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Remote sensing of sagebrush canopy nitrogen

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ABSTRACT

This paper presents a combination of techniques suitable for remotely sensing foliar Nitrogen (N) in semiarid shrublands – a capability that would significantly improve our limited understanding of vegetation functionality in dryland ecosystems. The ability to estimate foliar N distributions across arid and semi-arid environments could help answer process-driven questions related to topics such as controls on canopy photosynthesis, the influence of N on carbon cycling behavior, nutrient pulse dynamics, and post-fire recovery. Our study determined that further exploration into estimating sagebrush canopy N concentrations from an airborne platform is warranted, despite remote sensing challenges inherent to open canopy systems. Hyperspectral data transformed using standard derivative analysis were capable of quantifying sagebrush canopy N concentrations using partial least squares (PLS) regression with an R^2 value of 0.72 and an R^2 predicted value of 0.42 ($n = 35$). Subsetting the dataset to minimize the influence of bare ground ($n = 19$) increased R^2 to 0.95 (R^2 predicted = 0.56). Ground-based estimates of canopy N using leaf mass per unit area measurements (LMA) yielded consistently better model fits than ground-based estimates of canopy N using cover and height measurements. The LMA approach is likely a method that could be extended to other semiarid shrublands. Overall, the results of this study are encouraging for future landscape scale N estimates and represent an important step in addressing the confounding influence of bare ground, which we found to be a major influence on predictions of sagebrush canopy N from an airborne platform.

1. Introduction

Dryland ecosystems are extremely vulnerable to desertification and account for roughly 40% of the Earth's land surface (e.g., Mortimore, 2009). This paper presents a combination of techniques that are suitable for remotely sensing foliar Nitrogen (N) in semiarid shrublands – a capability that would significantly improve our limited understanding of vegetation functionality in dryland ecosystems. Whereas vegetation indices such as Modified Soil-Adjusted Vegetation Index (MSAVI) attempt to quantify vegetation abundance, estimates of foliar N across arid and semi-arid environments could help answer process-driven questions related to topics such as controls on canopy photosynthesis (Polley et al., 2010) and the influence of N on carbon cycling behavior. Also, in systems where soil water is the primary limiting resource and influenced by changes in available N (Inouye, 2006), there is opportunity for remote sensing of foliar N to augment studies related to nutrient pulse dynamics and post-fire recovery.

Remote sensing of sagebrush N, in particular, can yield assessments of forage nutritional status across large areas. Sagebrush (*Artemisia* spp.) communities constitute the largest temperate semi-desert in North America and occupy approximately 60 million hectares of rangelands in the western US including the Great Basin (Anderson & Inouye, 2001). Sagebrush communities provide important habitat for wildlife and rangelands for livestock. Sagebrush species are the dominant or co-dominant species of over 40 habitat types (Blaisdell et al., 1982; Monsen et al., 2004), where they provide food and cover necessary for over 350 wildlife species including Greater Sage Grouse (*Centrocercus urophasianus*) (Suring et al., 2005).

Studies have been surprisingly successful at estimating leaf and canopy N from reflectance measurements despite challenges associated with radiosity modeling of leaf N (Kokaly et al., 2009) and spectral discrimination of sagebrush and semi-arid backgrounds (Mundt et al., 2006a; Okin et al., 2001). A growing number of remote sensing studies have used airborne hyperspectral imagery to directly estimate canopy biochemistry in forested (e.g., Martin & Aber, 1997; Martin et al., 1998; Matson et al., 1994; Smith et al., 2002; Townsend et al., 2003; Wessman et al., 1989) and open canopy landscapes (Huang et al., 2004; Mutanga et al., 2004; Serrano et al., 2002; Skidmore et al., 2010) using reflectance spectroscopy techniques developed empirically in the laboratory. Near-infrared spectroscopy (NIRS) is highly accurate at predicting the abundance of organic compounds in dry foliage (e.g.,

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Bolster et al., 1996; Curran, 1989; Curran et al., 2001; Petisco et al., 2006) despite the relationship between reflectance variation and plant material composition being complicated by similar and overlapping absorption features (Barton et al., 1992; Kokaly & Clark, 1999; Kumar et al., 2001). Techniques in NIRS are successful enough to have replaced wet chemistry as the biochemical assay standard in food and agricultural industries (Williams & Norris, 1987).

Laboratory spectroscopy studies of N traditionally apply derivative transformations to smoothed reflectance data (i.e. logarithm of the inverse of reflectance) to minimize noise and background signal variation and resolve overlapping absorption features (Hruschka, 1987). Kokaly and Clark (1999) illustrated the use of continuum removed reflectance and band normalization (Clark & Roush, 1984) to reduce the effects of leaf water, soil background, sensor noise, bandwidth, and atmosphere on biochemical estimations at field and remote sensing scales. While this Kokaly and Clark study cautions the need to develop remote sensing algorithms that remove the influence of water, the methodologies are intended to be less sensitive to the influence of soil background than traditional methods. In fact, linear mixture modeling in the study indicated N estimates were insensitive to soil background until soil cover exceeded 40%. Spectral transformation techniques for estimating foliar biochemistry with relatively low sensitivity to partial canopy coverage hold particular promise in semi-arid landscapes, where changes in leaf chemistry are not thought to translate to landscape level detection unless cover exceeds 70% (Asner et al., 2000).

Overall, current literature indicates that sagebrush appears to be a viable candidate for retrieving biochemical information from subtle absorption features associated with N concentration. Kokaly et al. (2003) analyzed broad absorption features using continuum removal for vegetation mapping purposes. The authors reported late summer sagebrush samples had relatively low water and chlorophyll content and relatively strong absorption features related to constituents such as nitrogen, lignin and cellulose at 2100 and 2300 nm. A study of sagebrush N conducted at the field scale (Mitchell et al., 2012) reported encouraging results when estimating N concentrations using spectroradiometer data collected over individual shrub canopies and transformed using standard derivative analysis. The field spectroscopy study determined that leaf water and a known N absorption feature near 2180 nm accounted significantly for variations in N concentration in the live shrub dataset analyzed.

The primary objective of our study was to determine if sagebrush canopy signals are strong enough to support detection of sagebrush canopy N from an airborne hyperspectral platform. The bare ground, wood, litter and soil crust that surround sagebrush crowns contribute to high albedo, which is further exacerbated by the vertical leaves and grey trichome leaf hair of sagebrush and lack of an optically dense vegetation target. Consequently, expression of N information at the canopy scale is likely weak and the results are largely dependent on factors such as bare ground percent cover and methods of scaling from the leaf-level to the plot or whole canopy-level. Thus, a second objective of our study was to compare how two different methods for estimating whole canopy-level N affect agreement between wavelength predictors and N concentrations in sparse desert shrubland. The first method estimates phytomass by expressing cover on a mass basis using dry leaf mass per area (LMA) ratio (e.g. Smith et al., 2002) while the second method estimates phytomass using a shrub volume surrogate that combines absolute cover and height (Serrano et al., 2002).

2. Materials and Methods

2.1. Study Area

The study area is located in a cold desert sagebrush-steppe environment on the Department of Energy, Idaho National Laboratory (INL) in eastern Idaho. The sampling area consists of all land within an 805 m radius of an unmanned aerial vehicle test runway (43° 35' N; -112° 54'W), with elevations ranging from approximately 1479 m to 1496 m. Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis*) is the dominant shrub, while basin big sagebrush (*Artemisia tridentata* subsp. *tridentata*) occurs in depressional areas and drainage channels. The sagebrush species have both persistent and ephemeral leaves that are vertical with fine grey trichome hair. The canopies have relatively sparse leaves with many woody stems covered by rough grey bark. Collectively, these characteristics contribute to spectrally indeterminate signals of sagebrush. Other species common to the area include yellow rabbitbrush (*Chrysothamnus viscidiflorus*), pricklypear cactus (*Opuntia* spp.) and crested wheatgrass (*Agropyron cristatum*). Air tends to be relatively dry (the average annual precipitation is 285 mm) and the area experiences extreme diurnal and seasonal fluctuations in ground temperature, with an average daily temperature that ranges from −12.22 °C in January to 21.11 °C in July (DOE-ID, 1989). Plant water stress in this ecosystem is minimal in the spring and early summer, increases during the mid and late summer, and is greatest in August (DePuit & Caldwell, 1973). Accordingly, sagebrush crude protein content is usually highest in the spring and gradually decreases into winter. Local precipitation records for summer 2010 are consistent with these trends. Total precipitation recorded by the Atomic City NOAA mesonet station for the months of May, June, and July 2010 were 37, 17, and 12 mm, respectively.

2.2. Field data collection and analysis

A roaming ground survey was conducted from 09 August 2010 to 10 August 2010 to sample a total of 35 square plots (7 m X 7 m) for percent cover (sagebrush, shrubs other than sagebrush, grass/ herbaceous, bare ground, and dead wood), average sagebrush height and foliar N content. Plots were located in places where bare ground and sagebrush were the dominant land cover features. Understory vegetation, grasses, and other shrubs were minimized to control for the influence of non-target vegetation. It should be noted that forbes and grasses were senescing at the time of field sampling, and that litter and surface crusts were not green. For each plot, locations were recorded for two opposite corners using a Wide Area Augmentation System (WAAS) enabled Trimble GeoXT (Sunnyvale CA) model GPS receiver and locations were differentially corrected using GPS Pathfinder software (v3.10, Trimble Navigation Limited, Sunnyvale CA). Post-processed point data from this GPS unit is capable of sub-meter positional accuracy (Serr et al., 2006). To calculate percent cover, the 7 m X 7 m plots were divided into 49 subplots (1 m X 1 m) and dominant cover was recorded for each subplot. Average sagebrush height was estimated for each plot by measuring all shrubs in the plot from the ground level to the highest point of stem growth, then averaging all sagebrush height measurements. Foliar N content was analyzed by collecting green-leaf samples from four randomly-selected sagebrush shrubs in each plot. Two long stem specimens (approximately 40 cm in length) containing representative leaf forms (i.e., ephemeral and persistent) were clipped from the top of each sagebrush and air dried for several days until laboratory analysis. The four specimens collected from each plot were combined into single samples, prepared, and analyzed for leaf level N concentrations of oven-dried ground foliage (g N / 100 g sample) using a Leico TrueSpec CN analyzer (St. Joseph, MI).

We scaled N concentrations from leaf level to plot level (total sagebrush canopy within 7 m X 7 m plots) by adapting Smith and Martin's (2001) plot-based method for estimating forest canopy chemistry to a shrub environment. Smith and Martin's approach has been implemented in several remote sensing studies to rapidly estimate forest canopy N (e.g., Martin & Aber, 1997; Ollinger & Smith, 2005; Smith et al., 2002; Townsend et al., 2003) by weighting the fraction of canopy foliar mass per species by the mean foliar N concentrations for each species in a stand. In these studies, each species contribution to total canopy mass