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Mapping biomass change after forest disturbance: Applying LiDAR footprint-derived models at key map scales

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ABSTRACT

Accurate estimate of biomass and its changes at local to regional scales are important for a better understanding of ecosystem function, biodiversity and sustainability. In this study we explored the forest biomass prediction and dynamic monitoring from Light detection and ranging (LiDAR) waveform metrics at different key map scales. NASA's Laser Vegetation Imaging Sensor (LVIS) data were acquired in Penobscot County, Maine, USA, during August 2003 and 2009 airborne campaigns in the New England region. Field data were collected in 2003, and 2009 to 2011. Regression models developed at the scale of footprint were applied to all LVIS waveforms within the two study sites: Howland Forest (HF) and Penobscot Experiment Forest (PEF). The effect of forest disturbances on LVIS biomass prediction models was investigated. Two types of models, i. e. combined model without consideration of disturbances and disturbance-specific models were developed and compared. Field data from nested field plots of 0.25 ha, 0.5 ha and 1.0 ha were used to evaluate the averaged, footprint-level (~0.03 ha, 20 m diameter) estimates in these plots. The results demonstrate that: 1) prediction model at the scale of individual LVIS footprints is reliable when the geolocations of the measured footprints were determined by DGPS with a best accuracy of 0.5–1.0 m. 2) The differences between biomass prediction models for disturbed and undisturbed forests were statistically significant ($p < 0.001$) at the scale of footprint, and the disturbance-specific models performed slightly better ($R^2 = 0.89$, RMSE $= 27.9$ Mg·ha^{-1}, and relative error of 22.6%) than the combined model ($R^2 = 0.86$, RMSE $= 31.0$ Mg·ha^{-1}, 25.1%). 3) The evaluation using field plot data showed that the predictions of biomass were improved markedly with the increase of plot sizes from 0.25 ha to 1.0 ha and that the effect of disturbance was not strong. At 1.0 ha plot-level, both disturbance-specific and combined models agreed well with field estimates ($R^2 = 0.91$, 23.1 Mg·ha^{-1}, 16.1%; and $R^2 = 0.91$, 22.4 Mg·ha^{-1}, 15.6%). 4) Sensitivity analysis on levels of variation and error to footprint density suggests that a certain density of LVIS footprints is required for biomass mapping. The errors were minimized when footprint coverage approached about 50% of the area of 1.0 ha plots (16 footprints). 5) By applying the footprint-level models developed from 2009 LVIS data to both 2009 and 2003 LVIS data, the change of biomass from 2003 to 2009 could be assessed. The average annual biomass reduction rate from forest disturbance at two sites is -7.0 Mg·ha^{-1} and -6.2 Mg·ha^{-1}, the average annual biomass accumulation from regrowth is $+4.4$ Mg·ha^{-1} and $+5.2$ Mg·ha^{-1}, respectively.

1. Introduction

Above-ground biomass (here after biomass) stock from forest represents a significant component of the global carbon cycle (Goetz & Dubayah, 2011). Accurate estimate of forest biomass and its spatial distribution at fine resolution is required for a better understanding of terrestrial ecosystem function, biodiversity and sustainability (Bergen et al., 2009; Hall et al., 2011). Biomass can be estimated from field measurements based on well-defined allometric equations (Clark & Kellner, 2012). This traditional inventory method, which forms the basis for many national forest inventories, can be complemented and enhanced by the use of remote sensing techniques.

A variety of passive and active remote sensing techniques have been investigated for measuring and monitoring forest carbon stocks (Goetz & Dubayah, 2011; Lu, 2006). Light detection and ranging (LiDAR) is promising because of its ability to directly measure canopy vertical profile, providing canopy height information which is highly correlated with the forest biomass. LiDAR systems are categorized as small- or large-footprint based on the size of the illuminated ground

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area. Small-footprint LiDAR systems (5–30 cm diameter) provide dense samples for detailed representation of the canopy structure, but their use is restricted to low-altitude airborne platforms. Small footprint full waveform systems have appeared in recent years with ability to record the complete waveform (Mallet & Bretar, 2009). Large-footprint laser systems (10–70 m diameter) record a continuous, vertical profile of returned signal. Although large-footprint LiDAR data is not able to capture the very fine spatial details of forest canopies, structural attributes can be derived from vertical profiles of return energy for application in ecology studies (Mather, 2004). LiDAR derived metrics from small-footprint discrete return LiDAR (Asner et al., 2010; Gonzalez et al., 2010; Lim & Treitz, 2004; Næsset & Gobakken, 2008; Nilsson, 1996; Pang et al., 2008; Zhao et al., 2011) and continuous returned full-waveform LiDAR (Drake et al., 2002, 2003; Dubayah et al., 2010; Lefsky, 2010; Lefsky et al., 1999, 2002, 2005a, 2007; Means et al., 1999; Ni-Meister et al., 2010; Sun et al., 2008) have been used for estimation of forest canopy height and biomass. Various multi-sensor fusion (Asner et al., 2010, 2012; Kellndorfer et al., 2010; Lefsky et al., 2005b; Nelson et al., 2009; Saatchi et al., 2011; Sun et al., 2011; Swatantran et al., 2011) used LiDAR samples and optical or radar imagery data for regional to continental mapping of forest attributes.

Laser Vegetation Imaging Sensor (LVIS) (Blair et al., 1999) with a footprint size of 10–25 m, records the entire profile (waveform) of the return signal in ~30 cm vertical bins (Dubayah et al., 2000). Because the footprint size is larger than the diameter of a tree crown and the laser beam can pass gaps between trees, a waveform can capture the tree top and ground surface in a forest stand. Studies have confirmed the ability of LVIS-derived metrics to estimate biomass, even in dense tropical forests. Drake et al. (2002) reported that height of mean energy (HOME or RH50) is the best single term predictor for estimating tropical forest biomass at the LVIS footprint-level (~0.05 ha, 25 m diameter) and the plot-level (~0.5 ha). The issue of sampling sizes has also been discussed by several studies with small- to large-footprint LiDAR system. Drake et al. (2002) compared regression models at the footprint-level and the plot-level for a tropical wet forest at La Selva, Costa Rica. They found that because of geolocation uncertainties, large tree location, and species composition, the prediction model was better at plot-level with the R^2 of 0.73 and RMSE of 60.02 $Mg \cdot ha^{-1}$. Results from Hyde et al. (2005) indicated a strong agreement between field data and LVIS measurements for height ($R^2 = 0.75$; RMSD = 8.2 m) and biomass ($R^2 = 0.83$; RMSD = 73.5 $Mg \cdot ha^{-1}$) at Sierra Nevada sites in California, but not for canopy cover. Anderson et al. (2006) found good relationship between LVIS metrics and height ($R^2 = 0.80$), but the relationship is weaker between metrics and biomass ($R^2 = 0.61$, RMSE = 58 $Mg \cdot ha^{-1}$) at Bartlett Experimental Forest (BEF) in New Hampshire, USA. According to Anderson et al. (2008), the possible factors for a weaker correlation include geolocation error, species composition, and intensity of disturbance. Dubayah et al. (2010) applied the LVIS data for mapping biomass change. They found various issues that need to be considered in detecting and mapping the biomass change with LVIS data, and suggested using range-distance based ΔRH_E metrics to develop the uniform biomass change equation at plot-level to avoid errors caused by ground detection and two sets of regression models. Asner et al. (2010) noted the scaling issue that the small-footprint LiDAR prediction errors decrease with the increase of plot size. Mascaro et al. (2011) proposed a "crown-distributed" approach to address the plot and edge scaling issues caused by the disagreement between LiDAR and field measurements.

The effects of disturbance on the relationship between biomass and height metrics were investigated by field observations and model simulation. Drake et al. (2003) investigated the relationships of simple LiDAR metrics (i.e. RH50) with estimated biomass, and indicated that there are significant differences between different types of forest (i.e. tropical wet forest and tropical moist forest). Ni-Meister et al. (2010) indicated that combined height and gap fraction could improve the estimation of biomass particularly for coniferous. Ranson and Sun (2010) simulated the waveform RH metrics from different stands (disturbed and undisturbed forest) by a 3D-LiDAR model, and showed that the relationships between forest biomass and LiDAR metrics were distinguishable. Asner et al. (2011) found that the fitted curves between forest carbon stocks and LiDAR signals are different from plantations and natural regrowth after disturbance because of stocking differences. Inventory data and modeling results also demonstrated that young forests accumulated biomass much faster than the matured forest for the first 10 to 20 years after disturbance (Chazdon, 2003). Vegetation change tracker (VCT) algorithm was designed for detecting forest disturbance (Huang et al., 2010) via spectral–temporal information from Landsat time series stack (LTSS). The products of yearly disturbance maps from LTSS-VCT were used in this study.

The biomass prediction models can be developed at the scale of footprints and larger plots. To facilitate regional and global biomass mapping using LiDAR waveform data, models at footprint-level are desirable because sampling large plots is much more time consuming than footprint-level sampling. The accuracy of biomass estimation at coarser scales will depend on the accuracy of the footprint-level models and the number of samples (footprints) at this scale. In this study we will investigate 1) if the model at footprint-level can be developed with desirable accuracy in our study sites, 2) if the forest management practices in terms of disturbances will affect the models, and 3) what will be the proper scale with concern of uncertainties for mapping biomass from LVIS data in our study sites. Forest biomass map at 1.0 ha pixel size was produced from LVIS acquired in 2003 and 2009. The changes of biomass from 2003 to 2009 were analyzed in this study.

2. Study area and data acquisition

The study sites are located in Penobscot County, Maine, USA (Fig. 1). These include Howland Forest (HF) in the Northern Experimental Forest (45°08′–45°14′ N, 68°42′–68°45′ W), and the Penobscot Experimental Forest (PEF) (45°49′–45°52.5′ N, 68°30′–68°38.5′ W). Both sites consist of boreal forest with mixed deciduous and coniferous tree species (Hollinger et al., 1999; Safford et al., 1969). The dominant species include *Populus tremuloides* (quaking aspen), *Betula papyrifera* (paper birch), *Tsuga canadensis* (eastern hemlock), *Picea rubens* (red spruce), *Abies balsamea* (balsam fir), and *Acer rubrum* (red maple). The region features relatively level and gently rolling topography. According to USGS 1/3-Arc Second National Elevation Dataset (NED) published in 2009, the elevation ranges from 40 m to 178 m at HF, and from 29 m to 83 m at PEF. HF has an American Flux Tower within intermediate aged forest, and the surrounding areas are private land owned by a timber production company with different forest management manipulations such as clear-cut, select-cut and stripe-cut.

2.1. Field campaign

Field measurements were conducted during August 2009 to 2011. Both footprint-level (~0.03 ha, 20 m diameter) and plot-level (0.25 ha–1.0 ha) plots (see Fig. 2 for typical layout) were measured. Differential Global Position System (DGPS) instruments were used to locate LVIS footprints and establish sampling plots.

At the plot-level, twenty-four 1.0 ha (200 m × 50 m) plots and ten 0.5 ha (100 m × 50 m) plots were established in 2009 and 2010, respectively. The longer edges of these plots were in the range direction of the NASA/JPL Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) flight lines. The layout of these plots is illustrated in Fig. 2, where each plot consists of sixteen 25 m × 25 m subplots.

At the footprint-level, ninety-one circular plots with 20 m diameter centered at each LVIS footprint were selected in both undisturbed forest and disturbed forest. Forty-seven footprints were measured in August, 2010 and forty-four were measured during January and August of 2011.