Remote Sensing of Environment 123 (2012) 25–40

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

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

Quantifying aboveground forest carbon pools and fluxes from repeat LiDAR surveys

Andrew T. Hudak [a,*,1], Eva K. Strand [b,1], Lee A. Vierling [b], John C. Byrne [a], Jan U.H. Eitel [b,c], Sebastián Martinuzzi [d], Michael J. Falkowski [e]

[a] Rocky Mountain Research Station, United States Forest Service, Moscow, ID, United States
[b] Forest, Rangeland, and Fire Sciences, University of Idaho, Moscow, ID, United States
[c] McCall Outdoor Science School, University of Idaho, McCall, ID, United States
[d] Forest and Wildlife Ecology, University of Wisconsin, Madison, WI, United States
[e] School of Forest Resources and Environmental Science, Michigan Technological University, United States

A R T I C L E   I N F O

Article history:
Received 31 October 2011
Received in revised form 23 February 2012
Accepted 25 February 2012
Available online 5 April 2012

Keywords:
Discrete return LiDAR
Multi-temporal
Aboveground carbon
Mixed conifer forest
Random forest algorithm
Imputation
Biomass change
Carbon Measuring Reporting and Verification (MRV)

A B S T R A C T

Sound forest policy and management decisions to mitigate rising atmospheric CO_2 depend upon accurate methodologies to quantify forest carbon pools and fluxes over large tracts of land. LiDAR remote sensing is a rapidly evolving technology for quantifying aboveground biomass and thereby carbon pools; however, little work has evaluated the efficacy of repeat LiDAR measures for spatially monitoring aboveground carbon pools through time. Our study objective was therefore to evaluate the use of discrete return airborne LiDAR for quantifying biomass change and carbon flux from repeat field and LiDAR surveys. We collected LiDAR data in 2003 and 2009 across ~20,000 ha of an actively managed, mixed conifer forest landscape in northern Idaho. The Random Forest machine learning algorithm was used to impute aboveground biomass pools of trees, saplings, shrubs, herbaceous plants, coarse and fine woody debris, litter, and duff using field-based forest inventory data and metrics derived from the LiDAR collections. Separate predictive tree aboveground biomass models were developed from the 2003 and 2009 field and LiDAR data, and biomass change was estimated at the plot, pixel, and landscape levels by subtracting 2003 predictions from 2009 predictions. Traditional stand exam data were used to independently validate 2003 and 2009 tree aboveground biomass predictions and tree aboveground biomass change estimates at the stand level. Over this 6-year period, we found a mean increase in tree aboveground biomass due to forest growth across the non-harvested portions of 4.1 Mg/ha/yr. We found that 26.3% of the landscape had been harvested during this time period which outweighed growth at the landscape level, resulting in a net tree aboveground biomass change of −5.7 Mg/ha/yr, and −2.3 Mg/ha/yr in total aboveground carbon, summed across all the aboveground biomass pools. Change in aboveground biomass was related to forest successional status; younger stands gained two- to three-fold less biomass than did more mature stands. This result suggests that even the most mature forest stands are valuable carbon sinks, and implies that forest management decisions that include longer harvest rotation cycles are likely to favor higher levels of aboveground carbon storage in this system. A 30-fold difference in LiDAR sampling density between the 2003 and 2009 collections did not affect plot-scale biomass estimation. These results suggest that repeat LiDAR surveys are useful for accurately quantifying high resolution, spatially explicit biomass and carbon dynamics in conifer forests.

Published by Elsevier Inc.

1. Introduction

Forests cover approximately one third of the Earth's land surface and have a tremendous capacity to store and cycle carbon (e.g. Dixon et al., 1994; Harmon & Marks, 2002). Indeed, the total carbon stored in forested ecosystems, including live and dead wood, litter, detritus, and soil, exceeds the amount of carbon found in the atmosphere (FRA, 2005; Heath et al., 2010). Accelerated pressure on forest resources to provide a wide range of environmental services, including mitigation of atmospheric carbon dioxide, has given rise to concerted study of how change in forest cover and land use affects emissions of CO_2 to the atmosphere (McKinley et al., 2011), and how forests may be managed for carbon benefits (Hines et al., 2010). Because forest change is a highly dynamic, broad scale phenomenon, such efforts to understand the carbon balance of forests via frameworks such as the Reduction of Emissions from Deforestation and forest Degradation (REDD; e.g. Gibbs et al., 2007) in developing nations and through various other carbon Measuring, Reporting, and Verification (MRV) protocols require repeatable, objective, and accurate remote sensing methods for estimating aboveground forest carbon pools and fluxes over large areas (Goetz & Dubayah, 2011). Improved quantitative methods at the landscape level, where forest

* Corresponding author. Tel.: +1 208 883 2327; fax: +1 208 883 2318.
E-mail address: ahudak@fs.fed.us (A.T. Hudak).
[1] Equally contributing authors.

0034-4257/$ – see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2012.02.023

management decisions are made, could lead to more accurate forest carbon accounting at the national level, where policy decisions are made (Heath et al., 2010; Hines et al., 2010).

Remote sensing approaches for quantifying components of forest biomass are rapidly evolving. Vine and Sathaye (1997) suggested that to quantify aboveground forest carbon pools and fluxes across broad extents, it is important to combine remote sensing techniques with carbon estimation methods that are based on existing standard forest inventory principles. Light Detection And Ranging (LiDAR) has been employed to successfully quantify vertical structure and forest attributes such as canopy height distribution, tree height, and crown diameter (e.g. Hudak et al., 2002; Lefsky et al., 2002; Nilsson, 1996; Yu et al., 2008). Robust methods for producing wall-to-wall maps of aboveground forest carbon pools using single-date LiDAR combined with field data collections and Monte Carlo statistical methods have recently been developed with errors <1% (Gonzalez et al., 2010). Single-date LiDAR combined with field data and satellite imagery was used to quantify carbon pools at high spatial resolution at the landscape level (~10^6 ha) in Hawaii (Asner et al., 2011), and recently, spaceborne LiDAR was used in combination with spaceborne radar and MODIS data to quantify tropical carbon stocks across three continents (Saatchi et al., 2011).

Observing landscape level changes in carbon pools (i.e. carbon fluxes) at high spatial resolution requires repeat acquisition of LiDAR data via aircraft or satellite sensors. However, few studies have used repeat LiDAR acquisitions for any purpose. Dubayah et al. (2010) used repeat collections of waveform LiDAR data from the NASA Laser Vegetation Imaging Sensor (LVIS) instrument in 1998 and 2005 to determine change in forest height in a humid tropical forest of Costa Rica, and were able to infer whether primary and secondary tropical forests were sources, sinks, or neutral with respect to their carbon emissions during the intervening time interval. Bater et al. (2011) assessed the reproducibility of height and intensity metrics derived from multiple LiDAR acquisitions of coniferous forest on Vancouver Island collected on the same day and found that most metrics provided stable repeated measures of forest structure. Yu et al. (2004) applied an automated, object-oriented tree-matching algorithm to two LiDAR acquisitions collected two years apart to estimate height growth of ~5 cm at the stand level and 10–15 cm at the plot level. These studies show promise for multi-temporal LiDAR based assessment of forest dynamics and carbon flux. However, as LiDAR technology continues to evolve, much additional work is needed to extend this approach and narrow uncertainties in the quantification of forest carbon dynamics. Of particular importance are areas of active forest management (e.g., timber harvest) comprised of different forest successional and structural stages (Falkowski et al., 2009). Understanding biomass and carbon dynamics across varied forest management and successional regimes is highly useful for predictive modeling and carbon management because it connects forest ecosystem processes such as growth and harvest with landscape-level carbon pools and fluxes.

The primary objective of this research is to utilize repeat LiDAR and field plot surveys and statistical modeling to predict biomass pools and estimate rates of aboveground carbon flux in managed mixed conifer forests of the Northern Rocky Mountains, USA. Specifically, we utilize field forest inventory data and airborne LiDAR data collected during the summers of 2003 (Hudak et al., 2006) and 2009 to quantify the effects of forest growth and timber harvest on carbon pools of trees, saplings, shrubs, coarse and fine woody debris, herbaceous plants, litter, and duff across an actively managed forest landscape, and examine relationships among changes in these pools during this 6-year interval with respect to forest height and successional status. The study serves a broader objective of demonstrating a repeatable methodology for inventory and monitoring of forest carbon pools and fluxes across actively managed forest landscapes to support much needed carbon measuring, reporting, and verification methodologies over time.

2. Methods

2.1. Study area

The study is centered on Moscow Mountain (~20,000 ha; Latitude 46° 48′ N, Longitude 116° 52′ W), located in the Palouse Range in Northern Idaho, USA (Fig. 1). The area is topographically complex, ranging from 770 m to 1516 m in elevation. Climate is characterized by a warm dry summer and fall, and a wet winter and spring when most of the mean annual average precipitation of 630–1015 mm falls in the form of snow in the winter and rain in the spring. Vegetation is primarily comprised of temperate mixed-conifer forest with dominant species being ponderosa pine (*Pinus ponderosa* C. Lawson var. *scopulorum* Engelm.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. glauca (Beissn.) Franco), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), western red cedar (*Thuja plicata* Donn ex D. Don), and western larch (*Larix occidentalis* Nutt). Habitat types include: ponderosa pine series at xeric sites on southern and western aspects; Douglas-fir and grand fir series on moister sites, and cedar/hemlock series at mesic sites on northern and eastern aspects (Cooper et al., 1991). Volcanic ashcap is an important component of the soil structure across the study area, especially on northeastern aspects, and increases soil water holding capacity (Kimsey et al., 2011). The land ownership is dominated by private timber companies with many interspersed private and public land inholdings. The variety of habitat types and management strategies of the landowners has created a forest that is diverse in species composition, stand age, and structure, representing a variety of biophysical settings and forest successional stages (Falkowski et al., 2009; Martinuzzi et al., 2009). Major disturbances occurring during the time period 2003 to 2009 included harvest, thinning, and prescribed fires associated with forest management. The study area is bounded by croplands associated with dryland agriculture to the north, west, and south.

An overview of the methodology is diagrammed in Fig. 2.

2.2. LiDAR surveys and data processing

LiDAR data were collected during the summers of 2003 (by Horizons, Inc., Rapid City, SD, USA), 2007 (by Surdex, Inc., Chesterfield, MO, USA) and 2009 (by Watershed Sciences, Inc., Portland, OR, USA). The extent of the 2003 LiDAR survey was 32,708 ha and included much agricultural land surrounding the contiguous forest block, while that of the 2009 survey was 19,889 ha of the core contiguous forest (Fig. 1). As a cost-saving measure to maximize repeat coverage of the forested area of interest, the 2009 survey was purposely contracted to be outside of a relatively small area (840 ha) of forested land flown just two years prior in 2007 (Fig. 1). Fig. 3 illustrates at a single field plot the dramatic difference in LiDAR survey point densities between 2003 (0.4 points/m^2) and 2009 (nearly 12 points/m^2); the point density of the 2007 LiDAR survey was intermediate at almost 6 points/m^2. All three LiDAR systems operated at 1064 nm. Other characteristics of the three LiDAR surveys are provided in Table 1.

The LiDAR data delivered as binary files were converted to ASCII text files for processing, with ~0.5 million points per tile. The relevant attributes of each LiDAR point included: x and y coordinates, absolute elevation (z), the number of LiDAR returns and the return number in the pulse, as well as the unnormalized return intensity ranging from 0 to 255.

Points were converted from text format into the ArcInfo coverage format using the GENERATE command in Arc Macro Language (AML). The ground returns were separated from the vegetation returns using multiscale curvature classification (MCC, Evans & Hudak, 2007). The scale parameter used in the MCC AML was set to match the LiDAR post-spacing. We created a digital terrain model (DTM) of 1 m resolution from the classified ground returns through iterative finite