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Remote sensing of foliar nitrogen in cultivated grasslands of human dominated landscapes

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ABSTRACT

Foliar nitrogen (N) in plant canopies is central to a number of important ecosystem processes and continues to be an active subject in the field of remote sensing. Previous estimates of foliar N at the landscape scale have primarily focused on intact forests and grasslands using aircraft imaging spectrometry and various techniques of statistical calibration and modeling. The present study extends this work by examining the potential to estimate the foliar N concentration (%N) of residential, agricultural and other cultivated grassland areas within a suburbanizing watershed in southeastern New Hampshire. These grasslands occupy a relatively small fraction (17.5%) of total land area within the study watershed, but are important to regional biogeochemistry and are highly valued by humans. In conjunction with ground-based vegetation sampling ($n = 20$ sites with 54 sample plots), we developed partial least squares regression (PLSR) models for predicting mass-based canopy %N across management types using input from airborne and field-based imaging spectrometers. Models yielded strong relationships for predicting canopy %N from both ground- and aircraft-based sensors ($r^2 = 0.76$ and 0.67, respectively) across sites that included turf grass, grazed pasture, hayfields and fallow fields. Similarities in spectral resolution between the sensors used in this study and the proposed HyspIRI mission suggest promise for detecting canopy %N across multiple forms of managed grasslands, with the possible exception of areas containing lawns too small to be captured with HyspIRI's planned 60 m spatial resolution.

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1. Introduction

Through its association with proteins and plant pigments, foliar nitrogen (N) plays an important regulatory role in photosynthesis, leaf respiration and net primary production in terrestrial ecosystems (Field & Mooney, 1986; Ollinger & Smith, 2005; Reich et al., 2006). Because N is a common and widespread limiting resource to plants, spatial patterns of foliar N are also related to fluxes of carbon, water and energy, and are therefore central to understanding the role terrestrial ecosystems play within the larger Earth system (Ollinger et al., 2008; Ustin, 2013). At the landscape scale these patterns are driven by environmental attributes including climate, species composition, soil condition, disturbance history and management practices. Given its importance, foliar N has been the focus of considerable attention in the field of remote sensing spanning several decades (e.g., Martin, Plourde, Ollinger, Smith, & McNeil, 2008; Ramoelo et al., 2012; Wessman, Aber, Peterson, & Melillo, 1988). Many investigations use high spectral resolution data from airborne and orbital platforms for their ability to distinguish subtle reflectance features that relate to plant biophysical status, including N (Chambers et al., 2007). While the foundational methods are rooted in sample-based spectroscopy in laboratory and agricultural settings (Marten, Buxton, Brink, Halgerson, & Hornstein, 1984; Park, Agnew, Gordon, & Steen, 1998), more recent efforts at estimating foliar N using high spectral resolution data have primarily concentrated on intact forests and grasslands due to their spatial extent and documented importance to the Earth system (He, Guo, & Wilmshurst, 2006; McNeil et al., 2008; Ramoelo et al., 2012; Smith et al., 2002; Townsend, Foster, Chastain, & Currie, 2003). Although these and other investigations have successfully classified N status in forests and grasslands, difficulties associated with the diversity of land ownership and land management objectives have been an impediment to applications in developed landscapes (Milesi et al., 2005). Several studies have successfully delineated lawns and other urban plant canopies using high spatial resolution imagery (Walton, Nowak, & Greenfield, 2008; Wu & Bauer, 2012), but the use of remote sensing for estimating biochemistry and nutrient status in developed landscapes remains in its infancy (Davies, Edmondson, Heinemeyer, Leake, & Gaston, 2011).

The cultivation of grasses for animal forage or esthetic purposes is a near ubiquitous practice in human-dominated landscapes and often represents important shifts in terms of ecosystem function and services from surrounding ecosystems (Foley et al., 2005). Turf grass surface area in the United States has been estimated at 163,812 km^2, an area larger

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than that of corn, the nation's largest irrigated crop (Milesi et al., 2005). When pastures and hayfields are included, cultivated grasses comprise 707,627 km^2, or 8.76%, of total land area in the conterminous United States (Fry et al., 2011). As with many intensively managed systems, these grasslands embody tradeoffs among various ecosystem services, with consequences affecting both human and environmental welfare (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006). They comprise an important base of our food system and help define the locations we inhabit, while often requiring inputs of chemical fertilizers, irrigation water, and energy to meet desired management goals (Cassman, Dobermann, & Walters, 2002; Falk, 1976). Through these pathways, and by altering soil structure, ground water penetration, and surface water flow, the cultivation of grass has substantial influence on terrestrial and aquatic biogeochemical cycles (Kaushal, McDowell, & Wollheim, 2014; Pataki et al., 2011; Trowbridge, Wood, Underhill, & Ellsworth, 2013).

Accurate estimates of grassland N status in developed landscapes would stand to advance our understanding of management decisions and their implications at a variety of scales — vis-à-vis estimation of nutrient use efficiency and yield estimation, as well as tradeoffs of nutrient additions versus runoff, to name a few examples. High fidelity, ground-based remote sensing provides a tool for characterizing canopy N at fine spatial and temporal scales (e.g., lawns and small pastures at frequent intervals throughout a growing season), while airborne remote sensing platforms offer the potential for characterizing N across larger landscapes. The proposed HyspIRI sensor, with a repeat cycle of nineteen days, would provide an opportunity for mapping N at landscape to regional scales, holding particular promise for grass management and adaptive grazing practices aimed at maximizing rangeland and pasture resources.

From a remote sensing standpoint, the diversity of management objectives in developed systems poses challenges that are less prevalent in more natural ecosystems (Boegh et al., 2002; Booth & Tueller, 2003). Moreover, while remote sensing imagery has been used to detect water stress (Gao, 1996; Tilling et al., 2007), N status (Boegh et al., 2002; Gamon, Field, Roberts, Ustin, & Valentini, 1993; Ramoelo et al., 2012) and plant biomass (Paruelo, Epstein, Lauenroth, & Burke, 1997; Running et al., 2004) in grasslands, our understanding of the combined effect of these factors on whole canopy reflectance is incomplete (Ollinger, 2011). It remains unclear whether a generalizable approach for estimating foliar N via remote sensing can accommodate the range of management strategies encountered within a developed landscape. Resolving this is particularly pertinent in light of the proposed HyspIRI mission, which will provide global coverage of high-fidelity imaging spectrometer data from an orbital platform. To address this question, we sought to examine the use of high spectral resolution remote sensing from both airborne and ground-based platforms for detecting foliar N within cultivated grasslands. Calibrations of measured canopy N with reflectance were developed using spectral data from both platforms to explore questions regarding scaling and to address the utility of each towards developing a generalized approach of estimating N in grasslands. Our study focused on a mixed-use landscape in southeastern New Hampshire that included a wide range of grass management strategies including turf grass, hayfields, actively grazed pastures, and fallow fields. Results are presented with respect to the utility of methods we tested and their potential application to environmental modeling, resource management and for future applications with HyspIRI.

2. Methods

2.1. Study sites

The study was conducted within the Lamprey River Watershed (LRW) in southeastern New Hampshire (43.10°N, 71.11°W), a coastal area encompassing 479 km^2 and nine towns that drains into the Great Bay National Estuarine Research Reserve. The watershed has a diverse history with more than 300 years of land use change following European settlement (Hamilton, 1882). Today, rural to urban development gradients are present throughout the watershed with human population ranging from zero in state park lands to greater than 620 people km^{-2} within larger towns. Although the watershed is predominately forest, non-forested land accounts for 17.5% of the total area. Residential turf and agricultural grasslands are mixed throughout this fraction and represent important loci for human–environment interactions. The cultivation and maintenance of grasses has a strong influence on biogeochemistry within the watershed (Fissore et al., 2012) and the U.S. Environmental Protection Agency has established that water quality in both the Lamprey River, and the Great Bay estuary, is impaired by excess N. Twenty-seven percent of the total non-point source N pollution coming into Great Bay is attributed to residential

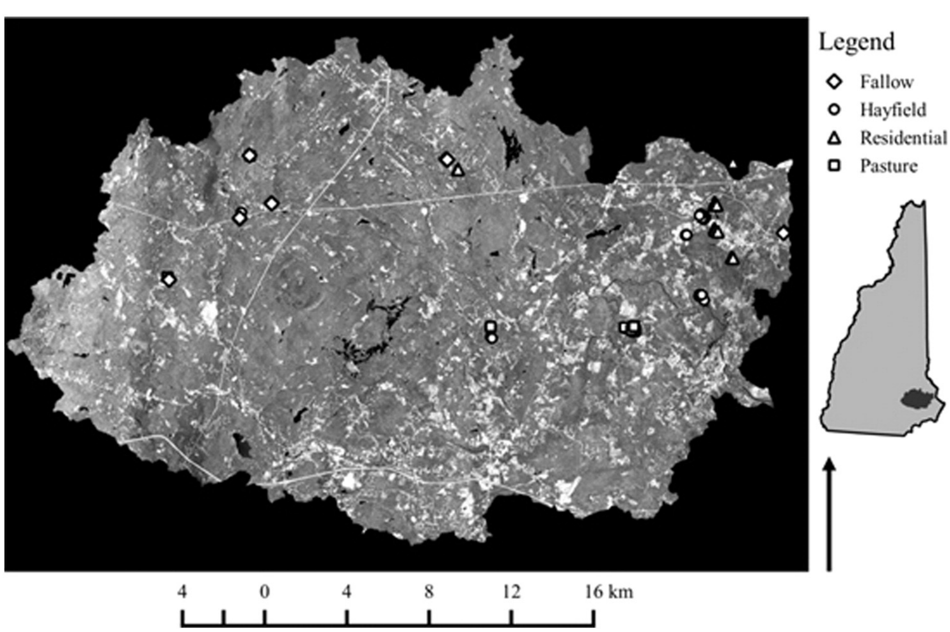

Fig. 1. Aerial image of the Lamprey River Watershed, its location in New Hampshire, and distribution of field sites surveyed in this study. The grayscale image highlights the mixed landscape and land cover of the Lamprey River Watershed, where dark gray areas are forest, and light gray areas are dominated by residential and agricultural grasslands.

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