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A tree-based approach to biomass estimation from remote sensing data in a tropical agricultural landscape

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ABSTRACT

Agricultural land now exceeds forests as the dominant global biome. Because of their global dominance, and potential expansion or loss, methods to estimate biomass and carbon in agricultural areas are necessary for monitoring global terrestrial carbon stocks and predicting carbon dynamics. Agricultural areas in the tropics have substantial tree cover and associated above ground biomass (AGB) and carbon. Active remote sensing data, such as airborne LiDAR (light detection and ranging), can provide accurate estimates of biomass stocks, but common plot-based methods may not be suitable for agricultural areas with dispersed and heterogeneous tree cover. The objectives of this research are to quantify AGB of a tropical agricultural landscape using a tree-based method that directly incorporates the size of individual trees, and to understand how landscape estimates of AGB from a tree-based method compare to estimates from a plot-based method. We use high-resolution (1.12 m) airborne LiDAR data collected on a 9280-ha region of the Azuero Peninsula of Panama. We model individual tree AGB with canopy dimensions from the LiDAR data. We apply the model to individual tree crown polygons and aggregate AGB estimates to compare with previously developed plot-based estimates. We find that agricultural trees are a distinct and dominant part of our study site. The tree-based approach estimates greater AGB in pixels with low forest cover than the plot-based approach, resulting a 2-fold difference in landscape AGB estimates between the methods for non-forested areas. Additionally, one third of the total landscape AGB exists in areas having < 10% cover, based on a global tree cover product. Our study supports the continued use and development of allometric models to predict individual tree biomass from LiDAR-derived canopy dimensions and demonstrates the potential for spatial information from high-resolution data, such as relative isolation of canopies, to improve allometric models.

1. Introduction

At 38% of Earth's surface area, cropland and pasture exceeds forest as the dominant global terrestrial biome (FAO, 2016). A common pathway from forest to agriculture, especially prevalent in tropical areas, is conversion of forest to pasture land, followed by conversion to croplands (Graesser et al., 2015). Globally, an estimated 83 million hectares of primary and degraded tropical forest have been converted to agricultural land between the 1980s and 1990s (Gibbs et al., 2010). These large shifts from forest area to cropland are associated with a loss of carbon storage and sequestration because of the reduction of standing biomass and soil carbon (Pan et al., 2011).

Despite the global decline of forest cover, agricultural areas in the tropics are characterized by remnant trees that provide ecosystem services, including seed sources for forest recovery, habitat for wildlife, and valuable forest products for landowners (Harvey et al., 2005, 2006; Harvey and Haber, 1999; León and Harvey, 2006; Medina et al., 2007; Prevedello et al., 2017; Slocum and Horvitz, 2000; Zahawi et al., 2013). Agricultural tree cover can exist as individual trees, scattered groups of trees, live fences, windbreaks, and small forest fragments or riparian forests (Griscom et al., 2011; Harvey et al., 2006; Plieninger, 2012). In addition, while tropical agricultural lands contain less standing biomass than forests, agricultural trees are important sinks and pools of carbon in the form of living biomass (Zomer et al., 2016). The dominance of agricultural land means that tropical agricultural areas have an influential role in global carbon dynamics with potential for additional

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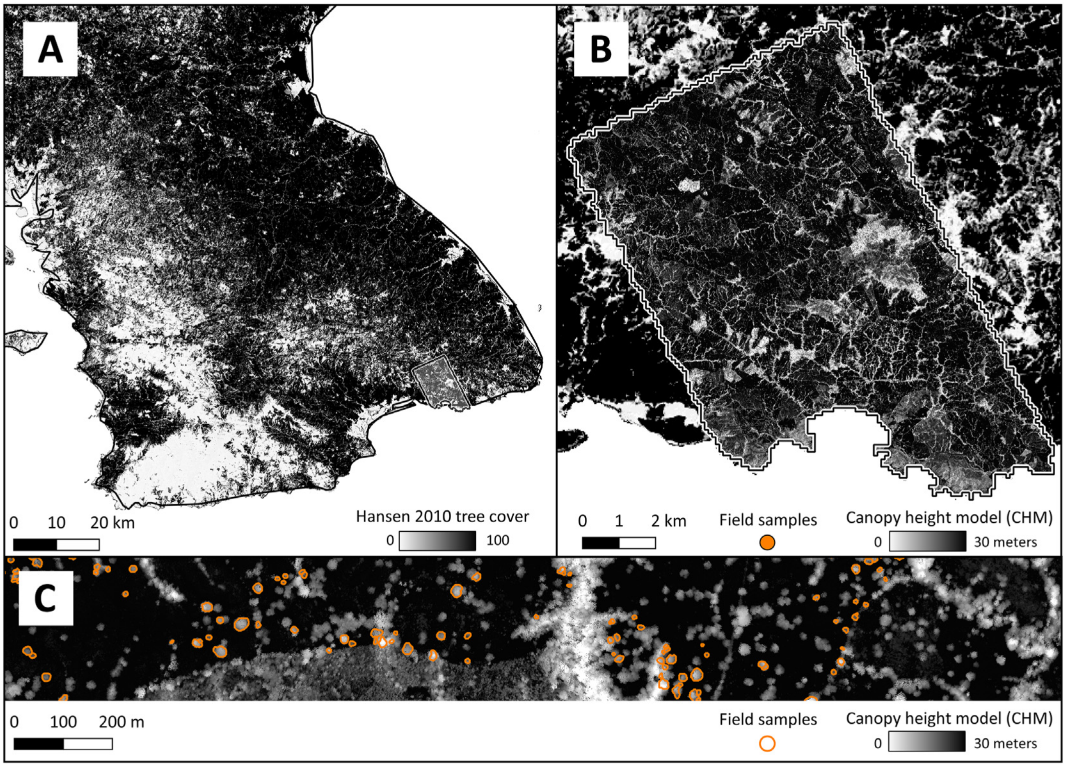

Fig. 1. Map of the study site on the Azuero Peninsula of Panama. A) Tree cover on the Azuero Peninsula from the 2010 Hansen global tree cover analysis (Hansen et al., 2013). B) Carnegie Airborne Observatory (CAO) canopy height model (CHM) from 2012 of the 9280-hectare study site. Orange dots show the locations of the field data. The global tree cover product is shown outside the study site. C) Subset of study site showing mapped crown polygons on the CHM.

emissions through the loss of existing agricultural tree biomass (Harvey et al., 2011), or enhanced sequestration through forest and landscape restoration (Chazdon et al., 2016b).

Remotely sensed data are increasingly used to estimate forest cover and carbon stocks from local to global scales. Landcover classification into discrete categories by optical satellite data, such as the Landsat and MODIS systems, has contributed to an understanding of dynamics between forest and agricultural areas in Latin America (Aide et al., 2013; Graesser et al., 2015). Given the large difference in biomass and carbon between forest and agricultural areas, these land cover classifications provide critical information for quantifying biomass and carbon dynamics. However, variation in biomass within forest and agricultural areas can be substantial, and the boundary between what is forest and not forest imprecise. As a result, continuous measurements of vegetation structure, such as percent tree cover and tree height, are critical for understanding forest dynamics in heterogeneous landscapes, and indirect estimation of vegetation structure from optical sensors remains an important challenge (Caughlin et al., 2016; Hansen et al., 2013).

Active remote sensing technologies, such as light detection and ranging (LiDAR), can provide structural information to further resolve variation in canopy cover and aide in biomass estimation. For example, LiDAR measurements of the canopy surface height (at 0.1 to 1 ha spatial resolution), when matched to field-measured tree inventory plots where biomass has been estimated, can be used to refine estimates of AGB from optical image data to provide country-wide estimates of biomass or carbon density (Asner et al., 2013, 2016; Asner and Mascaro, 2014). One primary benefit of this approach is that field-calibrated models of plot biomass can be applied to large areas to provide spatial data on the variation in a property of interest.

However, methods that combine inventory plots with remote sensing data at the plot scale (0.1 to 1 ha) may perform poorly in tropical agricultural areas. This is because the vegetation structure of agricultural areas is different than that of forests. Agricultural areas contain large areas with few or no trees, so plot sampling approaches typically used in forest studies do not measure agricultural tree structure well. To accurately quantify the contribution of agricultural trees to landscape AGB requires remote sensing methods that can represent individual trees, rather than the height of a smoothed canopy surface. With advent of high spatial resolution LiDAR data, and algorithms to detect individual trees (Coomes et al., 2017; Dalponte et al., 2015; Duncanson et al., 2014; Ferraz et al., 2016; Zhen et al., 2016), more tree-centered AGB estimates are possible, where the size of individual trees, rather than the height or canopy cover of forest plots, is measured from remote sensing data and linked to field observations of those same individuals.

Studies comparing plot- and tree-based approaches to estimate AGB in ecosystems with heterogeneous tree cover highlight the importance of measuring individual trees. In an African savanna, Colgan et al. (2013) found that a plot-based method underestimated AGB because the plot-level top of canopy height measurement could not distinguish between differences in plot structure, such as a homogeneous canopy of small trees versus a heterogeneous canopy of one or a few large trees. Additionally, Coomes et al. (2017) implemented a tree-based approach to estimate biomass in closed canopy tropical forest in Malaysia. The authors argue that while the tree-based approach had slightly higher uncertainty than the plot-based approach, the continued development of these methods is needed to provide input to models of individual tree dynamics and fine-scale forest biomass, which may be hard to resolve with plot-based data and analysis. Finally, the utility of using individual tree crown size metrics to quantify biomass and carbon stocks with LiDAR data was recently demonstrated with a global dataset across forest types (Jucker et al., 2016), paving the way for application of these methods in different ecosystems and landscapes.

In this study, we implement a tree-based method for estimating AGB of an agricultural landscape in Panama, and compare our tree-based estimates with plot-based estimates for the same area. The objective of this study is to assess a tree-based versus a plot-based approach to estimate AGB of agricultural landscapes, with respect to the agricultural tree cover contribution to landscape AGB, model error, and the