Remote Sensing of Environment 112 (2008) 3511–3519

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

# A generalizable method for remote sensing of canopy nitrogen across a wide range of forest ecosystems

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ARTICLE INFO

*Article history:*
Received 24 April 2007
Received in revised form 10 April 2008
Accepted 12 April 2008

*Keywords:*
Hyperspectral
AVIRIS
Hyperion
Foliar nitrogen
Remote sensing

ABSTRACT

A growing number of investigations have shown that remote sensing of foliar nitrogen (N) concentration in plant canopies can be achieved with imaging spectroscopy, or hyperspectral remote sensing, from satellite or airborne sensors. Development of this approach has been fueled by recognition that foliar N is related to a variety of ecological and biogeochemical processes, ranging from the spread of invasive species to the ecosystem effects of insect defoliation events to patterns of N cycling in forest soils. To date, most studies have focused on building site-specific foliar N detection algorithms applied to individual scenes or small landscapes that have been intensively characterized with local field measurements. However, the growing number of well-measured sites, combined with improvements in image data quality and processing methods provide an opportunity to begin seeking more general N detection methods that can be applied to a broader range of sites or to locations that lack intensive field measurements.

Here, we combine data from several independent efforts in North America, Central America and Australia, to examine whether development of calibration methods to determine canopy nitrogen concentration across a wide range of forest ecosystems is possible. The analysis included data from 137 individual field plots within eight study sites for which imagery has been acquired from NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and/or Hyperion instruments. The combined dataset was used to evaluate site-specific calibration results as well as results obtained with data pooled across all sites. We evaluated the accuracy of results using plot- and site-level cross-validation wherein individual plots or entire sites were withheld and used as an independent validation of the resulting algorithms. In instances where all sites were represented in the calibration, canopy-level foliar N concentration was predicted to within 7–15% of the mean field-measured values indicating a strong potential for broadly applied foliar N detection. When whole sites were iteratively dropped from the calibration and predicted by remaining data, predictions were still significant, but less accurate (7–47% of mean canopy-level N concentration). This suggests that further development to include a wider range of ecosystems will be necessary before cross-site prediction accuracy approaches that seen in site-specific calibrations. Nevertheless, we view these results as promising, particularly given the potential value of foliar N estimates, even at a reduced level of confidence, at sites for which there is no possibility of conducting field data collections.



## 1. Introduction

The mass-based concentration of nitrogen in foliage is a key feature of forest canopies that influences a variety of important ecosystem processes. Foliar nitrogen (N) concentration is a primary regulator of physiological processes such as photosynthesis and leaf respiration (Evans, 1989; Field & Mooney, 1986; Reich et al., 1998, 2006) and is related to canopy and stand-level traits such as light use efficiency, wood growth and net primary production (Green et al., 2003; Ollinger & Smith, 2005; Smith et al., 2002) and soil factors such as litter quality, decomposition and nutrient mineralization (Aber et al., 1990; Ollinger et al., 2002; Scott & Binkley, 1997). Spatial variation in foliar N is caused by a combination of local factors such as tree species composition, soil type and disturbance history (McNeil et al., 2005; Ollinger et al., 2002), and regional- to continental-scale factors such as latitude, mean annual temperature, nitrogen deposition and incident solar radiation (Haxeltine & Prentice, 1996; McNeil et al., 2005; Yin, 1992). Temporal variation can result from short-term changes in climate or disturbance, or longer-term processes such as N deposition or plant exposure to rising $CO_2$ (Magill et al., 2004; Nowak et al., 2004).

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doi:10.1016/j.rse.2008.04.008

Given the importance of foliar N in ecosystem processes and the complexity of predicting spatial patterns across a range of scales, it is not surprising that effort has been directed towards methods of detection using remote sensing. The ability to remotely sense foliar N was first demonstrated soon after the advent of airborne imaging spectrometers. Initial work in this field (Wessman et al., 1988) built upon a history of laboratory spectroscopy in the field of agriculture (Norris et al., 1996; Shenk et al., 1979; Williams et al., 1984), but marked a shift from analysis of individual dried-ground samples to multi-pixel analysis of fresh vegetation at the canopy level. During the past two decades imaging spectrometers that have been developed include the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), the EO-1 Hyperion space-based instrument, and numerous airborne commercial instruments. Using both AVIRIS and Hyperion, investigators have recently been able to predict image-scale foliar chemistry based on intensive plot sampling (Asner et al., 2006; Coops et al., 2003; Martin & Aber, 1997; Ollinger et al., 2002; Smith et al., 2002, 2003; Townsend et al., 2003; Wessman et al., 1988) and through applications of advanced photon transport models that include relationships between leaf reflectance properties and biochemical constituents (Asner et al., 1998; Asner & Vitousek, 2005). In addition to these individual-site studies, the work of Kokaly and Clark (1999) has evaluated foliar nitrogen concentration with respect to dried-leaf reflectance over a wide range of species using a continuum-removal technique. Huang et al. (2004) has built upon this technique in their analysis of eucalypt tree-level reflectance spectra.

Despite the potential power of canopy N detection with hyperspectral remote sensing, the number of applications has been limited by data availability, difficulties associated with correcting for atmospheric effects and the expense of field campaigns required for image calibration for each individual scene. However, over the past 5–10 years, there have been substantial improvements both in sensor signal-to-noise ratios and methods for atmospheric correction. Over that same time period, the number of field sites where foliar chemistry data and coincident imagery have been collected has grown steadily. Subsequently, it is now possible to seek more generalized canopy chemistry algorithms that can be applied across a range of sites and remote sensing scenes. Development of a generalized and, hence, more operational approach would expand both the scientific user base and the ecological utility of the growing volumes of hyperspectral data that have become available. The focus of this paper is to describe an effort to combine multiple image datasets from a wide range of forest ecosystems in the development and validation of a canopy foliar nitrogen concentration algorithm that will not require image-specific plot data and calibration. In recent years, we have acquired image and plot data for multiple datasets covering diverse forested sites (mixed hardwood and conifer, tropical species), over a wide geographic range (from northern New England to Northern Florida, to Central America and Australia). These datasets have provided a unique opportunity to revisit the issue of developing a generalized foliar N prediction equation across a diversity of sites.

## 2. Methods

The analysis described in this paper was made possible through a combination of datasets collected from 2001 to the present. Prior to this effort, data were collected and analyzed for each site individually. With this effort, we combine data from eight different sites with consistent field data collections and image data from one of two hyperspectral instruments.

### 2.1. Study sites

Five of the eight sites in this study were sampled under a NASA-funded North American Carbon Program field and remote sensing campaign. The five sites, each centered on a carbon flux tower, represent a latitudinal gradient from lower coastal plain pine plantations in Florida through mixed northern hardwoods in Massachusetts and New Hampshire to the cool, moist spruce-dominated forests of Maine. Three additional study areas were sampled by this research team through different projects, and include data from New York State, Costa Rica, and Australia. The sites included in this analysis are as follows:

*Austin Cary Memorial Forest (ACMF, Florida) 29.75° N, 82.20° W*. This site comprises two AmeriFlux towers in slash pine–long-leaf pine stands (*Pinus palustris* P. Mill., *Pinus elliottii*. Engelm.). Maintained by the University of Florida, the ACMF houses a flux tower in a 65-year-old naturally regenerated slash pine–long-leaf pine forest. A tower in the adjacent Donaldson Tract measures $CO_2$ flux in a long-leaf pine plantation that has been regenerating since 1990 (Gholz & Clark, 2002).

*Duke Forest (DF, North Carolina) 35.97° N, 79.09° W*. Two of three flux towers operated in the Duke University-owned Duke Forest are included at this study site: one in an even-aged loblolly pine (*Pinus taeda* L.) plantation (~17 years old), and the other in a mature mixed hardwood stand. Both are part of the AmeriFlux network (Oren et al., 2006).

*Harvard Forest (HF, Massachusetts) 42.54° N, 72.17° W*. The Harvard Forest site includes native mixed hardwood and conifer stands and a series of conifer plantations, mainly derived from old agricultural fields and pastures. The site was established in 1907 by Harvard University, and is one of 24 NSF Long-Term Ecological Research sites. Data from the Harvard Forest includes the longest continuous carbon balance record for a forest ecosystem (Goulden et al., 1996; Wofsy et al., 1993).

*Bartlett Experimental Forest (BEF, New Hampshire) 44.06° N, 71.29° W*. The USDA Forest Service-administered Bartlett Experimental Forest is a 1050-hectare tract of secondary successional northern hardwood and mixed northern conifer forest located in the central White Mountain region of New Hampshire (Ollinger & Smith, 2005). In the early 1930s the USDA Forest Service Northeastern Research Station established 500 permanent (0.1 ha) plots across the BEF. The majority of these plots (444) have been re-measured in at least three periods, the most recent being in 2002. Elevations range from 200 m to more than 850 m. In 2003, an eddy covariance tower was constructed at Bartlett, and has been in continuous operation since April 2004 (Jenkins et al., 2007). This tower is part of the AmeriFlux network and is a North American Carbon Program Tier III site.

*Howland Forest (HOW, Maine) 45.20° N, 68.74° W*. The Howland Forest is located in the boreal-northern hardwood transitional zone and consists of stands dominated by spruce, hemlock, and other conifer species. Flux measurements were initiated in 1995 and there are now three ~30-m-tall flux towers located in structurally and floristically similar stands. One of these continues to be operated as a control treatment while ecosystem-scale manipulations (i.e. nitrogen fertilization, harvesting) have been initiated around the other two towers. All three towers are part of the AmeriFlux network (Hollinger et al., 1999).

*Adirondack Park (AP, New York) 44.00° N, 74.40° W*. The largely forested expanses of the Adirondack Park cover a mountainous landscape ranging from 300 to 1500 m in elevation. Northern hardwood forests grade into the boreal forests that occur above 750 m in elevation or within poorly-drained valley bottoms. Over half of the Adirondack Park's 2.5 million hectares are preserved by New York State as “forever wild”, while the remaining half are privately owned and managed as conservation easements, logging tracts, or commercial and residential land within small towns and villages. Field plots were drawn from a wide variety of forest alliances (McNeil, 2006) and located within a subset of watersheds that have been studied for surface water chemistry by the Adirondack Long Term Monitoring program (Driscoll et al., 2003) or the Direct Delayed Response Program (Lee et al., 1989).

*La Selva (LS, Costa Rica) 10.42° N, 84.02° W*. A humid tropical rain forest in the Caribbean lowlands of northern Costa Rica, the La Selva Biological Station resides on land with a rich land-use history that includes shifting cultivation, selective cutting, and some clearing for