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Total carbon stocks in a tropical forest landscape of the Porce region, Colombia

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Abstract

Detailed ground-based quantifications of total carbon stocks in tropical forests are few despite their importance in science and ecosystem management. Carbon stocks in live aboveground and belowground biomass, necromass, and soils were measured in a heterogeneous landscape composed of secondary and primary forest. A total of 110 permanent plots were used to estimate the size of these carbon pools. Local biomass equations were developed and used to estimate aboveground biomass and coarse root biomass for each plot. Herbaceous vegetation, fine roots, coarse and fine litter, and soil carbon to 4 m depth were measured in subplots. In primary forests, mean total carbon stocks (TCS) were estimated as 383.7 ± 55.5 Mg C ha^{-1} ($\pm$S.E.). Of this amount, soil organic carbon to 4 m depth represented 59%, total aboveground biomass 29%, total belowground biomass 10%, and necromass 2%. In secondary forests, TCS was 228.2 ± 13.1 Mg C ha^{-1}, and soil organic carbon to 4 m depth accounted for 84% of this amount. Total aboveground biomass represented only 9%, total belowground biomass 5%, and total necromass 1% of TCS in secondary forests. Monte Carlo methods were used to assess the uncertainty of the biomass measurements and spatial variation. Of the total uncertainty of the estimates of TCS, the variation associated with the spatial variation of C pools between plots was higher than measurement errors within plots. From this study it is concluded that estimates of aboveground biomass largely underestimate total carbon stocks in forest ecosystems. Additionally, it is suggested that heterogeneous landscapes impose additional challenges for their study such as sampling intensity.

Keywords: Aboveground biomass; Belowground biomass; Biomass equations; Heterogeneous landscapes; Necromass; Soil organic carbon

1. Introduction

Estimates of carbon stocks in tropical ecosystems are of high relevance for understanding the global C cycle, the formulation and evaluation of global initiatives to reduce global warming, and the management of ecosystems for C sequestration purposes. However, detailed knowledge about the absolute and relative distribution of C stocks in tropical forests is still limited (Clark, 2004; Houghton, 2005).

Estimating carbon stocks and their distribution in different ecosystem pools is important to understand the degree to which C is allocated to labile and stable components. This information is also useful to estimate the amount of C that is potentially emitted to the atmosphere due to land use changes as well as from natural or human-caused fire events. In the tropics, estimates of C stocks using ground-based measurements are usually focused on quantifying the aboveground component (Houghton, 2005), while other carbon pools such as belowground biomass, necromass, and soil carbon are seldom measured. Detailed quantifications of total C stocks in tropical areas are scarce, a major cause of uncertainty associated with the assessment of this region's C balance (Schimel et al., 2001; Clark, 2004; Houghton, 2005).

Although estimations of forest biomass are abundant in the tropics, it can be inferred from Houghton et al. (2001) that there

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are several problems in published estimates of C stocks from ground-based measurements: (1) uncertainty associated with spatial variability, (2) lack of distinction between primary and secondary forests, (3) small inventory areas (<1 ha), (4) incomplete measurements of all C pools, (5) biased sample designs, (6) inadequate use of regression equations, and (7) lack of continuity in surveys.

Secondary forests are also an important component of land cover area in the tropics and for this reason they play an important role in the carbon balance of this region (Brown and Lugo, 1990). According to FAO, in 1990 secondary forests accounted for 335 million ha in Latin America (Smith et al., 1997). In Colombia, secondary forests are an important fraction of total forested area and their distribution is highly heterogeneous, mixed with croplands, grasslands, and primary forests (Etter and van Wyngaarden, 2000).

The methodological issues mentioned above, in conjunction with spatial variation of biophysical variables over landscapes, are important sources of variation and uncertainty in the estimation of carbon stocks in forested ecosystems. An average value of C stocks for an ecosystem might not be the best descriptor of this variable when spatial variation and uncertainties are high. Measures of variability such as the standard error of the mean or 95% confidence intervals should be reported in addition to the average (IPCC, 2003).

In this study we present a detailed estimation of C stocks in a tropical premontane landscape composed of a mixture of primary and secondary forests that addresses the methodological issues mentioned above. The first objective of this study was to quantify the absolute and relative quantities of C stored in different ecosystem pools and the degree of uncertainty in these estimates. The second objective was to compare the relative C stocks between primary and secondary forests for the different carbon pools to assess the effects of land use change.

2. Methods

2.1. Study site

This study was carried out in the Porce Region, Colombia (6°45′37″N, 75°06′28″W) at the area locally known as Porce II where a dam was constructed in 2000 for hydropower generation. Mean annual precipitation between 1990 and 2003 was 2078 ± 601 mm (±S.D.). Precipitation is relatively homogeneous during the year with a short dry season (<15 mm per month) between December and January. Mean annual temperature at 975 m a.s.l. is 22.7 °C, with a monthly minimum of 21.3 °C and a maximum of 24.1 °C. Altitude ranges from 900 to 1500 m, a zone that represents the transition from lowland to premontane moist tropical forests. Soils are derived from granitic rocks, have low fertility, and high acidity. Twenty soil series have been described in the site and grouped in two main orders: Entisol and Inceptisol. The most common soil subgroups are *Ustoxic Dystropept*, *Typic Tropaquent*, and *Typic Tropopsamment* (Jaramillo, 1989). Mean bulk density at 30 cm depth in primary forests was estimated as 1.1 Mg m^{-3} and in secondary forests as 1.3 Mg m^{-3}.

Evidence of human settlement dates from 9000 years B.P. and suggests that shifting cultivation began 2000 years B.P. (Castillo, 1998). After Hispanic colonization (∼16th century), land use changed to intensive cattle ranching, mining, and agriculture in small parcels. During the 1990s, the farms were sold and the land was abandoned due to the dam project, which promoted forest succession. Today, there is a mosaic of primary and successional forests of different ages. Primary forest fragments covers nearly 694 ha and secondary forests 1462 ha. Species composition and diversity indexes of these forests were found to be very similar to other primary forests in lowland areas. The main tree species in primary forests, according to their importance value index, are: *Anacardium excelsum* (Bertero and Balb. ex Kunth), *Jacaranda copaia* (Aubl.) D. Don, *Pourouma cecropiaefolia* Mart., *Virola sebifera* Aubl., *Oenocarpus bataua* Mart., *Miconia albicans* (Sw.) Triana, *Vochysia ferruginea* Mart., *Cordia bicolor* A. DC., *Pera arborea* Mutis, and *Pseudolmedia laevigata* (Poepp. and Endl.) Rusby. Secondary forests and fallows are dominated by light-demanding tree species such as *Vismia baccifera* (L.) Triana and Planch, *Piper aduncum* L., *Myrsine guianensis* A. DC., *Jacaranda copaia*, *Psidium guajaba* L., *Miconia affinis* DC., *Erytroxylon* sp. and *Vismia ferruginea* H.B.K. (Jaramillo and Yepes, 2004).

2.2. Permanent plots

In 1999, 33 permanent plots (20 m × 50 m, 0.1 ha) were established in primary forests and 77 in secondary forests (20 m × 25 m, 0.05 ha) by random assignment on a map for a total sampling area of 7.15 ha. Sampling points were located in the field using a GPS unit. For methodological purposes, secondary forests were distinguished in the field from primary forests by the presence of legacies that suggested previous anthropogenic interventions. The presence of large stumps, unusual soil compaction or erosion, and the massive abundance of light demanding tree species are examples of the legacies considered.

All trees, lianas and palms ≥10 cm in *D* (diameter at 1.3 m for trees without irregularities) in primary-forest plots and all plants ≥5 cm in secondary-forest plots were measured. Moreover, plants ≥1 cm in *D* were measured in one subplot (10 m × 10 m in primary forests and 5 m × 5 m in secondary forests) within each plot. All trees that had more than 50% of their diameter inside the plot were considered as being inside the plot; however, occurred in very few cases. Diameters were measured using calipers for plants ≥10 cm and digital calipers for plants $10 > D \geq 1$ cm. For buttressed trees, *D* was measured just above the highest buttress. Trees with irregularities were measured following the protocols reported by MacDicken (1997).

In each plot, six 1 m^2 (1 m × 1 m) subplots were established to harvest all herbaceous and non-woody vegetation <1 cm in *D* and all standing fine litter. Herbaceous vegetation and fine litter were completely harvested from these subplots and all material transported to the laboratory for subsequent dry weight determination. Coarse woody debris (>2 cm in diameter) was