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Live aboveground carbon stocks in natural forests of Colombia

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A B S T R A C T

Emission factors are essential in order to accurately account and report land use and land use change emissions due to deforestation at a national level, in accordance with the United Nations Framework Convention on Climate Change reporting guidelines. Nonetheless, in many tropical countries its availability is still scarce, especially in Colombia where a National Forest Inventory is lacking. Here, we estimate the amount of carbon stored in the live aboveground biomass of the forests of Colombia, using data from 4981 sampling forest plots of various sizes established between 1990 and 2014. Our study included an analysis of the influence of the choice of allometric model and the carbon density estimation method employed in the estimation. We found that the most conservative total mean value for the entire country was 226.9 ± 4.5 Mg ha^{-1}, obtained by using a previous set of allometric equations developed for the natural forest of Colombia and an inverse-variance weighting that accounts for the variation in plot size, which represents a potential stock of 6.44 ± 0.13 Pg of carbon. Thus, our study provides a method to utilize existing sample data to assess forest carbon stocks at national level, make available conservative carbon stocks estimates for the natural forests of Colombia, and reports enhanced and adequate information subject to national capabilities and policies in the context of results-based payments for reducing emissions from deforestation and forest degradation and the conservation.

1. Introduction

Deforestation and forest degradation account for ~10% of the anthropogenic greenhouse-gas (GHG) emissions (Houghton et al., 2012; Le Quéré et al., 2014). After fossil-fuel emissions, it is the second largest source of human-caused GHG, and has been shown to stimulate climate change (Denman et al., 2007; Houghton, 2005; Strassburg et al., 2012). In order to accurately quantify land use change carbon emissions, information about forest carbon stocks and deforestation rates is essential. Remote-sensing based carbon stock estimates for Colombia are 8.1 Pg of carbon (Saatchi et al., 2011); however, it is known that these estimates are not reliable on hilly terrain (Gibbs et al., 2007), which covers most of the country. Hence, it is essential to develop estimates based on ground measurements. Nevertheless, in tropical countries the availability of this information is still scarce (Chave et al., 2005; Clark, 2004; Clark et al., 2001; Dixon et al., 1994; Djomo et al., 2011; Malhi and Phillips, 2004). This, lack hampers the Monitoring, Reporting

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and Verification (MRV) of the effectiveness of the programs that aim to reduce GHG emissions from deforestation and degradation (e.g. REDD+) (Gibbs et al., 2007; Goetz et al., 2010). Therefore, improving the quality of national-level estimates of forest carbon stocks is mandatory to be able to execute programs that aim to receive payments to mitigate climate change by regulating the carbon cycle (Clark, 2002; Phillips et al., 2002).

In forest ecosystems, the carbon stocks are stored in three different pools: living biomass, necromass and soils (GOFC-GOLD, 2009; IPCC, 2007). Although it is desirable to assess all carbon pools (BioCarbon, 2008; Gibbs et al., 2007; GOFC-GOLD, 2009; IDESAM, 2008), the live aboveground biomass (AGB) has been shown to be paramount in tropical forests as it stores around half of the total carbon pool (Aragão et al., 2009; Chave et al., 2003; Malhi et al., 2009), and is the most affected and depleted carbon pool during forest clearing and degradation. To accurately assess the AGB at the national scale we need to rely on large and high-quality field inventories, and to develop appropriate methods of AGB estimation, together with associated uncertainty.

In tropical forests, the use of National Forest Inventories (NFI) or plot networks that cover the environmental heterogeneity of a country, together with statistical methods involving the use of generic allometric models to estimate tree AGB (Álvarez et al., 2012; Chave et al., 2005, 2014), is one of the most reliable ways to estimate the AGB at large spatial scales (Fang et al., 1998; Gibbs et al., 2007; Saatchi et al., 2007). Although the use of remote sensing to assess carbon density in forest ecosystems has significantly advanced in the last decade (Asner et al., 2009, 2013; Marvin et al., 2014; Saatchi et al., 2011), in tropical countries, ground sampling faces specific challenges in conducing intensive ground inventories owing to the extent and structure of native forests. In theory, a combination of intensive ground sampling and remotely sensed information is the best scenario to ensure efficiency and accuracy (IPCC, 2003). However, in countries as Colombia, the lack of a NFI obligates to use non-randomly plot-networks previously established for different purposes than carbon assessments, which hampers to probabilistically address questions about the AGB distribution at a national scale. Nonetheless, in absence of a NFI, large plot-networks spread out across the main biogeographic regions, such as that employed here, combined with forest stratifications via remote sensing, can open new ways to compare design-based and model-based estimates of the AGB (Köhl et al., 2011). This kind of information will surely set up the baseline for carbon-based conservation programs such as REDD+ as well as it will help filling the voids we have in tropical countries on forest characterization and environmental services quantification.

In the present study, we aim to estimate the amount of carbon stored in the AGB of natural forests of Colombia. In Colombia, the large range of edaphoclimatic and topography variability may mirror the spatial distribution of the AGB. Using plot-based forest inventories, remote sensed information, and general allometric equations, we aim to answer these questions: (1) How much carbon is stored in the natural forests of Colombia? (2) How much is the assessment of AGB influenced by the allometric model and the carbon density estimation method employed? By answering these questions, we hope to provide information required in Colombia for the implementation of climate change mitigation programs, such as REDD+.

2. Methods

2.1. Study site

Colombia is located in the northwest corner of South America, between latitudes 4° South and 12° North, and between 67° and 79° longitude West, with coasts on both the Caribbean sea and Pacific ocean (Fig. 1). The country has an area of 2,070,408 km^2, of which 55% correspond to its mainland terrestrial (i.e. continental) area. The dominant landscapes in the country are hills (35%), mountains (26%), valleys and plains (20%); the remaining 19% is represented by foothills, plateaus and flattening surfaces (Malagon-Castro, 2003). Elevation ranges between 0 to 5775 masl. The climate conditions are diverse and determined, in general, by trade winds, altitude, and humidity. The mean annual temperature (MAT) generally decreases as altitude increases, with a drop of about 6.5 °C for every 1000 m in increased height (IDEAM, 2005). From the country, 91% has a warm climate (>24 °C), 5% temperate climate (18–24 °C), and 2% cold climate (12–18 °C). The remaining 2% has very cold (6–12 °C), subpáramo (3–6 °C), páramo (1.5–3 °C) or nival (<1.5 °C) climate (IDEAM, 2005). The rainfall distribution fluctuates greatly due to the mountain ranges and other meso- and macro-climate factors (e.g. ITCZ, ENSO, IAS dipole, etc.). However, in general, the northern portion of the country and the Andes shows a bimodal precipitation regime over the year, receiving in average 500–2000 mm and 2000–6000 mm, respectively, while east of the Andes the regime is monomodal and the annual precipitation ranges 2000–4500 mm, and in the west (very-wet) there is no clear trend due to slight differences in the total rainfall among months, receiving rainfall of 3000–12,000 mm (IDEAM, 2005).

2.2. Forest plot-data compilation, preparation and cleaning

Since Colombia lacks an NFI, we used data tallied on 4981 square or rectangle shape plots that were established non-randomly in forests of Colombia between 1990 and 2014 (Fig. 1), representing 119 different research projects conducted by national and international researchers affiliated with different government-related and non-government organizations. Plots establishment was not statistically-designed for estimating carbon stocks at a national scale, as most of the information comes from local o mesoscale plant ecology studies or floristic characterizations, in which plots were established in subjective locations to ensure within-plot homogeneity or for providing information for unsampled forests types. Plot size varied between 0.02 ha and 4.00 ha (mean = 0.24 ha; median = 0.10 ha) (Fig. S1, Supplementary Materials), and minimum recorded stem size was 10 cm of diameter at breast height (DBH). The total amount of forest inventoried was ca. 1190 ha. Data were compiled and/or collected as part of the project "Consolidation of the National Forest and Carbon Monitoring System to Support Environmental Policy and Management in Colombia", which was implemented by the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM). Although the information was generated using different sampling protocols (e.g. size and shape of plots varied), it is the largest dataset available to estimate AGB carbon stocks in Colombia at the present time.

We checked taxonomic nomenclature using the iPlant Collaborative platforms and tools (Boyle et al., 2013). The entire database included information from 583,612 individuals, 183 families, 990 genera and 4065 species of plants. From the 527,030 individuals that were determined to family level, 97% were identified to genus taxonomic rank. Meanwhile, from the 511,172 records that were determined to genus level, 68% were identified to species taxonomic rank. Based on the botanical identification of each individual, we assigned wood density (WD) values according to the information available in the literature (Chave et al., 2006, 2009). In cases in where we could not assign a WD value at the species level, we used the average value at the genus or family level. For individuals without a botanical identification, we used the average WD for all species found in the plot.