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# Forest biomass recovery after conventional and reduced-impact logging in Amazonian Brazil

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ABSTRACT

Growing concerns about unnecessarily destructive selective logging of tropical forests and its impacts on greenhouse gas (GHG) emissions motivated this study on post-logging biomass dynamics over a 16-year period in a control plot and in plots subjected to conventional logging (CL) or reduced-impact logging (RIL) in Paragominas, Pará State, Brazil. All trees >25 cm were monitored in 25.4 ha plots of each treatment, each with a subplot of 5.25 ha for trees >10 cm dbh. The commercial timber volumes in felled trees were 38.9 and 37.4 $m^3$ $ha^{-1}$ in the RIL and CL plots, respectively, but the extracted volumes were 38.6 and 29.7 $m^3$ $ha^{-1}$, respectively. Immediately after logging, plots subjected to RIL and CL lost 17% and 26% of their above-ground biomass, respectively. Over the 16 years after logging, the average annual increments in above-ground biomass (recruitment plus residual tree growth minus mortality) were 2.8 Mg $ha^{-1}$ $year^{-1}$ in the RIL plot but only 0.5 Mg $ha^{-1}$ $year^{-1}$ in the CL plot. By 16 years post-logging, the RIL plot recovered 100% of its original above-ground biomass while the CL plot recovered only 77%; over the same period, biomass in the control plot maintained 96% of its initial stock. These findings reinforce the claim that conversion from CL to RIL would represent an efficient forest-based strategy to mitigate climate change under the REDD+ and would be an important step towards sustainable forest management.


## 1. Introduction

Tropical forests play an important role in climate regulation as sinks for greenhouse gases (GHG), storing 471 ± 93 Pg C, which is equivalent to 55% of the carbon stored in Earth's forests (Pan et al., 2011). Due to their high species density and lack of markets for the wood of most species, the large volume of woody biomass in tropical forests does not necessary imply substantial volumes of commercial timber (Wadsworth, 1997). Because so few tree species produce marketable wood, logging in tropical forest is selective and damage per unit area is low, but damage per cubic meter of harvested wood can be substantial (Dykstra, 2002). One option to reduce greenhouse gas (GHG) emissions from logging activities is to decrease the associated damage to residual forests by employing reduced-impact logging (RIL) techniques (Sasaki et al., 2012). Common RIL techniques include pre-harvest mapping of crop trees, pre-harvest planning of roads and skidtrails, pre-harvest liana cutting, and the use of appropriate felling techniques including directional felling and cutting stumps low to the ground to avoid waste (Johns et al., 1996; Putz et al., 2008a). To improve forest management, a case can be made that RIL should be among the options of the United Nation REDD+ program (reduced emissions of atmospheric heat-trapping gases from deforestation and forest degradation, including the role of conservation, sustainable management of forests and enhancement of forest carbon stocks). The conversion from conventional logging (CL) to RIL should be eligible for compensation in both voluntary and regulated carbon-based payment schemes (Angelsen, 2008; Sasaki et al., 2012; UN-REDD, 2008).

The immediate impacts of logging on residual forest structure and biomass vary with logging intensity but also with logging methods. Reportedly, collateral damage can be reduced by up to 50% when RIL techniques are applied (Pinard and Cropper, 2000). If RIL techniques were used in the entire 350 million ha of tropical forests officially designated for logging in the tropics, global GHG emissions would be reduced by 0.16 Gt C $year^{-1}$ (Putz et al., 2008b). Unfortunately, due to the scarcity of long-term data on biomass recovery of tropical forests subjected to RIL and CL, this estimate is based mostly on short-term studies and computer simulations. The objective of this study is to estimate how RIL and CL influenced biomass recovery dynamics 16 years post-logging in Amazonian Brazil.

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## 2. Methods

The study area is in the eastern Brazilian Amazon (3°17′S, 47°34′W) at an elevation of about 200 m on private land where the Amazon Institute of People and the Environment (IMAZON) conducts this logging experiment (Fig. 1). The forest is evergreen with canopy heights of 25–40 m. The terrain is level to undulating and the soils are predominately yellow latosols, rich in aluminum. Average annual rainfall is 1700 mm with a January–May wet season followed by a June–November period during which average monthly rainfall is <50 mm (Barreto et al., 1998; Johns et al., 1996).

In 1993 the forest was subjected to either conventional logging (CL, 75 ha) or reduced-impact logging (RIL, 105 ha); an additional 30 ha was reserved as an unlogged control. Although no direct indications of previous logging or fire were observed, the abundance of lianas may be evidence of logging many years before the experiment was implemented. Two years prior to logging, a 24.5 ha plot (350 × 700 m) was established at a random location in each area with a more intensively studied 5.25 ha (75 × 700 m) sub-plot in the center of each. All trees >10 cm DBH (stem diameter at 1.3 m from the ground or above buttresses) in the 5.25 ha sub-plots and all trees > 25 cm DBH in the 24.5 ha plots were marked, mapped, and identified to species. Furthermore, trees were described in terms of the presence or absence of lianas, crown exposure (adapted from Dawkins, 1958), and trunk and crown quality. At the time of initial establishment of the RIL plot, all lianas >2 cm DBH on trees to be harvested were cut. About one year after logging, trees were remeasured, described as explained above, and recorded as having suffered trunk or crown damage during logging. During subsequent measurements, these same data were collected and new recruits were recorded (for further information related to sample design and data collection see Johns et al. 1996). Data collected in 2005 included substantial inconsistencies with previous and subsequent inventories and were therefore discarded. Felled volumes were similar in both treatments (39 $m^3$ $ha^{-1}$ in RIL and 37 $m^3$ $ha^{-1}$ in CL) but the extracted volumes from the CL plot were much lower Barreto et al. 1998; Table 1).

To estimate the above-ground biomass of each sampled tree and the forest as a whole, we used an allometric equation based on DBH and wood density (Chave et al., 2005) and then scaled up using the methods recommended by the UNFCCC (2011). Biomass was calculated from data from the 24.5 ha plots, with data for trees 10–25 cm DBH extrapolated from the 5.25 ha sub-plots. For trees larger than the maximum included in calculation of the allometrical equation (>156 cm DBH; 5 of the 26,846 trees sampled), biomass values were estimated by extrapolation. Species-specific wood densities were obtained from the literature following the procedures described by Medjibe et al. (2011). Biomass increments were assumed to proceed at the average rate between measurements (UNFCCC, 2011). Additionally, annual forest biomass was separated into diameter classes to evaluate changes in forest structure.

Given the lack of replication of the treatments in this study and the consequent possibility that any observed treatment effect is the result of pre-existing conditions, we compared median post-logging growth rates of residual trees of species represented by ⩾5 individuals with 20–40 cm DBH in both the CL and the RIL plot. Additionally, we also used geoR package (Ribeiro and Diggle, 2001) available for R v.3.0.2 (R Core Team, 2013) to construct a semivariogram of the area that includes both CL and RIL plots to detect any spatial auto-correlation in the data.

## 3. Results

Residual trees with 20–40 cm DBH of species represented by ⩾5 individuals in both RIL and CL plots grew faster in the latter. Concerns about the possibility of spatial auto-correlation in the aboveground biomass that might have confounded the results in this pseudoreplicated study were allayed by the lack of any apparent spatial trends in a semivariogram of the RIL and CL plots (see Supplementary materials for the detailed results).

Pre-logging (1993) above-ground biomass estimates for the RIL, CL, control plots were 260, 264, and 238 Mg $ha^{-1}$, respectively. Soon after logging (1994), plots subjected to RIL and CL had lost 17% and 26% of their above-ground biomass, respectively. Over

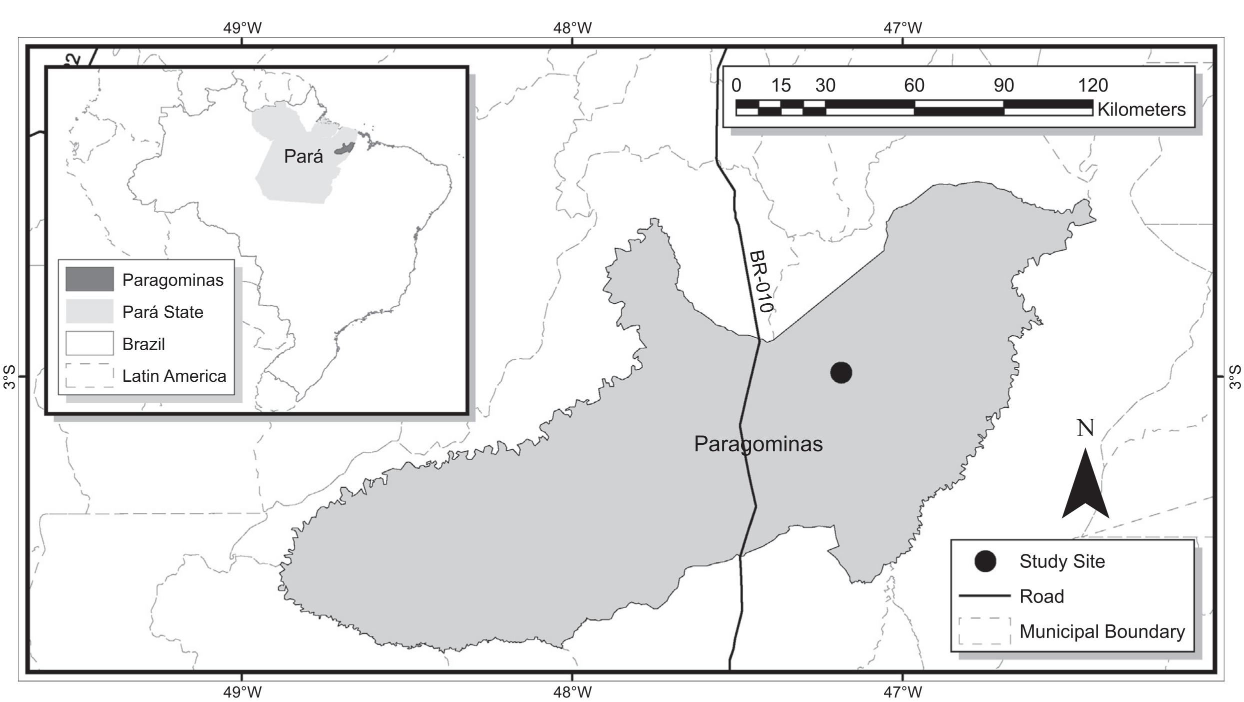


**Fig. 1.** Location of the study site.

**Table 1**
Intensities of reduced-impact logging (RIL) and conventional logging (CL) reported for the studied plots in 1993 in Paragominas in the eastern Brazilian Amazon (adapted from Barreto et al., 1998).

| Logging characteristics | RIL | CL |
|---|---|---|
| Mean felled volume ($m^3$ $ha^{-1}$) | 38.9 | 37.4 |
| Extracted volume ($m^3$ $ha^{-1}$) | 38.6 | 29.7 |
| Bole wood volume abandoned after felling (%) | 1 | 26 |
| Extracted trees (number $ha^{-1}$) | 4.5 | 5.6 |
| Basal area extracted ($m^2$ $ha^{-1}$) | 2.2 | 2.3 |
| Mean volume ($m^3$) per tree extracted (sd; *n*) | 8.2 (6.22; 138) | 5.3 (3.83; 279) |
| Mean diameter (cm) at base of extracted trees (sd; *n*) | 79.0 (23.9; 138) | 71.8 (17.8; 279) |

the subsequent 16 years, average annual increments in above-ground biomass (recruitment plus residual tree growth minus mortality) were 2.8 Mg $ha^{-1}$ $year^{-1}$ under RIL and 0.5 Mg $ha^{-1}$ $year^{-1}$ under CL. Over this same period, control plot biomass decreased by 0.6 Mg $ha^{-1}$ $year^{-1}$. It is important to note that an extreme drought in 2005 (e.g., Nepstad et al., 2008; Phillips et al., 2009) could account for the substantially lower biomass estimates of the last two measurements (i.e., 2006 and 2009). When the biomass recovery period after logging is limited to 1994–2003, the average annual increments observed were still more than twice as high in the RIL than in the CL plot (4.1 Mg $ha^{-1}$ $year^{-1}$and 1.8 Mg $ha^{-1}$ $year^{-1}$for RIL and CL, respectively).

By 16 years post-logging, the RIL plot recovered 100% of its original above-ground biomass; newly recruited trees contributed 9% of the recovered biomass (Fig. 2). The CL plot, in contrast, recovered only 77% of its original above-ground biomass stock over the same period, of which newly recruited trees comprised 11%. The recovery percentages observed in 2003, before the drought, were 98% and 81% in the RIL and CL plots, respectively. Above-ground biomass stocks remained fairly stable in the control plot, with 103% of the 1993 stocks in 2003 (before the drought) and 96% in 2009.

Although above-ground biomass in the RIL plot fully recovered within 16-years after logging, timber stocks were still depleted. Before logging, 29% of the above-ground biomass was stored in trees >60 cm diameter class in the RIL plot, 30% in the CL plot, and 33% in the control plot. Sixteen years after logging, these large trees contributed a substantially smaller proportion of the biomass (21%, 19%, and 36% in the RIL, CL, and control plots, respectively). Losses in the RIL and CL plots were mostly due to logging whereas losses in the control plot might be drought-related. Over this same period, biomass of trees 20–60 cm increased but biomass of trees 10–20 cm and >60 cm decreased in the RIL plot (Table 2). In contrast, biomass of all size classes decreased in the CL plot when compared to pre-logging levels; trees >60 cm diameter still only contained 48% of their previous biomass (Table 2). Even with the extreme drought of 2005, biomass of large trees in the control plot increased by 5%.

## 4. Discussion

Pre-logging above-ground biomass estimates for the three plots (238–264 Mg $ha^{-1}$) were similar to IPCC (2003, 2006) estimates for tropical moist forests (210–280 Mg $ha^{-1}$) and values reported by Malhi et al. (2006) for the Brazilian Amazon (200–350 Mg $ha^{-1}$). In contrast, Saatchi et al. (2007) reported that Amazonian forest biomass is generally >300 Mg $ha^{-1}$, other than in intensively logged areas and open floodplains. Similarly, Mazzei et al. (2010) reported a mean pre-logging biomass in 17 plots of 1 ha of 410 ± 65 Mg $ha^{-1}$ in a forest only 200 km from our study area. These findings suggest that our study area may have experienced some logging or other disturbances prior to the initiation of the

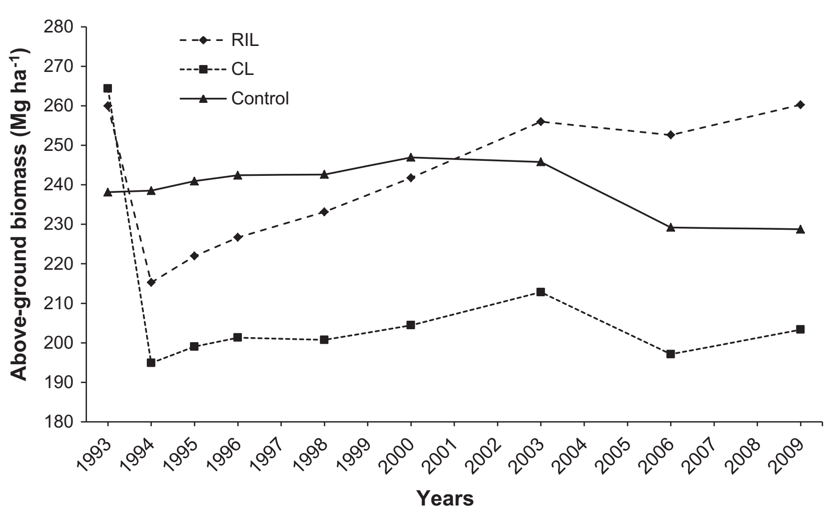


**Fig. 2.** Above-ground biomass dynamics in 24.5 ha plots subjected to reduced-impact logging (RIL), conventional logging (CL), or left unlogged (control) in Paragominas, in the eastern Brazilian Amazon. Logging occurred between 1993 and 1994.

**Table 2**
Proportion of above-ground biomass prior to and 16 years after selective logging by stem diameter class in the reduced-impact logging (RIL), conventional logging (CL), and control plots in Paragominas in the eastern Brazilian Amazon.

| Treatment | Proportional change in above-ground biomass 1993–2009 | | | | | | |
|---|---|---|---|---|---|---|---|
| | 10–20 cm (%) | 20–30 cm (%) | 30–40 cm (%) | 40–50 cm (%) | 50–60 cm (%) | >60 cm (%) | Total (%) |
| RIL | −16 | +14 | +19 | +30 | +21 | −28 | 0 |
| CL | −11 | −13 | −9 | −11 | −7 | −52 | −23 |
| Control | −4 | −18 | −4 | −8 | −5 | +5 | −4 |

research but, even if this is the case, the comparative biomass dynamics results we report are not compromised.

The short-term effects of selective logging on aboveground biomass were 17% and 26% reductions in the RIL and CL plots, respectively. The average of these findings is close to the 24% reduction calculated as part of a meta-analysis of 22 studies on undifferentiated selective logging impacts on tropical forest biomass (Putz et al., 2012). In our plot subjected to RIL, above-ground biomass recovered at 2.8 Mg $ha^{-1}$ $year^{-1}$ for the first 16 years after logging, which is lower than the average rate reported by Mazzei et al. (2010) for the first 4 years after RIL (4.6 Mg $ha^{-1}$ $year^{-1}$), but within the range they observed in their 17 1-ha plots (−4.0 to 10.6 Mg $ha^{-1}$ $year^{-1}$). Perhaps more importantly, our finding that biomass recovered more quickly after RIL than CL contradicts the results of an Amazonian forest simulation study by Keller et al. (2004) but supports the predictions of Pinard and Cropper (2000) for a field study in Malaysia. We also note that residual trees 20–40 cm DBH of species represented by ⩾5 individuals in both RIL and CL plots grew faster in the latter, as expected (e.g., Keller et al., 2004; see Supplementary materials for the detailed results).

In contrast to the reported increases in biomass of primary tropical forests in South America (IPCC, 2003, 2006; 2 Mg $ha^{-1}$ $year^{-1}$) and Africa (Lewis et al., 2009;[1] 1.3 Mg $ha^{-1}$ $year^{-1}$), we observed a small decrease in above-ground biomass of the control plot over the monitoring period. If we restrict our analysis to the period prior to the 2005 drought, control plot biomass increased by 0.8 Mg $ha^{-1}$ $year^{-1}$, still a value lower than the average reported by Mazzei et al. (2010; 1.4 Mg $ha^{-1}$ $year^{-1}$) and Phillips et al. (2008†; 1.9 ± 1.2 Mg $ha^{-1}$ $year^{-1}$) for other old growth plots in Amazonia.

The plot subjected to RIL fully regained its above-ground biomass stocks in just 16 years after selective logging. This recovery period is 6 years (i.e., 40%) longer than that estimated by Valle et al. (2007) for the same area, but their analysis was based on pseudoreplicated sub-plots. In any case, our results reinforce the value of long-term monitoring of forest plots. The overall results of this study also reinforce the potential role of RIL in climate change mitigation (Mazzei et al., 2010; Putz and Pinard, 1993; Pinard and Putz, 1996; Pinard and Cropper, 2000; Putz et al., 2008b, 2012; Sasaki et al., 2012; UN-REDD, 2008).

## 5. Conclusion

Employment of RIL substantially reduced the effect of selective logging on residual forest biomass and enhanced above-ground biomass recovery for at least 16 years. If not for the extreme drought of 2005, full biomass recovery after RIL would have been even faster, but disregarding extreme climatic events seems unjustified given that they are predicted to be even more frequent in the future (IPCC, 2007). In contrast to the RIL plot, above-ground biomass in the CL plot was still 23% below the pre-logging value after 16-years of recovery. While the biomass recovered rapidly after RIL, further studies are needed on the recovery of commercial timber volumes. Our findings lend support to efforts to promote the conversion from CL to RIL as a mitigate climate change mitigation measure under REDD+. If properly aligned with other regulations, RIL will also help sustain timber yields and maintain conservation values.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.11.022.

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[1] Value converted using a 0.5 carbon fraction.

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