>
<td>721</td>
<td>0.66</td>
<td>0.23</td>
<td>0.25</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>731, 1144, 656</td>
<td>0.75</td>
<td>0.21</td>
<td>0.23</td>
<td>0.13</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Year</th>
<th>Factors</th>
<th>( R^2 )</th>
<th>SEC(^\dagger )</th>
<th>SECV(^\ddagger )</th>
<th>CV(^* )</th>
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<tbody>
<tr>
<td>Uncorrected</td>
<td>1995</td>
<td>3</td>
<td>0.83</td>
<td>0.18</td>
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<td>0.13</td>
<td>1.83</td>
<td>0.93-2.48</td>
</tr>
<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>0.84</td>
<td>0.17</td>
<td>0.23</td>
<td>0.13</td>
<td>1.81</td>
<td>0.88-2.48</td>
</tr>
<tr>
<td>Minnaert</td>
<td>1995</td>
<td>3</td>
<td>0.80</td>
<td>0.19</td>
<td>0.24</td>
<td>0.13</td>
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<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>0.84</td>
<td>0.17</td>
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<tr>
<td>Cosine</td>
<td>1995</td>
<td>3</td>
<td>0.77</td>
<td>0.19</td>
<td>0.25</td>
<td>0.14</td>
<td></td>
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<tr>
<td></td>
<td>1997</td>
<td>3</td>
<td>0.79</td>
<td>0.19</td>
<td>0.25</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \dagger \) Standard error of calibration  
\( \ddagger \) Standard error of cross-validation  
\( \ast \) Coefficient of variation

\(^\dagger\) Standard error of calibration  
\(^\ddagger\) Standard error of cross-validation  
\(^\ast\) Coefficient of variation
the selection of wavelengths in the spectral region of lowest radiometric precision (≥ 2000 nm) and hence of highest sensitivity to noise in the AVIRIS spectra (1997 image). These differences may be artifacts of the correction approach and the resulting wavelength dependent change in spectral shape at higher wavelengths relative to the uncorrected spectra. These analyses suggest:

- The spectral first derivative (representing differences in the slope of the spectral response) is insensitive to variation in illumination introduced by varying sun-sensor-target geometries, effectively removing baseline illumination offsets.

- There is no demonstrable predictive benefit in the calibration of canopy chemistry introduced by topographic illumination compensation techniques.

- Evident reduction in prediction accuracy of canopy chemistry calibration is introduced by the Cosine correction approach because of wavelength and incidence angle dependent spectral artifacts introduced by this method.
AVIRIS Calibration: Comparison of Statistical Methods

Studies comparing various NIR calibration methods for prediction of chemical constituents have generally been restricted to laboratory analysis of mostly agricultural products. These studies have consistently shown the higher predictive power of partial least squares (PLS) derived calibration equations over those derived by other methods, including multiple linear regression (MLR) (Shenk and Westerhaus 1991). Similarly, in a laboratory study of woody species native to the northeastern U.S., Bolster et al. (1996) demonstrated that PLS performed better than stepwise MLR in the calibration and prediction of chemical constituent concentration of dry, ground, green foliage samples. A number of studies have employed MLR calibration in the prediction of forest canopy chemistry using full spectrum remote sensing data (Wessman et al. 1988; Matson et al. 1994; Martin and Aber 1997) however, no comparison of MLR and PLS calibration approaches for prediction of forest canopy chemistry, similar to those undertaken in laboratory studies, have been undertaken.

MLR is one of the most widely used spectroscopic calibration methods and is based on the concept, derived from Beer’s Law, that constituent concentration is a function of absorbance at a series of given wavelengths (Martens and Naes 1987). When applied in a step-wise manner, as in this analysis, many wavelengths combinations are iteratively tested for calibration, with the final equation consisting of the best statistical combination of wavelengths for prediction of constituent concentration. Although MLR is a robust model that is computationally efficient and relatively straightforward to interpret, MLR is subject to a number of limitations that are particularly significant relative to its application to full spectrum remote sensing data.

First, even in a laboratory setting where illumination and target can be well controlled, calibration wavelength selection by MLR is often difficult and/or inconsistent.
from sample set to sample set. This effect is likely to be more significant for "noisier" remotely sensed full spectrum data as the target, illumination, and path length can vary widely both within an image and between image dates. The AVIRIS sensor, as do all optical remote sensing systems, relies on natural illumination of a constantly varying target. Moreover, such sensors are of much lower signal-to-noise and of coarser spectral resolution than laboratory NIRS systems.

Second, the number of calibration samples limits the number of wavelengths used in an MLR calibration. A large number of samples (usually ten each per wavelength and regression constant) are required to avoid overfitting and to obtain an accurate and robust calibration (Hruschka 1987). Generally the most limiting factor in the classification of remote sensing data, and in this case the quantitative calibration of remote sensing data to canopy chemistry, is the adequacy of the ground reference data set. It is often difficult, time-consuming, and expensive to collect detailed, large sample size data over the extensive landscapes which are usually the target of remote sensing investigations. This is particularly true in the collection of field-based forest canopy chemistry, as temporal changes in canopy chemistry over the growing season further constrain sampling to relatively narrow time-frames (+/- 10 days) around sensor over-flight (Martin and Aber 1997).

An alternative calibration technique is PLS which is a quantitative spectral decomposition method that is computationally similar to principal component regression (PCR) (Martens and Naes 1987). In both PCR and PLS, full spectrum data is reduced to a smaller set of independent variables, or factors. However, instead of first decomposing the spectral data to a set of eigenvectors and scores and then regressing them against constituent concentrations as in PCR, in PLS the constituent concentration information is used directly during the spectral decomposition process (Shenk and Westerhaus 1991). As a result,
loadings for each wavelength for each PLS factor, from which regression coefficients for each wavelength are derived, are directly related to constituent concentration. The first few PLS factors describe the spectral variation most relevant to the modeling of the variation in the chemical data, with later factors segregating variation attributable to noise. Although PLS is similarly limited by constituent sample size in the number of factors to be included in the final calibration model (like MLR in the number of terms), the advantage of PLS lies in its use of the full spectral coverage in each factor rather than a few selected wavelengths as in MLR and in the direct relationship between regression factors and the constituent of interest rather than simply with the largest common spectral variations as in PCR (Martens and Naes 1987).

Comparisons between MLR and PLS regressions are based on several metrics including the coefficient of determination ($R^2$), the standard error of calibration (SEC) and cross-validation (SECV), and the coefficient of variation (CV) for each image data and sample set. SEC, the standard deviation of the residuals, is the difference between field-measured foliar chemistry and AVIRIS predicted foliar chemistry and is calculated as the square root of the mean square for the residuals for $n-1-p$ degrees of freedom. SECV is the square root of the mean square of the residual for $n-1$ degrees of freedom. SECV is calculated based on an iterative calibration and prediction of each sample and is usually larger than the SEC, but is a better estimate of the prediction accuracy of the equation. The CV is the ratio of the SECV to the mean and so expresses, as a simple percentage, the equation prediction variability relative to the mean nitrogen concentration for each year. Equation performance between years, where an equation developed for one year’s spectral and constituent data is applied to another year’s spectral and constituent data, is evaluated using the coefficient of determination and standard error of prediction (SEP). SEP is a true
measure of performance of the equation on unknown samples and is the preferred statistic to use for comparison of regression equations (Westerhaus 1989).

Comparisons between MLR and PLS regression (Table 2.4 (previous section), Fig. 2.8) show consistently higher $R^2$ values and lower SEC values for the PLS equations. Values of SECV, and consequently CV, are slightly higher for the PLS equations. However, when MLR and PLS equations from each image date were applied to constituent and spectral data from the other image date, PLS based equations performed better, having both lower and more similar SEP values and higher and more similar correlation coefficients between years than either MLR equation (Table 2.5). This difference in the between year MLR calibrations can be attributed to differences in equation wavelength selection for each year (Table 2.4).

These results suggest that the full-spectrum PLS based calibration equations are more robust to small to moderate between year differences in AVIRIS spectral response even when the calibration data set allows only a modest number of regression factors to be included in the calibration.

Table 2.5. AVIRIS between year prediction of nitrogen concentration. Results are obtained from the application of calibration equations developed for one image date, by each regression method, to spectral data from another image date.

<table>
<thead>
<tr>
<th>Calibration Equation</th>
<th>1997 Predicted Nitrogen (%)</th>
<th>1995 Predicted Nitrogen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>SEP†</td>
</tr>
<tr>
<td>1995 MLR</td>
<td>0.59</td>
<td>0.27</td>
</tr>
<tr>
<td>1995 PLS</td>
<td>0.67</td>
<td>0.27</td>
</tr>
<tr>
<td>1997 MLR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997 PLS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Standard error of prediction
‡ Coefficient of variation

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Figure 2.8. AVIRIS predicted vs. field measured canopy nitrogen concentration by calibration method and image date for the 48 chemistry calibration plots at the BEF.

Figure 2.9. AVIRIS derived between year prediction of nitrogen concentration, (a) 1995 nitrogen concentration predicted by 1997 image date MLR and PLS equations and (b) 1997 nitrogen concentration predicted by 1995 image date MLR and PLS equations.

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Overall, between year calibration was much poorer than within year calibration, demonstrating both prediction bias and greater dispersion of predicted values (Fig. 2.9). Several factors likely contribute to this result. Certainly variable atmospheric conditions exist between image dates, and hence differing ATREM calculated apparent reflectance is likely to affect application of wavelength specific regression coefficients between image dates as in PLS calibration, and in particular, wavelength selection as in the MLR calibration. This effect is likely greater when a small calibration data set constrains the number of factors or terms used in calibration equation development. Further, the interpolation of 1995 wavelength centers and radiance to 1997 wavelength centers by a simple linear interpolation might be inadequate and could require a more complex interpolation model.

This analysis suggests:

• As demonstrated by Bolster et al. (1996) in a laboratory setting and extended here with full spectrum remote sensing data to whole canopies, the full-spectrum calibration method, PLS, performed better than stepwise MLR in the prediction of forest canopy nitrogen concentration from AVIRIS data.

• Improved between image date calibration is achieved based on the full spectrum PLS approach and the normalization of between year radiance to uniform wavelength centers.

• Scene specific atmospheric corrections and a more complex wavelength centered radiance interpolation method may further improve between year canopy chemistry predictions.
Conclusions

The spectral effect of topography on AVIRIS spectral response has been described in this paper. The effect was found to be non-Lambertian and to vary with wavelength, incidence angle, and forest type. Even relatively simple illumination compensation methods incorporating the BRDF of vegetation, by employing the empirically derived Minnaert constant, were more effective in reducing this effect than were methods based on a purely Lambertian assumption. Lambertian based methods introduced significant wavelength and incidence angle dependent spectral artifacts not present in the original spectral data.

Image analytical methods based on derivative spectra effectively removed baseline offsets in illumination caused by variable within scene sun-sensor-target geometry, hence, canopy chemistry calibration methods based on derivative spectra were not sensitive to topographically dependent within scene illumination differences. Illumination compensation methods had little effect on canopy chemistry calibration, except for the Cosine (Lambertian) correction method which introduced significant spectral artifacts resulting in an overall poorer calibration.

The full spectrum NIRS calibration method, PLS performed better than stepwise MLR in the prediction of forest canopy nitrogen concentration from AVIRIS data both within a given image and between image dates. Scene specific atmospheric correction and improved between year correspondence among wavelength centered radiance are two radiometric correction strategies likely to further improve application of canopy chemistry calibration equations among image dates.
Chapter III

PREDICTION OF FOREST PRODUCTIVITY BY REMOTE SENSING OF CANOPY NITROGEN

Summary

The concentration of nitrogen in foliage has been related to rates of net photosynthesis across a wide range of plant species and functional groups (Field and Mooney 1986, Reich et al. 1999a) and thus represents a simple and biologically meaningful link between terrestrial cycles of carbon and nitrogen. Although foliar N is used by many ecosystem models to predict leaf-level photosynthetic rates, it has rarely been examined as a direct scalar to stand-level carbon gain. Establishment of such relationships would greatly simplify the nature of forest carbon and nitrogen linkages, enhancing our ability to derive estimates of net primary production at the landscape to regional scale (Scurlock et al. 1999, Fung 1997). Here, we report on a highly predictive relationship between whole canopy nitrogen concentration and aboveground forest productivity in 88 forested stands of varying age and species composition across the 300,000 ha White Mountain National Forest, New Hampshire, USA. We also demonstrate that hyperspectral remote sensing can be used to predict foliar nitrogen concentration, and hence forest production across a large number of contiguous images. Together these data suggest that canopy nitrogen concentration is a dominant physiological control on the rate of productivity and hence carbon accumulation.
in forested systems, and that imaging spectrometry of canopy nitrogen can provide direct estimates of forest productivity across large landscapes.

**Introduction**

Temperate forests have been identified as a potentially important sink for atmospheric CO$_2$ (Fan et al. 1998, Houghton et al. 1999). The production of new biomass is a key process in the total carbon balance of forests, but one that is difficult to estimate accurately over large areas due to fine scale variation in this process resulting from natural environmental heterogeneity overlain by complex patterns of human land use (Schimel et al. 1997).

A number of field studies across diverse biomes have documented strong linkages among foliar chemistry, particularly nitrogen (N) concentration on a mass basis, and rates of net photosynthesis (Field and Mooney 1986, Reich et al. 1999a) and soil N availability (Pastor et al. 1984, Yin 1992, Scott and Binkley 1997). These results suggest that foliar N concentration could provide a powerful indicator of ecosystem productivity, and one that could be used to capture fine-scale variation in this process, if a method were available to measure the nitrogen content of foliage with high spatial resolution over large areas. Despite this potential, such relationships have rarely been investigated. A limited number of studies have demonstrated relationships between foliar nitrogen concentration and forest productivity within individual species (Cole and Rapp 1981, Van Cleve et al. 1983), but no widely acknowledged patterns of whole-canopy foliar chemistry versus whole-forest production have emerged.

Similarly, the remote sensing of foliar chemistry has been generally restricted to small experimental areas (Wessman et al. 1988, Matson et al. 1994, Martin and Aber 1997). While the use of high spectral resolution reflectance methods for the direct measurement of
nitrogen, lignin, cellulose, and other chemical constituents of foliage has become an accepted laboratory technique (Martin and Aber 1997, Gillon et al. 1999, Kokaly and Clark 1999),
general applications of high spectral resolution remote sensing to the measurement of whole canopy chemistry have been few. Application of a single calibration equation across multiple contiguous images covering a large, forested landscape has not been achieved.

Here we present the first direct estimates of forest productivity across a complex forested landscape developed by estimating whole canopy foliar N concentrations from high resolution imaging spectrometry. These estimates are based upon a strong three-way relationship among measured canopy N concentration, measured wood and foliar production, and the remote sensing signal for a diverse and spatially extensive set of field sites.

Results and Discussion

Our research was conducted in the White Mountain National Forest, New Hampshire, USA and focused on 88 forested sites distributed across the 300,000 ha forest. The sites included a mix of deciduous broad-leaved and evergreen needle-leaved species and covered a broad range of environments and land-use histories.

Aboveground woody biomass production (AWBP) for each site was estimated by repeated measurements of stem diameter converted to biomass values with allometric equations. Production of foliar biomass was estimated by collection of leaf litterfall from a subset of these stands. Total above ground net primary production (ANPP) is the sum of these two processes.

Foliar N concentrations for species in each stand were determined by visible and near-infrared reflectance spectroscopy of mid-summer replicate collections of green foliage from upper- and mid-canopy positions (Martin and Aber 1997, McLellan et al. 1991, Bolster
et al. 1996). Whole canopy N concentration was calculated as the sum of foliar N concentration for individual species in each sample stand, weighted by fraction of canopy foliar mass per species.

ANPP varied by nearly a factor of three across the study sites (280 – 752 g m\(^{-2}\) yr\(^{-1}\)) and AWBP (163 – 516 g m\(^{-2}\) yr\(^{-1}\)) showed even greater relative variation. Foliar production varied more than five-fold (51 – 267 g m\(^{-2}\) yr\(^{-1}\)) reflecting differences in foliar retention time between functional types (broad-leaved deciduous and needle-leaved evergreen), and comprised from 20% to 45% of total ANPP. Canopy N concentration varied more than two-fold across all sites (1.09 % – 2.48 %) and differed in both mean and range between functional types (deciduous: 2.05 % (1.61% – 2.48 %); evergreen: 1.33 % (1.09 % –1.80 %)).

Across all sites, ANPP and AWBP were highly correlated with measured whole canopy foliar N concentration (Fig. 3.1). Production was more strongly related to mass-
based foliar N concentration than with either total canopy N content or canopy leaf area index (LAI). We attribute this to the greater importance of photosynthetic capacity in the upper, well-lit canopy layers of closed-canopy forests in determining total carbon gain and the lesser importance of additional leaf mass in lower, darker layers (Aber et al. 1996, Reich et al. 1999b).

Remote sensing data were acquired using NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) on 12 August 1997. Flying aboard an ER-2 aircraft at an altitude of 20 000 m, AVIRIS measures upwelling radiance from the solar reflected spectrum in 224 contiguous channels from 0.4 to 2.4 \( \mu \text{m} \) with a spectral resolution of 0.01 \( \mu \text{m} \) (Green et al. 1998). Fifty-six contiguous 10 x 10 km scenes with a spatial resolution of 20 m comprise the AVIRIS data set for the study area.

Partial least squares regression (PLS), a quantitative spectral decomposition method by which full spectrum data and constituent concentration data are simultaneously reduced to a smaller set of independent factors, was used to relate AVIRIS spectral response to foliar nitrogen concentration (Martens and Naes 1987, Shenk and Westerhaus 1991). Strong correlations between measured whole canopy nitrogen concentration and transformed AVIRIS absorbance spectra were found both within and across scenes and were strongly associated with absorption features in both the visible and infra-red spectrum (Table 3.1, Fig. 3.2).

<table>
<thead>
<tr>
<th>PLS Factors</th>
<th>AVIRIS Scenes</th>
<th>N</th>
<th>( R^2 )</th>
<th>SECV*</th>
<th>CV*</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>48</td>
<td>0.84</td>
<td>0.23</td>
<td>0.13</td>
<td>1.81</td>
<td>0.88-2.48</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>88</td>
<td>0.82</td>
<td>0.25</td>
<td>0.13</td>
<td>1.88</td>
<td>0.88-2.48</td>
</tr>
</tbody>
</table>

* Standard error of cross-validation
* Coefficient of variation

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Figure 3.2. Results of PLS regression for 88 forest canopy nitrogen concentration calibration samples among 56 AVIRIS scenes. Latent variables (loadings) of the first three significant PLS factors are plotted against wavelength, excluding wavelength regions associated with strong water absorption features centered at 1450 and 1950 nm. Together these factors account for 82% of the variability in nitrogen concentration (Table 1), each factor accounting for 53%, 23%, and 6% of the variability, respectively. Important wavelength regions for prediction of canopy nitrogen concentration are those in the visible range centered near 490 nm and 680 nm associated with chlorophyll absorption features, and those in the near-infrared centered near 1150 nm, 1510 nm, 1740 nm, and 2050 nm associated with protein and nitrogen absorption features.
Important absorption features in the visible region have direct association with photosynthetic pigments, while those at near infrared wavelengths represent overtones of fundamental absorption characteristics of N-H and C-H bonds at longer wavelengths which are associated with leaf proteins and which differ from those of other major leaf components (Curran 1989, Barton et al. 1992). Because of this distinct pattern, nitrogen, which is typically a small percentage of leaf biomass, has been repeatedly correlated in many investigations with spectral absorbance over the spectral regions identified in this study (Matson et al. 1994, Martin and Aber 1997, Kokaly and Clark 1999).

These results represent the first successful derivation of a single calibration equation for the prediction of nitrogen concentration across multiple images. Moreover, the calibrations developed by this method for these data, both within and among AVIRIS scenes, fall well within the accuracy and precision required for mapping variation in foliar nitrogen necessary to distinguish between ecosystems in their photosynthetic and, hence, productive potential (Schimel 1995). We attribute this success to a careful, multi-step field data-to-image calibration process and to the use of the PLS method for calibration equation derivation.

The statistical relationships described in Table 1 were used in conjunction with AVIRIS data to produce a map of canopy nitrogen concentration for the White Mountain National Forest (Fig 3.3a), and thus, using the relationship in Fig. 1, a map of AWBP (Fig 3.3b). Spatial patterns in both images broadly reflect the distribution of functional types. Broad-leaved deciduous species dominate areas with foliar N concentrations higher than 1.9%, needle-leaved evergreens dominate those below 1.3%, and intermediate areas are of mixed types. Fine-scale spatial variations result from a variety of natural and anthropogenic
Figure 3.3. Spatial distributions of (a) AVIRIS predicted nitrogen concentrations for the White Mountain National Forest, New Hampshire (see inset) and (b) aboveground woody biomass production (g m$^{-2}$ yr$^{-1}$), as estimated from AVIRIS predicted whole canopy nitrogen concentrations.
factors including species successional sequences, historic and current land-use, natural disturbance regimes, elevation, soil texture and mineralogy.

Independent field measurements of the control watershed at the Hubbard Brook Experimental Forest, NH (Whittaker et al. 1974) and more recently the Cone Pond, NH watershed (J.W. Hornbeck, pers. comm.) provide validation for AWBP estimates. Measured AWBP values for the broad-leaved deciduous control watershed at Hubbard Brook and for similar forested stands at Cone Pond are 423 and 346 g m\(^{-2}\) yr\(^{-1}\), respectively, versus AVIRIS predicted values of 404 and 367 g m\(^{-2}\) yr\(^{-1}\). For needle-leaved evergreen sites at the Cone Pond watershed, field measured estimates of AWBP are 176 and 160 g m\(^{-2}\) yr\(^{-1}\) versus AVIRIS predicted values of 162 and 174 g m\(^{-2}\) yr\(^{-1}\). These values fall within the observed precision with which AWBP can be measured by this method at the stand level (Fig. 3.1).

The low values for foliar N and productivity among evergreens at Cone Pond may reflect a long-term reduction in nitrogen availability that is the legacy of a severe fire that consumed large parts of the watershed in 1820 (Aber and Driscoll 1997).

Together these data strongly suggest,

(1) that canopy nitrogen concentration is an important correlate of the rate of productivity and hence carbon accumulation in these forested systems reflecting, at the canopy-level, well known leaf-level relationships among foliar N and photosynthetic capacity (Reich et al 1999a);

(2) that canopy N concentrations may thus provide an indicator of the cumulative effects of a variety of historical and environmental factors on the productive potential of these forested systems; and,

(3) that imaging spectrometry of canopy nitrogen can provide robust, direct, and spatially explicit estimates of canopy nitrogen concentration and forest productivity across
large landscapes. Further development of this approach promises to bridge the gap between coarse-scale estimation and fine-scale variation in forest production and between broad-scale model outputs and direct field based measurements.

**Methods**

**Study Area**

A total of 88 long-term forest growth inventory plots maintained by the USDA Forest Service were used for measurements of whole canopy nitrogen content and forest productivity. Forty-eight of these were located at the 1025 ha Bartlett Experimental Forest, Bartlett, New Hampshire. The remaining stands, distributed across the White Mountain National Forest, were part of the USDA Forest Service Forest Inventory and Analysis (FIA) plot network. All stands were sampled for whole canopy nitrogen concentration, 58 of these stands were used for measurement of woody biomass production, 16 stands were also measured for foliar biomass production. The 0.1 ha stands include both early- and late-successional mixed hardwoods dominated by beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula allegheniensis* (L.) Carr), red maple (*Acer rubrum* L.) and paper birch (*Betula papyrifera* Marsh.) as well as mixed conifer stands dominated by red spruce (*Picea rubens* Sarg.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and eastern white pine (*Pinus strobus* L.).

**Calculation of Whole Canopy Mass-Based Nitrogen Concentration.**

Whole canopy N concentration was calculated as the sum of foliar N concentration for individual species in each sample stand, weighted by fraction of canopy foliar mass per species. Each species contribution to total canopy mass was determined by means of a camera-based point quadrat sampling method. The sampling device is a 35-mm camera with a telephoto lens used as a range finder, calibrated to distance in meters, and having a grid of
15 points marked on the view-finder. In each sample plot, 15 grid point observations at nine sample points for a total of 135 observations per plot were taken. Species and height to lowest leaf covering each grid point was recorded. Fraction of leaf area by height and by species was determined from foliage height profiles (Aber 1979a) and species distribution by height data. Fraction of species by leaf area was converted to fraction by weight by multiplying area fraction by measured specific leaf weight of each species and deriving a new fraction by weight for each species on sample plots.

**Calibration of AVIRIS Spectral Response to Canopy Nitrogen Concentration**

AVIRIS at-sensor radiance data were transformed to apparent surface reflectance and images were geometrically registered. AVIRIS reflectance spectra for 2x2 pixel areas covering each sample plot were extracted and converted to absorbance prior to calibration in order to linearize spectral response to chemical constituent concentration. A first-order derivative transformation was then applied to each absorbance spectrum in order to remove baseline offsets and reduce low frequency variation due to varying sun-sensor-target geometry over the study area and to resolve overlapping spectral peaks. Partial least squares regression was used to relate AVIRIS spectral response to whole canopy nitrogen concentration data for each sample stand. PLS regression methods reduce the full spectrum data to a smaller set of independent latent variables, or factors, with the constituent concentration data used directly during the spectral decomposition process. As a result, full spectrum wavelength loadings for significant PLS factors, from which regression coefficients are derived, are directly related to constituent concentration and thus describe the spectral variation most relevant to the modeling of variation in the chemical data.
REFERENCES CITED


