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Assessing the impact of N-fertilization on biochemical composition and biomass of a Douglas-fir canopy—A remote sensing approach

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ABSTRACT

Vegetation biochemistry is a critical driver of the forest carbon and water cycle and the fluxes between the land surface and the atmosphere. As result, monitoring biochemistry is a key to improving our estimates of the terrestrial carbon and energy budget. While destructive sampling techniques have been widely applied to determine nutrient content in foliage, scaling of these measurements to the stand and landscape is challenging. As an alternative to traditional field-based approaches, optical remote sensing is a powerful technique for sampling biochemical constituents in a spatially continuous fashion. Remote sensing of biochemical constituents is based on the understanding that leaf biochemistry is closely linked to absorption and reflectance properties in characteristic, often spectrally narrow, wavebands. Spectral absorption features can be identified to characterize and quantify biochemical properties at the leaf, stand and landscape level. At the same time, Light Detection and Ranging (LiDAR) remote sensing can allow inference about the impact of leaf biochemistry on tree growth and canopy structure. In this study, we report the effect of nitrogen-fertilization of a Douglas-fir dominated forest on Vancouver Island, British Columbia, Canada using active and passive remote sensing techniques. Leaf pigment concentrations were estimated from inversion of a canopy reflectance model (PROSAIL) and canopy nitrogen (N) was inferred from an airborne imaging spectrometer (AVIRIS). The impact of leaf biochemistry on canopy structure and tree growth was then investigated using a temporal sequence of LiDAR data acquired two years before, and after, the fertilization treatment. Results indicate that while fertilization had a significant impact on canopy pigment concentrations, it did not impact canopy nitrogen. A notable increase in tree growth was found for younger stands of less than 15 m of height, but not for more mature stand with taller trees. Fertilization had no immediate impact on canopy density measured from LiDAR derived leaf area and canopy volume. The use of advanced remote sensing tools and techniques such as those demonstrated in this study can be a powerful addition to ongoing efforts to model carbon and water fluxes throughout the landscape.

1. Introduction

Monitoring spatial patterns in the biochemical composition of plant foliage is required for understanding growth dynamics in plant communities (Field et al., 1992). While numerous studies have investigated patterns of pigment and nutrient distribution in forested environments (Aber, 1990; Gitelson et al., 2005; Margolis and Waring, 1986; Paul et al., 2003), our current understanding of environmental controls remains incomplete and our ability to predict and detect spatial patterns across forested landscapes is limited (Ollinger et al., 2002).

While traditional approaches, such as destructive sampling techniques (Lowther, 1980; Porra, 2002), yield accurate estimates of foliar biochemistry at the leaf level, up-scaling these findings to the canopy level is challenging. First, nutrient levels vary within the tree crown depending on stand structure (Chiang and Brown, 2010), intercepted solar radiation and vegetation type. As a result, measurements of individual foliage elements may not be representative of the entire canopy. Second, the spatial distribution of biochemical constituents across forest stands depends on numerous factors including soil quality and depth, slope and exposure, and vegetation type and can vary with locations.

Recent progress in sensor development has enabled high spectral resolution (i.e., bandwidths < 10 nm) remote sensing to be used as a potentially powerful alternative for monitoring canopy constituents in a spatially continuous mode. Based on the under-

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standing that leaf biochemistry is closely linked to reflectance observations in characteristic, often spectrally narrow wavebands, these optical properties can be used to determine the content of biochemical constituents in leaves. Imaging spectrometers are able to capture the full spectrum of reflected light at a fine spectral resolution, and thus allow for a more detailed analysis of these narrow waveband features than is possible with conventional, broad-band sensors (Ollinger and Smith, 2005). Spectroscopic measurement of plant biochemistry can broadly be classified into empirical, semi-analytical and analytical approaches (Hilker et al., 2011; Ustin et al., 2004). Empirical techniques are largely based on linear and non-linear combinations of discrete spectral reflectance bands, used to maximize sensitivity to canopy characteristics while minimizing sensitivity to other, unrelated phenomena such as background effects and viewing geometry (Hall et al., 1995; Price, 1992). Analytical techniques infer biochemical properties from more sophisticated canopy reflectance (CR) models, which are often based on radiative transfer theory and coupled with leaf optical models, to simulate the reflectance and the transmittance of a leaf as a function of its constituent properties (Meroni et al., 2004). Inversion of these CR models allows estimation of both leaf and canopy parameters in predictive mode, thereby overcoming the need to parameterize empirical models (Bicheron and Leroy, 1999; Jacquemoud et al., 2009; Privette et al., 1996).

Among the most important biochemical compounds with respect to carbon, water and nutrient cycling are nitrogen (N) and the light absorbing pigments, in particular chlorophylls (chl) and carotenoids (car), all of which have been directly related to the photosynthetic capacity in plants (Gitelson et al., 2006; Ollinger and Smith, 2005). Methods for remote estimation of N from high resolution remote sensing include analysis of spectral narrow spectral bands in the near infrared region (Matson et al., 1994), first-difference spectral bands (Martin and Aber, 1997), and eigenanalysis methods such as partial least squares (PLS) regression (Coops et al., 2003). Recently, Ollinger et al. (2008) used measurements of surface albedo to determine N-concentration over key forested regions of North America from NASA's Moderate Resolution Imaging Spectro-radiometer (MODIS) which yielded accurate predictions of N on a continental scale. Other methods for remote detection of canopy N from space-based platforms have also demonstrated accurate and robust predictions across a range of forest biomes (Martin et al., 2008; Townsend et al., 2003). While estimates of N are often valuable indicators of site nutrition, canopy pigment concentrations can be measured more directly from remote sensing, as pigments, by definition, absorb light in specific and characteristic spectral wavebands, typically between 400 and 700 nm wavelengths. As with N-based approaches, numerous methods have been developed from estimating canopy pigment concentrations from two-band indices (Carter and Miller, 1994), semi-analytical approaches (Gitelson et al., 2002, 2003) to inversion of canopy reflectance models (Di Vittorio, 2009; Jacquemoud et al., 1993; Jacquemoud et al., 2009).

In this study, we investigate the potential of fine spectral resolution imagery to measure the effects of repeated fertilization treatments on pigment and nutrient contents of a Douglas-fir (*Pseudotsuga menziesii* var *menziesii* (Mirb.) Franco) dominated forest stand on Vancouver Island, British Columbia, Canada. Leaf pigment and N concentrations are determined for fertilized and control areas from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) calibrated using field measurements acquired from destructive sampling methods. The effect of fertilization on tree growth, foliage density and crown volume is then investigated using two acquisitions of LiDAR observed 2 years before and after the fertilization treatment. To enable additional insight, the biochemical composition of plant canopy is then linked to growth rates over a larger, 5×5 km, research area. The methods presented in this paper contribute to the current understanding of determining foliage composition and growth rates from remote sensing and will be a vital step towards determining plant bio-geochemistry at a global scale from remote sensing.

2. Methods

2.1. Site description

The study area is a Canadian Carbon Program (CCP) flux-tower site (DF-49 site) on Vancouver Island, British Columbia, Canada, located at 300 m above sea level (49°52′7.8″ N, 125°20′6.3″ W). The 60-year old second-growth coniferous forest consists of 70% Douglas fir, 17% western red cedar (*Thuja plicata* Donn ex D. Don), 3% western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and 10% red alder (*Alnus rubra* Bong.) and is highly productive with rotation cycles as short as 60 years (Morgenstern et al., 2004). The site is located within the dry maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm), which is characterized by cool summers and mild winters with occasional drought during late summer (Humphreys et al., 2006). The stand density around the tower is 1100 stems ha^{-1}, with tree height ranging between 30 and 35 m. The average diameter at breast height (DBH) is 29 cm, while the effective leaf area index (L_e) at the tower site was estimated to be 7.3 m^2 m^{-2} using TRAC-L-2000 measurements (Chen et al., 2006). The relationship between stand height and stand age is assumed to be relatively constant throughout the study area due to the favourable growing conditions throughout and the limited variability in climate and topography.

Three fertilization treatments of N in the form of urea were applied to the study area at a rate of 200 kg ha^{-1}. In 1994, the fertilization area included 1788 ha; in 2004, this 1788 ha area was expanded to include an additional 191 ha. The most recent fertilization was carried out on January 13, 2007, over an area of 1115 ha, encompassing the eddy covariance tower and most of its flux footprint. A Eurocopter SA315B helicopter (Western Aerial Applications Ltd., Chilliwack, British Columbia Canada) was used with an in-house engineered hydraulic-driven spreader bucket and a GPS-assisted guidance system (Jassal et al., 2010).

2.2. Field measurements

Canopy %N (in g of N per 100 g of dry leaf matter) and chlorophyll a and b concentrations (in $\mu g\,cm^{-2}$) were sampled between July 15 and 18, 2008 at several plot locations within the study area (see Fig. 1 for details). A total of 16 sample plots were established, 30×30 m in size, stratified based on height classes and fertilization treatments (for location see Fig. 1). At each plot, between 4 and 6 dominant and co-dominant trees were selected. The majority (72%) of these trees were Douglas-fir, due to the species distribution found at the site, 9% of the trees sampled were red alder, while 12% and 7% were western red cedar and western hemlock, respectively. Foliage samples were taken at three different height levels of each tree (upper middle and lower part of the green canopy) through the expertise of professional tree climbers. For determination of leaf-level N concentration, samples were dried (70 °C) and ground through a 1 mm mesh sieve before they were analyzed using near-infrared spectroscopy (Bolster et al., 1996; McLellan et al., 1991). Plot-level whole canopy N concentration (g/100 g) was then calculated as the mean of foliar N concentrations for individual species of each plot, weighted by fraction of canopy foliar mass per species (Smith and Martin, 2001). Contribution of canopy mass per species on each plot was determined using the camera-based point-quadrat method combined with mean leaf-level leaf mass