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Integrating waveform lidar with hyperspectral imagery for inventory of a northern temperate forest

Jeanne E. Anderson [a,*], Lucie C. Plourde [a], Mary E. Martin [a], Bobby H. Braswell [a], Marie-Louise Smith [b], Ralph O. Dubayah [c], Michelle A. Hofton [c], J. Bryan Blair [d]

[a] University of New Hampshire, Complex Systems Research Center, USA
[b] U.S.D.A. Forest Service, Legislative Affairs, USA
[c] University of Maryland, Department of Geography, USA
[d] NASA, Goddard Space Flight Center, USA

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Abstract

It has been suggested that attempts to use remote sensing to map the spatial and structural patterns of individual tree species abundances in heterogeneous forests, such as those found in northeastern North America, may benefit from the integration of hyperspectral or multi-spectral information with other active sensor data such as lidar. Towards this end, we describe the integrated and individual capabilities of waveform lidar and hyperspectral data to estimate three common forest measurements – basal area (BA), above-ground biomass (AGBM) and quadratic mean stem diameter (QMSD) – in a northern temperate mixed conifer and deciduous forest. The use of this data to discriminate distribution and abundance patterns of five common and often, dominant tree species was also explored. Waveform lidar imagery was acquired in July 2003 over the 1000 ha. Bartlett Experimental Forest (BEF) in central New Hampshire (USA) using NASA's airborne Laser Vegetation Imaging Sensor (LVIS). High spectral resolution imagery was likewise acquired in August 2003 using NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Field data (2001–2003) from over 400 US Forest Service Northern Research Station (USFS NRS) plots were used to determine actual site conditions.

Results suggest that the integrated data sets of hyperspectral and waveform lidar provide improved outcomes over use of either data set alone in evaluating common forest metrics. Across all forest conditions, 8–9% more of the variation in AGBM, BA, and QMSD was explained by use of the integrated sensor data in comparison to either AVIRIS or LVIS metrics applied singly, with estimated error 5–8% lower for these variables. Notably, in an analysis using integrated data limited to unmanaged forest tracts, AGBM coefficients of determination improved by 25% or more, while corresponding error levels decreased by over 25%. When data were restricted based on the presence of individual tree species within plots, AVIRIS data alone best predicted species-specific patterns of abundance as determined by species fraction of biomass. Nonetheless, use of LVIS and AVIRIS data – in tandem – produced complementary maps of estimated abundance and structure for individual tree species, providing a promising adjunct to traditional forest inventory and conservation biology planning efforts.

Keywords: Waveform lidar; Lidar; LVIS; Laser altimetry; AVIRIS; High spectral resolution imagery; Hyperspectral; Biomass; Basal area; Quadratic mean stem diameter; Forest structure; Height; Tree species distribution

1. Introduction

In northeastern North America, the spatial variation in forest structure across large tracts of land is driven by a heterogeneous mix of deciduous and coniferous species and enhanced by the complexity of species interactions with ecological factors such as topography, soil composition and disturbance history. These temperate forests are recognized as important components of the global carbon cycle. Yet, a comprehensive understanding of the overall spatial patterns of structural variation seen in these large landscapes is still largely lacking. The integration of optical sensor data, such as that obtained from hyperspectral imaging spectroscopy, with the structural information readily obtained

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* Corresponding author.
E-mail address: jeanne.anderson@unh.edu (J.E. Anderson).

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from active sensors, such as lidar, is believed to hold great promise for improving the accuracy of forest inventory and ecological modeling at a landscape scale. Images from lidar and optical sensors offer the possibility of combining very detailed information from both vertical and horizontal spatial planes (Hudak et al., 2002; Lefsky et al., 1999; McCombs et al., 2003; Popescu et al., 2004; Treuhaft et al., 2002). It has been suggested, as such, that each of these sensors brings complementary and potentially synergistic capabilities to land-cover classification and estimation of stand structure (Ackermann, 1999; Dubayah et al., 2000; Lim et al., 2003).

In recent years, hyperspectral remote sensing has been used to ascertain species-level abundance patterns in a variety of biomes (Plourde et al., 2007; Roberts et al., 1998; Ustin & Xiao, 2001). The advantage of hyperspectral remote sensing in detecting differences in species-level abundance patterns is found in the exactness of the spectral response (i.e. hundreds of narrow, contiguous spectral channels). Reducing the dimensionality of the data in order to discern the most meaningful spectral response is a common approach to working with hyperspectral data sets (Haskett & Sood, 1998; Plourde et al., 2007; Underwood et al., 2003; Williams & Hunt, 2002). To complement the advantages provided by hyperspectral imagery in detailing species abundance patterns, waveform lidar imagery can provide direct measures of canopy height. Strong indirect relationships between canopy and sub-canopy lidar metrics and traditional forest measures, such as biomass, can also be established at a landscape scale (Dubayah et al., 2000; Lefsky et al., 2002).

Plourde et al. (2007) have noted that given the inherent spatial and temporal variability of northern temperate forests and attendant problems with classification, measures of species' relative abundances across a forest landscape may provide a more functional representation of ground conditions than classification of discrete forest type classes. By adding information on forest structure to such compositional data, the combination of remotely acquired detailed distribution patterns reflecting both species abundance and aspects of size could provide essential information to pressing issues of management and research.

Several studies (Anderson et al., 2006; Ollinger & Smith, 2005; Plourde et al., 2007) conducted at the Bartlett Experimental Forest (BEF) in north central New Hampshire (USA) have already separately assessed the validity of using airborne hyperspectral data for the classification of individual tree species, prediction of forest growth and mapping of abundance patterns, as well as the use of airborne waveform lidar to describe and predict various forest metrics. Here we describe the advantage conferred by combining structural information with spectral approaches to quantify individual species abundances and associated physical metrics in a heterogeneous temperate forest using data integrated from both sensor types.

2. Methods

2.1. Study area

Bartlett Experimental Forest (44.06°N, 71.3°W) is located within the White Mountain National Forest, a heavily forested and mountainous region in north central New Hampshire (Fig. 1). Established by the US Forest Service in 1931, the BEF is a 1052-ha field site for the study of secondary deciduous and coniferous forest dynamics and ecology. Major tree species include American beech (*Fagus grandifolia* Ehrn.), red maple (*Acer rubrum* L.), eastern hemlock (*Tsuga canadensis* L. Carr.), sugar maple (*Acer saccharum* L.), yellow birch (*Betula alleghaniensis* Britt.), paper birch (*Betula papyrifera* Marsh.), red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill.), with some localized small stands of eastern white pine (*Pinus strobus* L.).

2.2. Field data: Height

A number of waveform lidar studies (Anderson et al., 2006; Drake et al., 2002; Hyde et al., 2005; Kimes et al., 2006) have noted disparate ways in which geo-location errors can confound the relationships between field measurements and corresponding LVIS footprint metrics. To explore aspects of the accuracy and precision of LVIS metrics at Bartlett pertinent to this study, 2003 LVIS height metrics were compared to maximum tree heights as measured from the ground for 79 field plots. The field data were drawn from multiple studies that included North American Carbon Program (NACP) sub-plots (established in 2004) centered within a 1 km region around the BEF Ameriflux tower (Jenkins et al., 2007), a set of ground plots (established in 2002–2003) specifically sited to be of use in the calibration and validation of individual LVIS waveforms (Anderson et al., 2006), and other unpublished U.S. Forest Service plot data (sampled in 2005). All field plots used for height analyses have distance and bearing measurements from plot center to the tallest tree within each plot. Laser rangefinders, laser hypsometers, surveying range poles, and sonic hypsometers were used to obtain tree height data and create detailed stand maps for the research plots. All of these plots have been geo-located to within 1-meter positional accuracy. None of the plots were originally geo-located with reference to specific 2003 LVIS footprint coordinates. In addition, multiple flight lines were flown over Bartlett creating a variable density of LVIS footprints across the forest. For these reasons, the distance from plot center to the closest center point of a LVIS footprint varies with each plot. The range was from 1.2 m to 11.4 m (mean of 5.5 m). The location of the tallest trees in these plots also varies, extending from 0.7 m to 18.8 m from plot center (mean of 8.5 m).

2.3. Field data: Basal area, biomass and quadratic mean stem diameter

Arrayed in a regular grid across the BEF are over 400 intensively sampled 0.1-ha plots measured in 2.54 cm diameter classes, most recently in 2001–03. All inventory plots have been geo-referenced to within 3-meter positional accuracy. Plot elevations range from approximately 200 to 800 m. (Anderson et al., 2006).

Basal area (BA) and dry weight biomass (AGBM: bole, branch, and foliar) by species for each inventory plot was calculated using regionally developed allometric equations based on stem diameter measurements (Jenkins et al., 2004). Fractions of biomass by species per plot were calculated from