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# Large trees as key elements of carbon storage and dynamics after selective logging in the Eastern Amazon

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## ABSTRACT

The long term effect of Reduced-Impact Logging (RIL) on above-ground live biomass (AGB) dynamics was investigated in 18 1-ha logged over permanent sample plots set up in a *terra firme* rain forest in the Eastern Amazon (Brazil, Paragominas). Both tree survival and growth were investigated among three Diameter at Breath Height (DBH) classes (20–40, 40–60, ⩾60 cm) to assess the contribution of each DBH class to the post-logging AGB recovery. Before logging, mean tree density and AGB per plot (dbh ⩾ 20 cm) were 187 ± 14 trees ha$^{-1}$ and 377.6 ± 62.8 Mg ha$^{-1}$ respectively. Although big trees (dbh ⩾ 60 cm) only represented 9.3% of the total tree density, they gathered almost half of total AGB. During the post-logging period (8 years), the mortality of large trees was found to drive the annual net changes and largely overcame the AGB gain in the smaller DBH classes. Indeed, plots with high post-logging mortality of large trees showed negative carbon balance t over the study period (8 years). The over mortality of large trees injured by logging contributed significantly to the annual AGB losses (up to 40%) in the first years after logging. Due to the overwhelming importance of this size class in carbon stocks and dynamic, reducing logging damages and intensity might have great impact in the post-logging biomass dynamics. We estimated that reducing logging intensity from 6 to 3 stems ha$^{-1}$ would save 27.7 Mg C ha$^{-1}$ for a 35 years rotation cycle. To compensate this loss of profits, compensatory payments of avoided $CO_2$ emission should worth US $ 6.5/Mg of $CO_2$. This price falls into the range of prices of the international carbon market. Sustainable forest management aiming at enhancing carbon stocks could therefore promote the preservation of the large trees. At our study site, we recommend the adoption of a maximum diameter cutting limit of 110 cm.

## 1. Introduction

Deforestation and forest degradation in the tropics accounts for approximately 15% of global anthropogenic carbon emissions (DeFries et al., 2002; Houghton, 2005b). In recognition of this contribution, incentives to reduce carbon emission from deforestation and forest degradation (REDD) are actively being considered for inclusion in the United Nations Framework Convention on Climate Change during the next commitment period (2012–2020). One major cause of forest degradation in the tropics is the unplanned selective logging carried out by untrained and poorly supervised crews (Putz et al., 2008a). It is estimated that this unplanned logging in Latin America would release annually 0.1Gt C in the atmosphere (Putz et al., 2008b). Selective logging could represent up to 25% of the carbon released by land use changes in the Amazon basin (Asner et al., 2005). Since the early 50s, the sustainable management of forest resources has been seen as a promising tool to preserve tropical forest from conversion and to ensure long-term timber production (Putz et al., 2012). While production in the tropics cover an estimated area of 403 million ha (Blaser et al., 2011), one of the major important contemporary management issue for these forests remains the identification of appropriate silvicultural systems able to preserve the ecosystem services furnished by forests across the landscape (Carpenter et al., 2006; Guariguata and Balvanera, 2009; Sist et al. 2008) and to be able to predict the responses of these ecosystems to future scenarios of climate change (Feeley et al., 2007; Malhi et al., 2008).

In the Brazilian Amazon, production forests represent around 70 million ha, while conservation areas already cover more than 200 million ha (Amaral et al., 2007). Considering the amount of

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carbon at stake and with global emphasis on reducing carbon emissions from human activities, a better understanding on carbon fluxes from managed tropical forests is urgently needed.

One of the main obvious impact of selective logging in tropical forests is the removal of the biggest trees (DBH > 60 cm) which play a critical ecological role (Lindenmayer et al., 2012, 2013) providing food and habitat for a myriad of organisms and are crucial in forest structure and dynamics, creating gaps and accounting for a large fraction of the total biomass (Clark and Clark, 1996; Keller et al., 2001; Nascimento and Laurence, 2002; Castilho de et al., 2006; Paoli et al., 2008; Slik et al., 2013). By targeting the largest trees, commercial logging generates an immediate collapse in carbon stocks, with significant consequences in the biomass net balance of the stand (Sist and Nascimento-Ferreira, 2007; Mazzei et al., 2010). Few studies have explored the impact of logging on biomass dynamics at the stand level (Blanc et al., 2009; Mazzei et al., 2010), but very little is known on the response of individual trees and among size classes to logging disturbances (Hérault et al., 2011).

In the present study, the effect of logging on AGB dynamics and among tree diameter size classes was investigated along four successive censuses carried out over 8 years after logging. Based on this, we proposed specific recommendations to improve forest management and reduce carbon emissions.

## 2. Methodology

### 2.1. Study site

The study site is located in eastern Pará, Paragominas, on the Fazenda Rio Capim owned by CIKEL-Brasil Verde group (Sist and Nascimento-Ferreira, 2007; Mazzei et al., 2010 for more details about the area). The area of about 140,000 ha includes large areas of pristine (12,000 ha) and logged *terra firme* forests (110,000 ha), along with some abandoned pastures (18,000 ha). In 2001, CIKEL received Forest Stewardship Council certification for the sustainable management of 75,000 ha of production forests. Since then, CIKEL has been harvesting under Brazilian forest management law using RIL techniques with a minimum cutting diameter of 55 cm for all commercial species, a cutting cycle of 35 years and a harvest intensity of 30 $m^3$ $ha^{-1}$.

Before logging in 2004, 18 × 1 ha experimental plots were set up in a 100 ha RIL block, described in Sist and Nascimento-Ferreira (2007), in which all trees ⩾20 cm DBH (stem diameter at 1.3 m or above buttresses) were identified with a common name, tagged and mapped, and their girth measured. The plots were first inventoried in May 2004 and logged in July 2004 by crews trained in RIL techniques. In the 18 plots, the average logging intensity was 6.3 trees $ha^{-1}$, representing a mean basal area of 3.4 $m^2$ $ha^{-1}$ (i.e. 14% of the original one before logging) and mean log volume of 21.3 $m^3$ $ha^{-1}$ (see Appendix 1 for more details on logging damages).

Three months later (October 2004), all injured trees were recorded including the type and severity of the injury, dead trees and the apparent cause and mode of mortality (natural death, standing tree; natural death, fallen tree; killed by the fall of another tree; standing dead and injured by logging; knocked over during logging; or harvested). Consecutive measurements were carried out in May 2005, November 2006, February 2008, March 2010 and April 2012.

In 2008, all trees were identified at least at the genus level by botanists, while 88% were identified at the species level. In 2008, the 18 plots encompassed 4102 trees representing 42 families, 119 genera, and 193 species. The Lecythidaceae, Sapotaceae, and Leguminosae families dominated the forest, accounting for 59% of all trees censused.

### 2.2. Calculation of AGB

We calculated the above-ground biomass (AGB) of living trees ⩾20 cm dbh before and after logging using the following formula developed for moist tropical forests and relying on dbh and wood density only (Chave et al., 2005):

$$\mathrm{AGB} = \rho \times \exp(-1.499 + 2.148 \times \ln(\mathrm{dbh}) + 0.207 \times \ln(\mathrm{dbh})^2 - 0.0281 \times \ln(\mathrm{dbh})^3)$$

where $\rho$ is the wood density (g/$cm^3$). Wood densities were obtained from the Brazilian Wood Database compiled by the Laboratorio de Produtos Florestais of the Brazilian Forest Service and the values published by Fearnside (1997) following the recommendations of Nogueira et al. (2008). If species were not present in this list, we used the genus level average to estimate the species value. For unidentified species, or species identified to family level only, we used the average wood density value of the 18 plots ($\bar{\rho} = 0.65$).

The validity of the above equation ranges between 5 and 156 cm dbh. At our site, two trees (218 and 248 cm dbh) exceeded this limit. We deliberately considered their diameter equal to 156 cm dbh, hence slightly underestimating AGB stocks in two plots. Estimating AGB of large trees with allometric models remains a major source of uncertainties due to the sampling bias (Clark and Kellner, 2012). For example, destructive samples tend to favor perfect trees (i.e. entire symmetric crown, cylindrical solid trunks) whereas many trees show imperfect crowns, hollowed and irregular stems. However with lack of alternatives, we decided to use this generic model, as it was shown to be more accurate than local ones in various forests (Vielledent et al., 2012; Rutishauser et al., 2013). For each period of measurement we calculated the yearly AGB lost due to tree mortality and AGB gained by both recruitment and growth.

## 3. Results

### 3.1. Impact of logging on stand structure and biomass stocks

Before logging (2004), mean density and mean AGB of trees (DBH ⩾ 20 cm) were 219 ± 24 trees $ha^{-1}$ and 378 ± 82 Mg $ha^{-1}$ (Table 1). Large trees (DBH ⩾ 60 cm) represented 9.3% of the tree density (18 ± 4 trees $ha^{-1}$), but gathered in mean 49% of total AGB. In contrast, small trees represented 73.9% of tree density, but contributed to only 26% of total AGB (98.5 Mg $ha^{-1}$, Table 1). Logging resulted in a collapse of AGB stock among large trees (Fig. 1). Eight years after logging, logged forest lost in average 96.6 Mg $ha^{-1}$.

### 3.2. Post-logging carbon dynamic

Apart from the 20–40 DBH class, biomass losses outbalanced biomass gains at each census (Fig. 2). At the plot-level, for the entire post-logging period (2006–2012), average biomass balance remained null (mean ± SE: 0.07 ± 0.61 Mg $ha^{-1}$ $yr^{-1}$) though the average biomass net change (Mean ± SE) progressively increased over time going from -2.17 ± 0.7 (2005–2006) to 1.91 ± 0.33 Mg $ha^{-1}$ $yr^{-1}$ (2010–2012). This increase is explained by low residual mortality and enhanced recruitment and growth in the 20–40 DBH class over time (Fig. 2). Annualized AGB changes in this class slowly increased to attain 2.6 Mg $ha^{-1}$ $yr^{-1}$. Contrastingly, biomass gains remain nearly constant in the other DBH classes (Fig. 2). The over-mortality of trees in the DBH ⩾ 60 cm class