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Aboveground carbon storage in tropical dry forest plots in Oaxaca, Mexico

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ABSTRACT

Tropical forests are subject to increasing pressures due to global change. Globally, tropical dry forests (TDFs) have been heavily impacted and these impacts have been poorly quantified. Despite its large coverage in tropical regions, and its important influence on the global C cycle, little is known of spatial variations in aboveground biomass (AGB) distribution of TDFs. The understanding of TDF aboveground biomass has been biased towards the secondary forests, with few studies of mature forests. The aim of this study is to quantify, allocate and understand the natural factors responsible for driving the AGB distribution and, consequently, on C stocks, in natural TDFs in Mexico. The study region represents ~14% of the total TDF area in Oaxaca. Remote sensing time series across field sites were used to identify suitable sampling locations for mature forests in Oaxaca. Aboveground biomass was normally distributed with a mean of 117 ± 5 Mg ha^{-1} (± 1 SE). Large trees (diameter at breast height, DBH ≥ 30 cm) were found at similar frequencies in small (300–400 m^2) and large (4 ha) plots. Depending on the selected allometric equation, at least 60% of the AGB is held in trees with DBH < 28.7 cm. At local scale, large trees (DBH ≥ 30 cm) did not show spatial autocorrelation and, in the landscape, AGB showed a spatial correlation in distances < 250 m. Because of low densities of very large trees (DBH ≥ 75 cm), the mean AGB estimates across different allometric equations only resulted in differences of ~10%. State factors including climate (mean annual precipitation, temperature and solar radiation) and topography (altitude and distance to streams) modulate the TDF structure and its potential for aboveground storage C across the landscape. Soil texture and pH were the most important soil properties in explaining variations in AGB, with stronger effects than soil nutrients. Across different scales of analysis, higher biomass estimates were related to water availability. This information can support spatial estimates of biomass storage capacity for Mexican TDF, crucial for land and C management.

1. Introduction

Forest land plays a major role in the global carbon (*C*) cycle, with nearly 50% of aboveground C stored in tropical forests (Houghton, 2005; Pan et al., 2011), and significant land use and land cover change leading to large C losses (Houghton and Nassikas, 2017). A majority of the research effort has focused on tropical rain forests, neglecting the C storage in tropical dry forests (TDFs) (Skutsch et al., 2009; Jaramillo et al., 2011; Gei and Powers, 2013), despite evidence indicates this ecosystem has broad extent and appreciable C pools in vegetation and soils (Read and Lawrence, 2003; Roa-Fuentes et al., 2012; Campo and Merino, 2016). TDFs accounted over 40% of all tropical forest biome (Murphy and Lugo, 1986a; Cao et al., 2016), and important C densities in vegetation (39–57 MgC ha^{-1}) and soils (40–80 MgC ha^{-1}) (Houghton and Nassikas, 2017).

Information on forest losses for TDFs are sparse and uncertain. According to Chomitz et al. (2007) nearly 78% of the original area that was once covered by TDFs had been modified, but other researchers suggest 48% (Miles et al., 2006; Dirzo et al., 2011). In Mexico about 25–36% of the original 33.5 million ha of primary TDFs remains (INEGI, 2003a), with important extension of secondary forest (Rzedowski, 1998; Dirzo et al., 2011; Tobón et al., 2017). This loss explains why TDF is considered as one of the most endangered ecosystem in the tropics (Janzen, 1998; Dirzo et al., 2011). Moreover, under the global change scenarios, land-use and land-cover and in climate changes, intensive studies are needed for a better understanding of long-term behavior and drivers of C sequestration in tropical forest.

Biomass and C stock estimations depends on forest inventories, which should be able to provide a full representation of the forest type. However, there are different sources of uncertainty. Chave et al. (2004)

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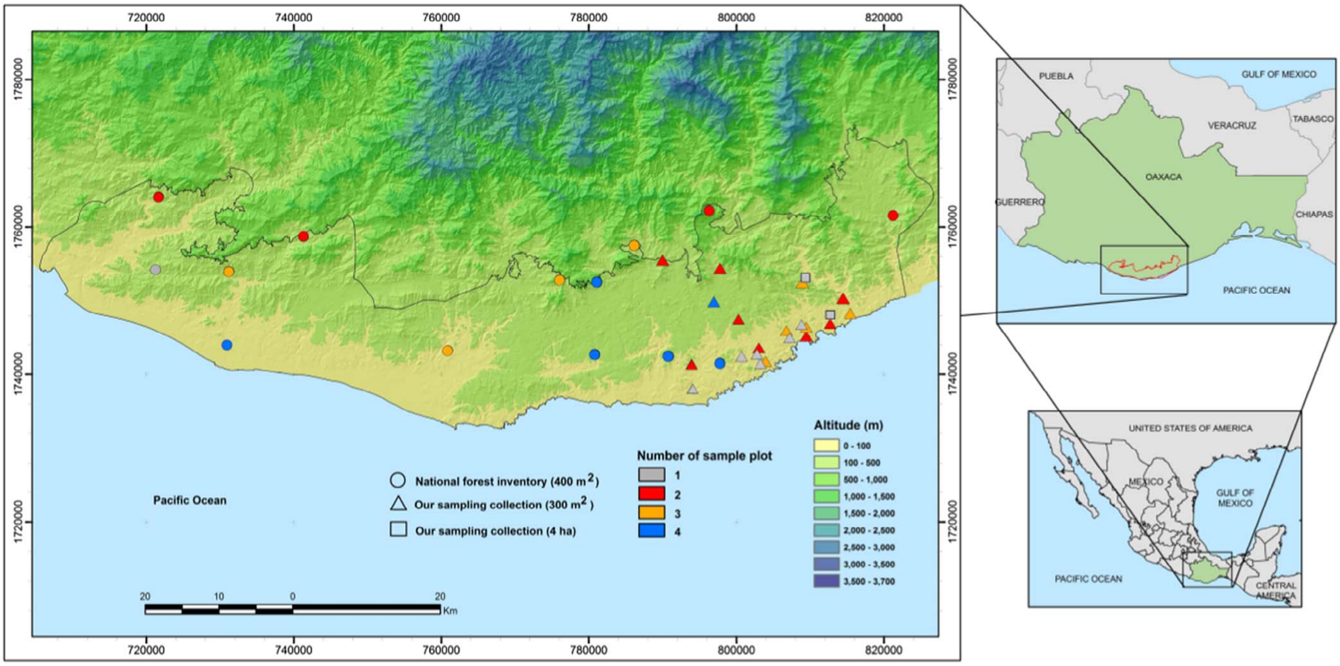

Fig. 1. The *left-hand panel* shows the sampling location of 83 plots of tropical dry forests over an altitude grid map. The *top right-hand panel* highlights in red the study site in the State of Oaxaca, Mexico. On the *bottom right-hand panel* is the location of the State of Oaxaca in the country. The icons refers the location of clusters of plots according to each sampling strategy. The location of the plots is approximate to the central coordinate of the clusters. The number of plots per cluster are presented in color coding.

suggest that primary sources of uncertainty are due to tree measurement and plot size. In this context, size and number of sample plots become fundamental issues to be considered during the inventory. Biomass is not normally distributed in small sampling plots - rare large trees can contribute to most of the biomass in the landscape - and it is recognized that larger plots could reduce this bias (Keller et al., 2001; Chave et al., 2004, 2005). However, there is not a clear understanding whether a small or large sampling design drive divergent conclusions regarding the TDF structure and C stocks. For example, in the last decade, studies on TDF have been collected over diverse sampling sizes, plots $\leq 100\,m^2$ (Cairns et al., 2003; Gallardo-Cruz et al., 2005; García et al., 2005), 100–400 m^2 (Sagar and Singh, 2006; Bijalwan et al., 2010; Burquez and Martínez-Yrizar, 2010) and 500 m^2 (Eaton, 2005; Sagar and Singh, 2006; Bijalwan et al., 2010; Burquez and Martínez-Yrizar, 2010; Návar, 2010). There are very few examples of plots with sizes near 10,000 m^2 or bigger (Jaramillo et al., 2003; Gasparri et al., 2010). Another source of uncertainty in biomass estimates comes from the proper selection of the allometric equation (Chave et al., 2004). Thus, it is important to identify the best sampling approach and allometric equations for reducing the uncertainty in aboveground biomass (*AGB*) estimates and consequently on C stocks.

Mean annual temperature (*MAT*) and mean annual precipitation (*MAP*), solar irradiation and soil nutrient availability are recognized as primarily responsible for ecosystem development (Holmgren et al., 1997; Vitousek, 2004; Ordoñez et al., 2009; Berdanier and Klein, 2011; Medeiros and Drezner, 2012; Peterson, 2012). However, depending on the scale of analysis and the ecosystem under study water availability and soil nutrients perform differently (Allen and Hoekstra, 1990; Turner, 2005; Currie, 2011). On the one hand, at global scales, climatic variables are main factors to explaining AGB (Becknell et al., 2012) and ecological processes such as nutrient cycling (Snyder and Tartowski, 2006). Different authors found that MAP explains over 50% of the variation in AGB with an inverse correlation (Brown and Lugo, 1982; Eaton and Lawrence, 2009; Becknell et al., 2012). On the other hand, at landscape scale solar irradiation, slope and slope expose, soil texture and terrain concavity are recognized to be the major influences on water availability for plants (Leitner, 1987) and biomass allocation (Berdanier and Klein, 2011; Peterson, 2012). Moreover, the availability of a suitable microclimate is critical for the response of species distribution (Bennie et al., 2008), by driving the individual development of trees (Holmgren et al., 1997; Berdanier and Klein, 2011). Nevertheless, precipitation regimen and soil properties are the main factors that module structural changes in TDF biomass at regional scale (Powers et al., 2009; Medeiros and Drezner, 2012; Roa-Fuentes et al., 2012). However, little is known about the influence of nitrogen (*N*) and phosphorus (*P*) availabilities on aboveground C storage in mature TDFs (Gei and Powers, 2013; Campo, 2016), despite TDFs productivity could be limited by both nutrients (Campo and Vázquez-Yanes, 2004).

This lack of integrity across scales complicates the understanding of the drivers of AGB in mature forests, making it even more complex in a heterogeneous natural landscape. Thus, the critical questions to be addressed by this study are, what is the typical biomass of undisturbed Mexican TDF, and what are the main factors that control biomass accumulation, and consequently C storage, in a natural landscape, across landscape scales? To be capable of answering these questions and in light of current knowledge the following hypotheses were developed:

H1. The ideal minimum sampling size to reach an AGB normally distributed in TDF ecosystems should be $\geq 2500\,m^2$, as suggested by Chave et al. (2004).
H2. Large trees dominate AGB storage, therefore the AGB spatial autocorrelation should show similar ranges to large tree locations.
H3. Over different spatial scales, water availability is the major limiting factor for AGB in mature TDFs.

2. Methods

2.1. Study region

The study region is located in Southern Oaxaca, Mexico (Fig. 1) with a total area of 215,687 ha within the boundaries of five municipalities (San Miguel del Puerto Sta. Ma. Colotepec, Sta. Ma. Huatulco, Sta. Ma. Ozolotepec, and Sta. Ma. Tonameca). The area represents 14.4% of the total TDF surface in Oaxaca (INEGI, 2008). The region shows an