Remote Sensing of Environment 173 (2016) 174–186

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Examining spectral reflectance features related to foliar nitrogen in forests: Implications for broad-scale nitrogen mapping

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ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form 10 November 2015
Accepted 23 November 2015
Available online xxxx

Keywords:
Foliar nitrogen
Canopy nitrogen
Spectral reflectance
Near infrared
AVIRIS
Landsat
MODIS
Spatial resolution
Spectral resolution
Sensor fidelity

ABSTRACT

The concentration of nitrogen (N) in foliage often limits photosynthesis and can influence a number of important biogeochemical processes. For this reason, methods for estimating foliar %N over a range of scales are needed to enhance understanding of terrestrial carbon and nitrogen cycles. High spectral resolution aircraft remote sensing has become an increasingly common tool for landscape-scale estimates of canopy %N because reflectance in some portions of the spectrum has been shown to correlate strongly with field-measured %N. These patterns have been observed repeatedly over a wide range of biomes, opening new possibilities for planned Earth observation satellites. Nevertheless, the effects of spectral resolution and other sensor characteristics on %N estimates have not been fully examined, and may have implications for future analyses at landscape, regional and global scales. In this study, we explored the effects of spectral resolution, spatial resolution and sensor fidelity on relationships between forest canopy %N and reflectance measurements from airborne and satellite platforms. We conducted an exercise whereby PLS, simple and multiple regression calibrations to field-measured canopy %N for a series of forested sites were iteratively performed using (1) high resolution data from AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) that were degraded spectrally from 10 nm to 30 nm, 50 nm, 70 nm, and 90 nm bandwidths, and spatially from 18 m to 30 m and 60 m pixels; (2) data representing Landsat and MODIS (Moderate Resolution Imaging Spectroradiometer) spectral bands simulated with data from AVIRIS; and (3) actual data from Landsat and MODIS. We observed virtually no reduction in the strength of relationships between %N and reflectance when using coarser bandwidths from AVIRIS, but instead saw declines with increasing spatial resolution and loss of sensor fidelity. This suggests that past efforts to examine foliar %N using broad-band sensors may have been limited as much by the latter two properties as by their coarser spectral bandwidths. We also found that regression models were driven primarily by reflectance over broad portions of the near infrared (NIR) region, with little contribution from the visible or mid infrared regions. These results suggest that much of the variability in canopy %N is related to broad reflectance properties in the NIR region, indicating promise for broad scale canopy N estimation from a variety of sensors.

1. Introduction

The concentration of nitrogen (N) in foliage is linked to numerous biogeochemical, physiological and ecological processes and serves as a useful indicator of ecosystem metabolism. Foliar N has been repeatedly identified as a useful predictor of photosynthetic capacity, or A_{max} (Evans, 1989; Field & Mooney, 1986; Reich et al., 1999; Wright et al., 2004); it has been related to stand-level processes such as net primary production (NPP) and canopy light use efficiency (Green, Erickson, & Kruger, 2003; Kergoat, Lafont, Arneth, Le Dantec, & Saugier, 2008; Smith et al., 2002); it provides a widely used measure of herbivore forage quality and susceptibility to defoliation (Jefferies, Klein, & Shaver, 1994; Mattson, 1980; Peeters, 2002); and can provide direct input to ecosystem models (Ollinger & Smith, 2005; Wythers, Reich, Tjoelker, & Bolstad, 2005).

In addition to its influence on carbon assimilation, foliar %N is also tied to the availability of N in soils through mechanisms involving litter decay, net mineralization and plant N uptake (Merilä & Derome, 2008; Ollinger et al., 2002; Parton et al., 2007). This is important given the degree to which humans have perturbed the N cycle globally (e.g., Galloway et al., 2003), and the tendency for N to limit productivity in terrestrial ecosystems (Jandl et al., 2007; Vitousek & Howarth, 1991).

Despite its many important roles, foliar %N is rarely used as a driver in regional- to global-scale analyses. This is, in part, because we lack a reliable means of extending foliar N field measurements to broad-scale spatial patterns. At finer scales (~100–1000 km^2), the capacity for foliar N estimation has been repeatedly demonstrated using high spectral resolution remote sensing instruments, or imaging spectrometers (e.g., Asner & Vitousek, 2005; Coops, Smith, Martin, & Ollinger, 2003; Martin & Aber, 1997; McNeil et al., 2008; Ollinger & Smith,

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http://dx.doi.org/10.1016/j.rse.2015.11.028
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2005; Smith, Martin, Plourde, & Ollinger, 2003; Townsend, Foster, Chastain, & Currie, 2003; Wessman, Aber, Peterson, & Melillo, 1988), whose narrow bands can record spectral features that result from electron transitions in pigments and/or are associated with other biochemical constituents in foliage (e.g., Curran, 1989; Curran, Kupiec, and Smith, 1997; Kokaly & Clark, 1999). Martin, Plourde, Ollinger, Smith, and McNeil (2008) further demonstrated that relationships between field-measured %N and canopy spectral properties were strongly driven by NIR reflectance patterns, and were consistent enough across boreal, temperate and tropical forests, to allow development of a single, generalized partial least squares (PLS) equation. Still, application of these methods has been limited because presently available imaging spectrometers have swath widths in the range of 10 km or less and because the potential for similar approaches using other instruments has not been thoroughly tested.

There are at least two potential solutions to this problem. The first is development of a space-based imaging spectrometer capable of providing regional to global coverage. Although planning for such instruments is underway (e.g., HyspIRI; Chien, Silverman, Davies, & Mandl, 2009; National Research Council, 2007), it will likely be years before data become routinely available. A second possibility is to evaluate the degree to which foliar %N might also be estimated using spectral features available from existing sensors that provide broader spatial coverage. Potential for this approach was suggested by Ollinger et al. (2008) and Ollinger (2011) who observed that reflectance over broad portions of the NIR region was strongly correlated with measured %N in temperate and boreal forests, and by Martin et al. (2008) whose generalized partial least squares %N model was most heavily influenced by reflectance across the NIR plateau from 750 nm to 1250 nm. Although there have been other indications that broad-band spectral features contain information related to variability in canopy N (Gamon et al., 1995; Hollinger et al., 2010; Zhao et al., 2005), no studies to date have focused explicitly on how variability in spectral resolution, spatial resolution and sensor fidelity affect foliar N estimation capabilities.

In this study, we examined the influence of spectral resolution, spatial resolution and sensor fidelity on relationships between observed patterns of foliar %N and canopy reflectance. Sensor fidelity refers to the combination of signal-to-noise ratio (SNR), detector uniformity and stability of electronics in an imaging system that together affect the quality of spectra (e.g., Asner et al., 2007; Chen, Ji, Zhou, Chen, & Shen, 2012; Kokaly, Asner, Ollinger, Martin, & Wessman, 2009, Mouroulis & McKerns, 2000). Our analysis draws on a combination of remote sensing and coordinated field measurements from 155 plots within 13 forested research sites across North America. Field measurements were used to evaluate imaging spectrometer data from AVIRIS (high spectral resolution, high spatial resolution, high sensor fidelity); broad-scale sensor data from MODIS (moderate spectral resolution, coarse spatial resolution, high sensor fidelity) and broad-band data from Landsat 5 (coarse spectral resolution, moderate spatial resolution, moderate data fidelity). We also examined relationships between field-measured foliar %N and reflectance in visible and infrared wavelengths on their own, and in several commonly used vegetation indices, in order to evaluate their potential roles in future studies of %N estimation.

2. Methods

2.1. Study sites and field data collection

Our analysis used an existing collection of data from several previous investigations (Ollinger, 2011; Ollinger et al., 2008; Martin et al., 2008) that included thirteen North American research sites representing temperate and boreal evergreen needleleaf and deciduous broadleaf and mixed forests, spanning a range of ages. Site descriptions and sampling dates are given in Table 1.

At each site, samples of sunlit canopy foliage were collected from eight to twenty ~20 × 20 m plots, generally located within a 7 × 7 km area, in conjunction with acquisition of AVIRIS imagery (see Section 2.2.1). Plots were chosen to capture the range of floristic and landscape conditions that occurred over the local landscape at each site. At each plot within each site, sunlit leaves from three or more trees of each dominant and co-dominant species were collected from several heights in the canopy. Leaves were collected either by employing professional tree climbers, by shotgun sampling of small branches (e.g., Smith et al., 2002), or by using telescoping pole pruners where this was sufficient for reaching upper canopy foliage. All foliage samples were oven dried at 70 °C and ground with a Wiley Mill to pass through a 1 mm mesh screen. Analysis for foliar N concentrations, recorded as percent by foliar mass, was conducted with a FOSS NIR spectrometer using methods developed by Bolster, Martin, and Aber (1996).

Converting species-level N concentrations to plot-level mean %N, or whole canopy %N, required estimates of canopy composition, so that foliar N concentrations could be weighted by the fraction of the canopy occupied by each species. Canopy composition at each plot was determined using a camera point-quadrat sampling technique, combined with leaf mass per unit area (LMA) measurements obtained for most of the sites and species we sampled. Where LMA data were not obtained directly (typically for species representing only a small fraction of the canopy), estimates were taken from other published sources (Reich, Kloeppel, Ellsworth, & Walters, 1995; Reich et al., 1999; Smith & Martin, 2001). The camera point-quadrat method employs a 35-mm camera with a telephoto lens used as a range finder (calibrated to distance in meters) and a gridded focusing screen. Using this method, 15 grid point observations at nine sampling stations (plot center and each of the four cardinal and off-cardinal directions at 15 m from plot center) were taken, for a total of 135 observations per plot. LMA data were used to convert fractional leaf area for each species to fractional canopy mass. The camera point-quadrat method has long been used for determining canopy composition and height distributions (Aber, 1979a,b) and has also been shown to produce foliar %N estimates consistent with those calculated with species compositions determined from leaf litterfall collection (Smith & Martin, 2001).

A total of 171 plots were sampled across all sites, with more than 2500 individual foliage samples collected for foliar N analysis. After screening for cloud cover and data quality, a total of 155 field plots were available for comparison with image data. Of these, 43 plots were pure deciduous broadleaf (DBF), 59 were evergreen needleleaf (ENF), and 53 were mixed forest (MF).

2.2. Image data acquisition and processing

2.2.1. AVIRIS

Image data from the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) were obtained for all sites between 2001 and 2008 (Table 1). AVIRIS captures upwelling spectral radiance in 224 contiguous wavelengths from 360 to 2500 nm, with a 10 nm nominal bandwidth. For data collections used in this study, AVIRIS was flown on an ER-2 aircraft at approximately 20 km above sea level, producing imagery with a swath width of approximately 11 km, and a pixel size of approximately 18 m. (Details for the sensors used in this analysis are listed in Table 2.)

Field data collection took place within 2–3 weeks of image acquisition whenever possible, although longer lags occurred where constraints were imposed by weather conditions or sensor availability. In a few cases, overflights during the year of field sampling were unsuccessful, but imagery was later obtained from a similar portion of the growing season during a subsequent year. Although less than ideal, we included these data in the analyses because spatial patterns of foliar N were likely to be retained, and also because inter-annual variation in foliar N is typically small relative to the large degree of spatial variation over which we sampled. Nevertheless, some inter-annual variation in