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Estimating aboveground carbon density across forest landscapes of Hawaii: Combining FIA plot-derived estimates and airborne LiDAR

R. Flint Hughes[a,*], Gregory P. Asner[b], James A. Baldwin[e], Joseph Mascaro[c], Lori K.K. Bufil[d], David E. Knapp[b]

[a] Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI 96720, USA
[b] Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305, USA
[c] Planet, San Francisco, CA 94103, USA
[d] Research Corporation of the University of Hawaii, Honolulu, HI 96848, USA
[e] Pacific Southwest Research Station, USDA Forest Service, Albany, CA 94710, USA

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ABSTRACT

Remote sensing data have increasingly been employed in combination with field plot data to estimate aboveground carbon (C) stocks across heterogeneous forested landscapes around the world. The Forest Inventory and Analysis (FIA) program of the US Forest Service offers a gridded network of field plots which potentially can be linked to airborne Light Detection and Ranging (LiDAR) data to estimate forest aboveground carbon density (ACD; units of $\mathrm{Mg\,C\,ha^{-1}}$). Here we utilized FIA plot and airborne LiDAR data sets collected across two contrasting landscapes known as Laupahoehoe and Puʻu Waʻawaʻa on Hawai'i Island to explore strengths and weaknesses of linking those two data sets to estimate ACD. We varied FIA plot sample designs with respect to sampling density (i.e., the number of plots across landscape) and intensity (i.e., the structural detail within inventory plots) to test the capability of the mapping approach. Results indicated that Laupahoehoe and Puʻu Waʻawaʻa landscapes supported an estimated 545 Gg C and 157 Gg C aboveground, respectively, and mean ACD values of the wet windward Laupahoehoe landscape ($109\,\mathrm{Mg\,ha^{-1}}$) were an order of magnitude greater than those of the leeward dry Puʻu Waʻawaʻa landscape ($9.7\,\mathrm{Mg\,ha^{-1}}$). Patterns of ACD were largely determined by combined factors of precipitation, lava substrate, prior land use, and presence of non-native, often invasive, species. Results demonstrated the relative importance of sample plot density over sample plot intensity, and showed that FIA inventory plots, even at their lowest sample intensity design, can be linked with LiDAR data to accurately estimate ACD across spatially heterogeneous landscapes. We also developed and applied a straightforward, statistically-robust approach to provide error estimates for the 100 million pixels that characterize the Laupahoehoe and Puʻu Waʻawaʻa landscapes as well as for any sub-units of those landscapes. We contend that augmenting existing FIA forest plot data with airborne LiDAR coverage, even if that requires an increase in plot density somewhat above the FIA standard 1X or 2X approaches, is a feasible, cost-effective, scientifically sound approach from which to obtain accurate landscape- to regional-scale ACD measures across the extensive and heterogeneous forests of the United States.

1. Introduction

Forests contain 70 to 90% of earth's estimated 1300 Pg of terrestrial biomass (Houghton et al., 2009), the majority of which occurs aboveground (Cairns et al., 1997). As carbon (C) accounts for approximately 50% of biomass, changes in forests due to natural or anthropogenic disturbances (e.g., storms, drought, pathogens, harvesting, deforestation, agricultural conversion) or through forest growth have a profound influence on the global carbon balance. For example, recent deforestation in the tropics has resulted in estimated 1.5 Pg C per annum fluxes to the atmosphere, or 16% of total anthropogenic emissions (Canadell et al., 2007), and C sequestration via forest growth in the United States offset an estimated 14% of that nation's C emissions in 2010 (US Environmental Protection Agency, 2012). Widespread recognition of the importance that forests play in the global C cycle has resulted in international programs, such as UN-REDD+, which seek to mitigate greenhouse gas emissions through forest protection (UN-REDD, 2012). An underlying tenant of such programs is that monetary

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* Corresponding author.
E-mail address: fhughes@fs.fed.us (R.F. Hughes).

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compensation for forest C sequestration be based on spatially explicit, not to mention accurate, accounting of C across often heterogeneous forest landscapes.

Although there is broad agreement regarding the need to accurately quantify forest C stocks and dynamics at regional, national, and global scales, doing so remains a challenge. To date, national forest inventory networks (NFI) have been used to provide forest carbon estimates (McRoberts, 2010); in the United States the Forest Inventory and Analysis (FIA) program of the US Forest Service has served this role (Domke et al., 2014). FIA employs a gridded network of field plots in which forest composition and structure are measured along with many additional parameters (Bechtold and Patterson, 2005) and from which aboveground biomass and C can be estimated at the individual tree- and plot-level (Chave et al., 2005). This program has provided useful information regarding such topics as forest productivity (Waring et al., 2014), timber harvest patterns (Belote and Aplet, 2014), species distributions and shifts in response to climate change (Desprez et al., 2014, Gibson et al., 2014), non-native plant invasions (Wang et al., 2011, Huebner et al., 2009,) and pest outbreaks (Thompson, 2009, Haavik et al., 2012). FIA data have also informed recent research addressing C storage and dynamics in U.S. forests (Blackard et al., 2008, Gray et al., 2014). Although the FIA plot network, when re-measured at regular intervals through time, can provide average aboveground forest C mass values and temporal changes of such values for given areas of interest (i.e., counties, forest types, land use designations), on its own it likely does not adequately address the spatial and temporal heterogeneity inherent across forested landscapes. Statistically, NFI programs including the FIA system are inherently limited to sampling, rather than producing wall-to-wall inventories, of aboveground forest C across broad regions.

Remote sensing in general, and large footprint LiDAR (light detection and ranging) in particular, has been employed in combination with field plot data to accurately estimate aboveground C across heterogeneous forested landscapes of the North America, Europe, South and Central America, Africa, and Polynesia (e.g., Lefsky et al., 1999, Drake et al., 2002, McRoberts et al., 2015). In most cases, these efforts have employed a plot-aggregate allometry approach in which sets of plot-based estimates of aboveground C density (ACD; units of Mg C ha^{-1}) are regressed against relevant LiDAR metrics from those same plot locations (e.g., mean canopy height for each given plot) to create models where the LiDAR metric and ACD value are the independent and dependent variables, respectively (Zolkos et al., 2013, Asner and Mascaro, 2014). In most cases, sampling plots used to estimate ACD have ranged from 0.1 ha to 1 ha in area, and all woody stems down to a relatively small diameter (e.g., ≥ 1 cm dbh, or ≥ 5 cm dbh) are measured across the entirety of the plot area (Zolkos et al., 2013, Asner and Mascaro, 2014).

Recently, FIA plot data have been combined with LiDAR data to estimate forest height, structure, and biomass across temperate landscapes of the United States, including Alaska (Skowronski et al., 2007, Walker et al., 2007, Kellndorfer et al., 2010, Chopping et al., 2011, Zhao et al., 2012). However, no studies have yet combined FIA and LiDAR data sets to estimate aboveground forest C mass across tropical landscapes. Nor have relationships between FIA plot data and LiDAR parameters been rigorously tested regarding the robustness of resulting C mass estimates and their attendant uncertainties. Previous studies on Hawai'i Island have inventoried aboveground C mass at landscape scales by combining airborne small footprint LiDAR data with non-FIA field plot estimates of aboveground C mass (Asner et al., 2009, Asner et al., 2011, Hughes et al., 2014). These non-FIA forest sampling plots have tended to be greater in area, and have measured woody stems in a more comprehensive manner relative to FIA plots (Asner et al., 2011). Given the recent installation of FIA plots across areas of Hawai'i Island where high resolution LiDAR data have been acquired previously (Asner et al., 2011), we now have the opportunity to explicitly evaluate the usefulness of FIA plot data in combination with LiDAR data to estimate aboveground forest C mass. Several questions arise regarding this approach. First, are sample areas of FIA plots sufficient in size to successfully integrate with LiDAR canopy parameters to predict aboveground C mass? If not, how much more area should be sampled to increase their utility? Second, does the FIA nested sampling approach, in combination with LiDAR canopy metrics, provide C mass estimates with low levels of uncertainty? If not, how should one alter sampling methods to make them more useful for this application? Third, what are the fewest number of FIA plots needed across a given landscape to develop useful relationships with LiDAR canopy metrics to predict aboveground C mass across that landscape?

Given the above questions, our objectives were to utilize recently acquired FIA plot and airborne LiDAR data sets collected within the boundaries of the Hawai'i Experimental Tropical Forest (HETF) to explore the strengths and weaknesses of using FIA plots to inform LiDAR metrics to estimate aboveground C mass across broad areas of LiDAR coverage. Specifically, we evaluated how differing levels of FIA plot sampling intensity (i.e., the manner in which aboveground C mass is measured on a given plot) and plot density (i.e., the number of plots across a landscape) used in combination with spatially explicit LiDAR data influence both the aboveground forest C mass values and the uncertainties associated with those values. We also wished to determine the effects of varying FIA plot intensity and density on aboveground forest C estimates and uncertainties when only FIA plots are used to estimate forest C mass at the landscape scale, rather than in combination with LiDAR data sets to estimate forest C mass.

2. Methods

2.1. Study area

We conducted this study across the Laupahoehoe and Pu'u Wa'awa'a regions of Hawai'i Island (Fig. 1), which constitute the wet windward and dry leeward units, respectively, of the Hawai'i Experimental Tropical Forest (HETF), part of the USDA Forest Service Experimental Forest and Range System. These areas are administered and managed by the state of Hawai'i's Department of Land and Natural Resources (DLNR); Laupahoehoe includes Forest Reserve and Natural Area Reserve management designations, and Pu'u Wa'awa'a includes Wildlife (Forest Bird) Sanctuary, Forest Reserve, and State Parks Reserve management designations. Together, both areas account for 20,726 ha.

The Laupahoehoe HETF unit occupies 4990 ha and ranges in elevation from ca. 700 m to 1900 m asl. Mean annual temperature (MAT) decreases from 20 °C at lower elevations to 12 °C at upper elevations (Sanderson, 1993); mean annual rainfall decreases from 4907 mm at lower elevations (i.e., 668 m) to 1980 mm at upper elevations (i.e., 1762 m) to (Table 1; Giambelluca et al., 2013). Soils originate from three distinct lava substrates emanating from Mauna Kea Volcano whose ages range from 4000 to 250,000 YBP (Wolfe and Morris, 1996).

The Pu'u Wa'awa'a HETF unit encompasses 15,706 ha and ranges in elevation from sea level to 1951 m asl. MAT decreases from 23 °C along the coast to 14 °C at upper elevations (Sanderson, 1993); mean annual rainfall increases from 266 mm along the coast to 703 mm at upper elevations (i.e., 1582 m) (Table 1; Giambelluca et al., 2013). Soils originate from lava substrates of 7 distinct flow age groups that emanated from Hualalai Volcano; flows range in age from CE 1790 or younger to 105,000 YBP (Wolfe and Morris, 1996).

Vegetation of Laupahoehoe varies with respect to elevation, hydrology, and native or non-native species dominance. The majority of the area has been characterized as closed forest co-dominated by Hawai'i's most common native tree species, *Metrosideros polymorpha* (ohia) and *Acaia koa* (koa) (Gon et al., 2006). Native forests at low elevations (i.e., 700–900 m) have been invaded by fast-growing, non-native species such as *Psidium cattleianum* (strawberry guava) and *Ficus rubiginosa* (banyan) (Asner et al., 2009). Upslope (i.e., 1400 to 1600 m