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# Dynamics of aboveground carbon stocks in a selectively logged tropical forest

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*Abstract*. The expansion of selective logging in tropical forests may be an important source of global carbon emissions. However, the effects of logging practices on the carbon cycle have never been quantified over long periods of time. We followed the fate of more than 60 000 tropical trees over 23 years to assess changes in aboveground carbon stocks in 48 1.56-ha plots in French Guiana that represent a gradient of timber harvest intensities, with and without intensive timber stand improvement (TSI) treatments to stimulate timber tree growth. Conventional selective logging led to emissions equivalent to more than a third of aboveground carbon stocks in plots without TSI (85 Mg C/ha), while plots with TSI lost more than one-half of aboveground carbon stocks (142 Mg C/ha). Within 20 years of logging, plots without TSI sequestered aboveground carbon equivalent to more than 80% of aboveground carbon lost to logging (−70.7 Mg C/ha), and our simulations predicted an equilibrium aboveground carbon balance within 45 years of logging. In contrast, plots with intensive TSI are predicted to require more than 100 years to sequester aboveground carbon lost to emissions. These results indicate that in some tropical forests aboveground carbon storage can be recovered within half a century after conventional logging at moderate harvest intensities.

*Key words: aboveground biomass; carbon sequestration; deforestation; French Guiana; global change; timber stand improvement; tropical forests.*

## Introduction

Tropical forests represent a major reservoir of global carbon, accounting for up to half of the estimated 558 Pg of carbon stored in vegetation (Houghton 2005), with an estimated 86 Pg of carbon in the Amazon basin alone (Saatchi et al. 2007). Land use changes in the tropics have become an increasing concern for their potential impacts on the global carbon cycle and climate change (Carpenter et al. 2006, Solomon et al. 2007).

Remote sensing studies, combined with models of land-cover dynamics, have revealed that over the past 20 years Amazonian deforestation contributed an estimated 0.30 Pg of carbon per year to the atmosphere (Ramankutty et al. 2007). These estimations ignore selective timber logging, which is largely invisible to classic remote sensing technologies. Degradation of tropical forests by selective logging, fuelwood removal, and fire encroachment contributes even further to these emissions (Nepstad et al. 1999, DeFries et al. 2002, Peres 2006, Achard et al. 2007).

Recently, high-resolution remote sensing studies have suggested that the contribution of selective logging in the Amazon could release up to 0.08 Pg C/yr, or 25% of the loss due to land use change through deforestation (Asner et al. 2005). And models from unlogged plots predict that selectively logged forests may lose of up to 70% of carbon storage potential (Bunker et al. 2005). Yet few direct data exist to evaluate the long-term contributions of selective logging to the carbon balance of tropical forests, and the trajectory of carbon sequestration in stands regenerating after logging.

In this paper, we analyze data collected over a 20-yr period following selective logging in replicated permanent plots in French Guiana. We examine the contribution of tree growth and recruitment vs. tree harvesting and death to changes in aboveground carbon fluxes over this period, and we use a bookkeeping model to extrapolate the long-term consequences of differences in forest dynamics after logging to the aboveground carbon balance of this tropical forest.

## Methods

All inventories were conducted at the Paracou experimental site (5°18′ N, 52°55′ W), a lowland tropical rain forest near Sinnamary, French Guiana (Gourlet-Fleury et al. 2004). The site receives nearly two-thirds of the annual 3041 mm of precipitation between mid-March and mid-June, and <50 mm per month in

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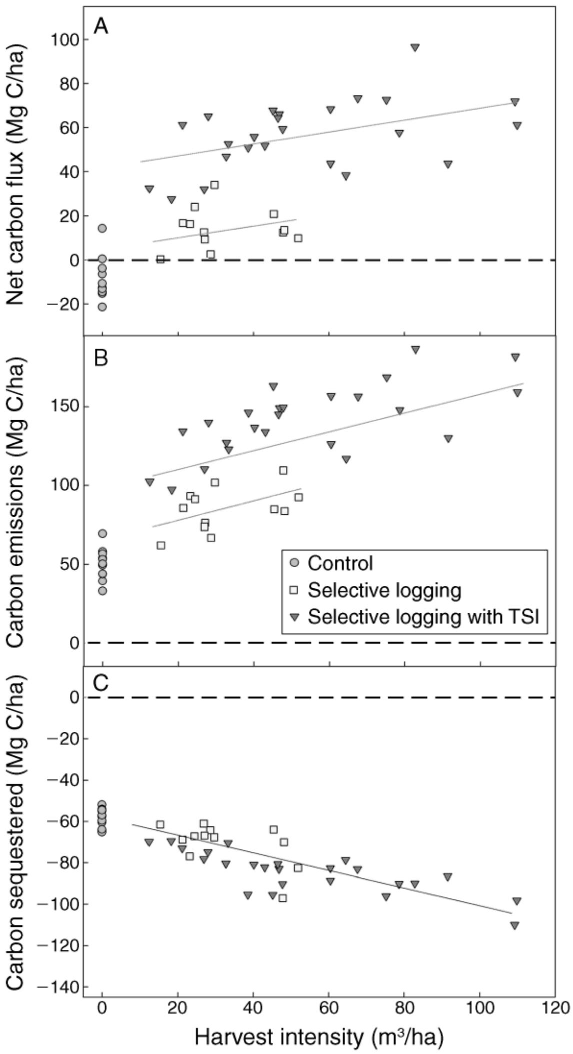


FIG. 1. Effects of logging intensity on carbon flux (the dashed line corresponds to a flux of 0) for aboveground biomass over a 20-yr period after selective logging. Each point represents the cumulative sum of carbon gains and losses for the period 1987–2007 from a 1.56-ha plot subjected to one of three treatments: control, selective logging only, and selective logging with timber stand improvement (TSI). (A) Net carbon flux; (B) carbon emissions from tree harvesting and death, estimated using decomposition constants and species-specific wood density; and (C) carbon sequestered by tree growth and recruitment, estimated from allometric measures incorporating tree diameter and species-specific wood density. Lines illustrate linear models fitted from ANCOVA performed to test the effect of harvest intensity and treatment on net flux, carbon emissions, and carbon sequestered over the 20-yr observation period; all coefficients were significant at $P < 0.0001$. For logged plots without TSI, flux $= 5.96 + 0.257 \times$ intensity, with the intercept changing to 43.0 for plots with TSI. For plots without TSI, carbon emissions increased with harvest intensity; flux $= 63.9 + 0.560 \times$ intensity, with the intercept changing to 101.0 for plots with TSI. Across all logged plots, carbon sequestered increased with harvest intensity (sequestered flux $= -57.9 - 0.313 \times$ intensity).

September and October (Gourlet-Fleury et al. 2004). The most common soils in Paracou are the shallow ferralitic soils limited in depth by a more or less transformed loamy saprolithe (Gourlet-Fleury et al. 2004). Some very thick ferralitic soils, with free vertical drainage, are primarily encountered on the highest residual summits of the area (~40 m above sea level). Surface soils at the site exhibit similar carbon and nitrogen properties to other eastern South American lowland forest soils, but have very low phosphorus availability (Baraloto and Goldberg 2004).

Beginning in 1984, 48 permanent tree plots totaling 75 ha of tropical rain forest were established at the site. All trees ≥10 cm diameter breast height (dbh) have been identified, tagged, mapped, and measured in these plots (see Appendix A). From 1986 to 1988 different logging treatments were applied to 36 plots, with 12 plots established as controls. In 12 logged plots, selected timbers were extracted, with an average of 10.4 tress (from 5.8 to 15.4 trees) ≥50 cm dbh removed per hectare, corresponding to a timber volume average of 32.5 $m^3$/ha (from 15.4 to 51.8 $m^3$/ha). In 24 plots in which intensive timber stand improvement (TSI) was applied, logging intensity averaged 20.6 trees (from 5.1 to 41.7 trees) ≥50 cm dbh removed per hectare, corresponding to a timber volume average of 53.4 $m^3$/ha (from 12.4 to 109.8 $m^3$/ha). Subsequent poison girdling of selected noncommercial species killed an average of 16.6 trees ≥40 cm dbh/ha (Appendix A: Table A1). Complete inventories were conducted annually until 1995, then every two years, with a most recent census in 2007.

We estimated the aboveground pools of carbon in trees from allometric formulas using wood specific gravity and trunk diameter (Chave et al. 2005), and we converted dry biomass into carbon assuming a carbon : dry biomass ratio of 0.5 (Penman et al. 2003). Aboveground carbon emissions were estimated by integrating carbon stored in each tree with census data for tree death and a model of coarse woody debris decomposition (Chambers et al. 2000). An additional source of aboveground carbon emissions was due to harvested logs, which we separated into decomposing and harvested proportions using field reports of the experimental logging operation in which the fate of 2-m segments of all harvested trees was followed. For harvested segments that arrived in sawmills, we estimated that only one-third of the aboveground carbon was stored in woody commercial products. The remaining two-thirds of aboveground carbon were considered as immediate emissions following wood transformation practices employed in most parts of tropical America (Keller et al. 2004).

## RESULTS AND DISCUSSION

During the 1987–2007 observation period, logged plots did not recover their original aboveground carbon stock. Over this period, net carbon flux was positive and ranged between 0.3 and 96.7 Mg C/ha (Fig. 1A; carbon emissions are described as positive fluxes according to IPCC conventions; Penman et al. 2003), depending on the timber volume harvested and on the logging treatment. Conventionally logged plots had an average net flux of 14.3 Mg C/ha. In contrast, logged plots with timber stand improvement (TSI) had almost four times the average net positive carbon flux over the period (56.7 Mg C/ha). Differences in net aboveground carbon flux among treatments were due more to differential emissions from dead and harvested trees (Fig. 1B) than to differential sequestration from subsequent tree growth and recruitment (Fig. 1C). Plots logged with TSI released two-thirds more aboveground carbon (141.2 Mg C/ha) over the 20-yr period than plots without TSI (85.0 Mg C/ha).

All 36 logged plots remained sources of aboveground carbon emissions for 10–12 years following harvesting activities (Fig. 2). Emissions from harvested trees peaked immediately after logging as an estimated two-thirds of the harvested biomass was burned in sawmills (see Appendix B). Annual emissions from harvested trees peaked at 9.1 Mg C/ha one year after logging, with the most intensively logged plots releasing >20 Mg C/ha in that year. Emissions due to increased mortality after logging were less severe but more sustained, both because of damaged trees that died several years after harvesting and because these emissions arose from coarse woody decomposition within the forest rather than from burning immediately after the logging operation. Plots with TSI maintained emissions of >10 Mg C/ha from tree mortality for several years after logging, as many of the poisoned trees did not die until several years after treatment and the canopy gaps they created resulted in additional tree mortality (Gourlet-Fleury et al. 2004).

Beginning about 10 years after logging, most logged plots began to sequester more aboveground carbon than they released from decomposing dead and harvested trees, and some logged plots actually had more positive net annual aboveground carbon flux than unlogged plots (Fig. 2). This reaction was due not only to reduced emissions from dead and harvested trees, but also to enhancement of tree growth and recruitment by >50% in logged vs. unlogged plots over a 20-yr period. Aboveground carbon sequestration due to tree recruitment (Appendix A: Fig. A1) peaked in most plots about 10 years after logging and this peak compensated for the

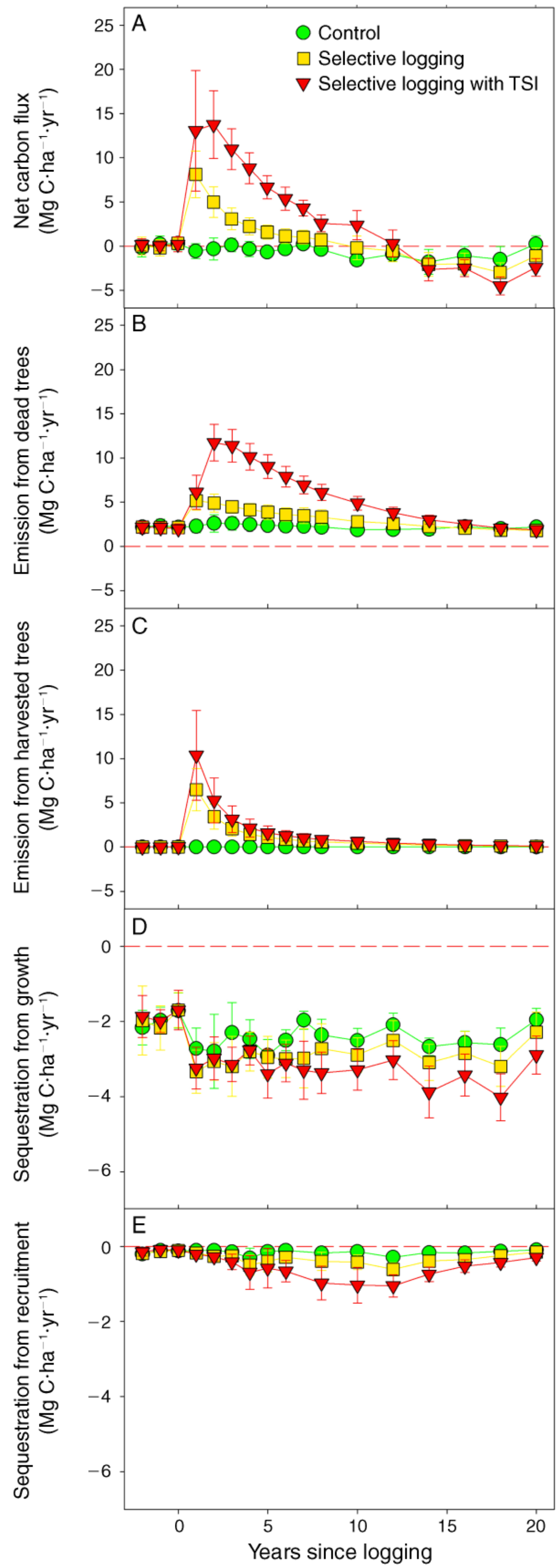


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FIG. 2. Net annual flux of carbon from aboveground biomass and its components across 23 years in logged and unlogged forest. Shown are the means (±SD) of 12 (or 24 for logging + TSI) 1.56-ha plots in each of three treatments including control (green circles), selective logging only (yellow squares), and selective logging with timber stand improvement (red triangles). (A) Net annual carbon flux; (B) annual carbon emissions from tree death; (C) annual carbon emissions from tree harvesting; (D) annual carbon stored by tree growth; and (E) annual carbon stored by tree recruitment.

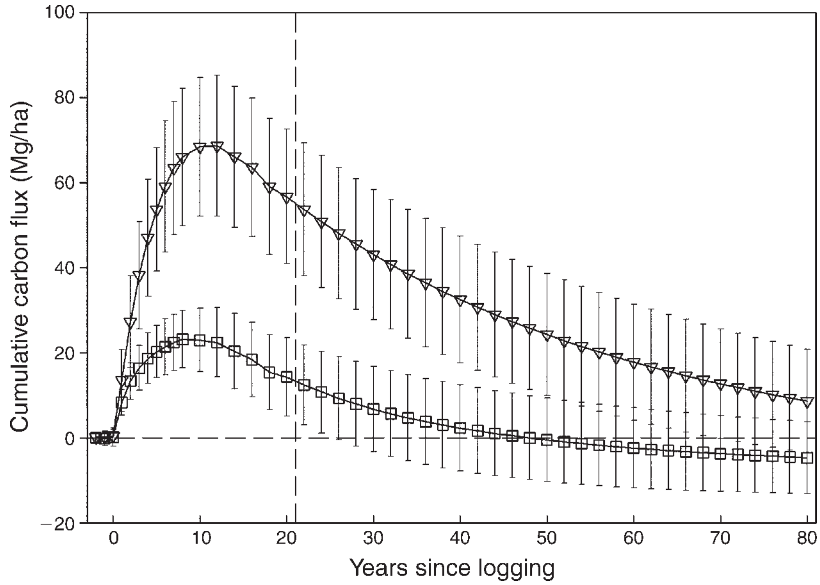


FIG. 3. Projected cumulative carbon flux of aboveground biomass in logged forest plots. Points indicate observed (to 2007; indicated by the vertical dashed line) and simulated mean values for 1.56-ha plots that were logged only (squares) or logged with timber stand improvement (triangles). Error bars indicate the maximum and minimum values among plots of each treatment. Simulations projected reduced carbon sequestration through time with maximum carbon stocks equivalent to mean values observed in unlogged plots at the most recent (2001–2007) census interval.

continued increased emissions from earlier tree mortality in these plots. Enhanced tree growth in logged plots occurred within two years of harvesting and was maintained until the most recent census.

To determine the long-term consequences of differences in forest dynamics after logging to the aboveground carbon balance of this tropical forest, we extrapolated the time trajectories of net aboveground carbon fluxes in the plots into the future using a bookkeeping model of aboveground carbon recovery through time (see Appendix B). The average time to recover the original aboveground carbon stock is projected to be 45 years for logged plots without TSI (Fig. 3). However, plots with timber stand improvement would take more than 100 years to recover their prelogging aboveground carbon stocks.

We believe these results represent a conservative estimate of aboveground carbon stock recovery in selectively logged tropical forests for two reasons. First, logging operations at Paracou were typical of conventional logging (CL) systems, with no effort to implement any of the recommendations suggested for reduced-impact logging (RIL) techniques, including reduced damage to forest structure and future crop trees, wasted timber left in the forest, and poor sawmill transformation efficiency (Appendix A: Fig. A3). No concerted effort was made to reduce impacts on the residual stand. Indeed, the surface areas damaged in the plots (Appendix A: Table A1) are among the highest values reported in the literature for similar extracted timber volumes (Feldpausch et al. 2005). In other tropical forests, where reduced-impact logging techniques have been implemented, the contribution to emissions from incidentally killed or damaged trees can be reduced by more than one-third (Pinard and Cropper 2000).

In addition, about one-third of the timber volume harvested at Paracou (34% $\pm$ 8% SD) was left to decompose on site. Training chainsaw operators in directional felling techniques could lead to marked reductions in this waste rate (Sist and Brown 2004). Recent improvements in chain-of-custody accompanying the certification of forest products in many tropical RIL operations will result in less transformation waste and thus reduced emissions from harvested trees. In operations attempting to maximize transformation efficiency, waste is estimated to be $<$30%. In summary, the use of RIL techniques at Paracou could have reduced initial emissions by $\sim$50%.

Our results from Paracou may also represent conservative patterns of aboveground carbon sequestration relative to other Neotropical forests, as evidenced from three factors of forest dynamics that drive carbon accumulation after logging: growth, mortality, and recruitment. The degree to which our results can be extrapolated to other sites depends on the site specificity of the response through time of these three factors to logging-associated disturbance. To our knowledge, long-term data in Neotropical logged permanent plots are available only for six sites in Brazil and one in Suriname (Table 1). The average stand-level diameter increment in the control (unlogged) plots at Paracou was equal to 1.2 mm/yr. This is low compared to other experimental studies (range, 1.1–3.2 mm/yr; Table 1). Stand-level mortality was also low (1.1%; range of the other study

TABLE 1. A comparison of forest dynamics in unlogged and logged plots at Paracou and six other Neotropical forest sites.

| Forest dynamics | Paracou | CELOS 67/9B | Jari | Tapajos km 67 | Tapajos km 114 | Paragominas | BIONTE |
|---|---|---|---|---|---|---|---|
| Growth (mm/yr) | | | | | | | |
| Unlogged | 1.2 | 1.1 | 2.1 | 2.0 | 1.4 | 3.2 | 1.6 |
| Initial | 2.2 | 4.1 | 3.8 | 3.0 | 3.6 | 2.9 | 2.9 |
| Subsequent | 2.1 | 4.2 | 3.1 | 2.5 | 2.2 | 3.4 | 1.9 |
| Mortality (%) | | | | | | | |
| Unlogged | 1.1 | 2.0 | 1.2 | 1.7 | 1.2 | 1.8 | 1.0 |
| Initial | 2.2 | 2.1 | 2.6 | 2.4 | 2.7 | 2.4 | 2.9 |
| Subsequent | 1.6 | 2.1 | 1.2 | 2.6 | 2.1 | | |
| Recruitment (%) | | | | | | | |
| Unlogged | 1.1 | | 1.5 | 4.8 | 1.2 | 1.7 | |
| Initial | 4.2 | | 2.6 | 5.2 | 7.8 | 2.4 | |
| Subsequent | 5.1 | | 2.0 | 1.8 | 1.6 | | |

*Notes:* "Initial" refers to averages across the first 6–8 years after logging; "subsequent" values are for available data >8 years after logging. Data are from plots where no timber stand improvement (TSI) treatments were employed. Size classes and data sources for each site (other than Paracou) are: CELOS, unrefined logged plots, stems >20 cm dbh (de Graaf 1986, Jonkers 1987, de Graaf et al. 1999); Jari, stems >20 cm dbh (De Azevedo 2006); Tapajos km 67, stems >5 cm dbh (Silva et al. 1995); Tapajos km 114, stems >5 cm dbh (De Carvalho et al. 2004, De Oliveira 2005); Paragominas, control and conventional logging sites, stems >10 cm dbh (Vidal et al. 2002, Vidal 2003); BIONTE, stems >10 cm dbh (Chambers et al. 2004, Rice et al. 2004, Vieira et al. 2004, 2005).

sites, 1.0–2.0%). In most of these forests, diameter growth rate increased up to fourfold after logging. What is the contribution of maintaining higher growth rates to aboveground biomass accumulation after logging? An important contrast among sites occurs for the subsequent response of the forest to logging after about six years post logging (Table 1). After this period, growth slowed in four of the five Amazonian forests, but not in the Guiana Shield sites (Paracou and CELOS; Table 1). In the BIONTE experiment, the only Amazonian study site with long-term data comparable with Paracou, aboveground biomass stocks returned to pre-logging levels after 16 years (Chambers et al. 2004). Hence the results of our study are consistent with other slow-growing Amazonian forest sites.

A second process influencing aboveground carbon sequestration that may differ among forests is tree mortality. Annualized mortality rates in unlogged Neotropical forests range between 0.8% and 2% per year (Swaine et al. 1987, Lugo and Scatena 1996, Lewis et al. 2004), within which fall the observations in unlogged plots at Paracou (Table 1). Following an initial period of high mortality directly after logging at Paracou, mortality rates remained ~30% higher than those observed prior to logging for about eight years after logging. Thereafter (since 1997), mortality rates between logged and unlogged plots have been similar. Reports from other permanent plots show increases in mortality after logging ranging from ~33% at Tapajos km 67 to nearly 200% at BIONTE, Brazil (Table 1). However, the few data that exist for longer term mortality rates show contrasting patterns. At CELOS and Tapajos km 67, mortality remained high up to 16 years after logging, whereas the Jari plots (and to a lesser extent the Tapajos km 114 plots) showed declines through time similar to those observed at Paracou (Table 1).

A third process that might influence aboveground carbon sequestration is recruitment of new stems. Recruitment rates in unlogged forest at Paracou (Appendix A: Fig. A1) are on the lower end of the range reported for Neotropical forests (0.8–2.32%, mean = 1.84%; Phillips and Gentry 1994, Laurance et al. 1998, Lewis et al. 2004). Given the local dominance of species with heavier wood from families including Chrysobalanaceae and Lecythidaceae, recruited stems appear to result in equal contributions of aboveground carbon as in other Amazonian sites with higher recruitment rates but lower community wood densities (Fig. 2E; ter Steege et al. 2003, 2006, Chave et al. 2006).

Few studies have reported recruitment rates after logging in permanent plots, and comparisons are difficult because these studies were using different minimum dbh for inventories. At Paracou, where the minimum dbh for recruitment was 10 cm, rates nearly quadrupled. A similar result was found at Tapajos km 114, but entry dbh there was 5 cm. More modest gains were observed at Paragominas (10 cm) and at Jari (20 cm). Results from Tapajos km 67 are difficult to interpret, with a very high rate of recruitment in unlogged plots and a large reduction in recruitment rates in the second 6-yr period following logging (Table 1). Nonetheless, the consistency in available data on recruitment rates and their response to logging disturbance suggests that results from the Paracou site can be extrapolated to other Neotropical forests.

## CONCLUSION

Conservation strategies in tropical forests must compromise among multiple objectives, including not only the preservation of biodiversity and the integrity of global biogeochemical cycles, but also the economic prosperity of landholders (Soares et al. 2006, Foley et al. 2007). Selective logging has been promoted as a tool enabling local landholders to maintain forest cover while deriving economic benefits from timber extraction (Holmes et al. 2002). However, critics have maintained that logging will negatively impact ecosystem processes, including aboveground carbon storage potential (Keller et al. 2004, Asner et al. 2005, Bunker et al. 2005). Our results suggest that selectively logged forest can recover aboveground carbon lost to emissions within a few decades if several conditions are met.

In French Guiana, mean harvest intensity is 14 $m^3$/ha and maximum harvest never exceeds 43 $m^3$/ha (Gourlet-Fleury et al. 2004). This is consistent with other Amazonian forests, where harvest intensity averages 23 $m^3$/ha (Keller et al. 2004, Asner et al. 2005, Feldpausch et al. 2005). If other Amazonian forests demonstrate similar or more rapid aboveground carbon recovery potential as Paracou, the average 0.08 Pg/yr of aboveground carbon released by selective logging in the Amazon (Asner et al. 2005) could be balanced by subsequent sequestration in the subsequent 40 years (committed flux; Ramankutty et al. 2007). Although cutting cycles in French Guiana (where demand for timber is low) are currently set at 65 years (Gourlet-Fleury et al. 2004), in most neighboring countries cycles of less than 30 years are employed (Zarin et al. 2007). On this schedule, it is unlikely that aboveground carbon stocks will be replenished, even if conventional logging is conducted at low harvest intensity.

Under conventional timber production, a large proportion of aboveground carbon emissions into the atmosphere are believed to be caused by unsustainable logging practices (Gullison et al. 2007). A recent analysis estimates that the use of improved timber harvest practices in tropical forests could retain 0.16 Tg C/yr, or >10% of the carbon released by deforestation (1.5 Tg/yr; Putz et al. 2008). These results strongly argue for promoting improved forest harvesting practices in Amazonian forests.

Timber stand improvement methods have been found to increase tree growth rates by 9–100% in several long-term tropical forestry concessions, including Paracou (Jonkers 1987, Gourlet-Fleury et al. 2004, Peña-Claros et al. 2008). However, our results suggest a possible trade-off between such rapid recovery of timber volume and the time to recovery of aboveground carbon stocks. At Paracou, where extreme TSI treatments were implemented (additional reduction of basal area by an average of 20%; Appendix A: Table A1), growth rates of some commercial species doubled (Gourlet-Fleury et al. 2004), but so does the estimated time to recovery of aboveground carbon stocks. In La Chonta, Bolivia, for example, moderate growth rate increases of up to 60% were observed in plots receiving less intensive TSI (reducing basal area by 10%; Peña-Claros et al. 2008), where we might predict a more rapid recovery of aboveground carbon stocks. Thus, the effects of TSI treatments may vary under different forest management operations. In particular, the use of TSI treatments in concert with reduced-impact logging (RIL) techniques merits exploration as a means by which to stimulate timber production with less reduction in aboveground carbon storage than we observed. For example, if the increased carbon sequestration observed under TSI from increased growth (Fig. 2D) were maintained for an additional decade, the estimated recovery time for carbon stocks would be reduced by >10%. For now, our results suggest that an appropriate compromise between timber production and carbon flux recovery will be necessary to meet regional management objectives. An additional consideration for TSI involves its potential to reduce the local abundance of tree species of limited timber value but exceptional conservation value for animal habitat and food.

Finally, selective logging is rarely an isolated activity and is frequently accompanied by other anthropogenic disturbances that may affect carbon sequestration and other important conservation goals (Asner et al. 2006, Peres 2006, Soares et al. 2006, Foley et al. 2007). Often, the road system used to remove timber from forest sites is subsequently used by colonists who hunt, remove more timber, or clear land for agriculture, which can significantly affect aboveground carbon storage potential (Asner et al. 2006, Foley et al. 2007). At Paracou these threats were mitigated by protection of the research site, and similar protection will likely be necessary in other tropical forests, either by local landholders and/or regional managers, to enable selectively logged forests to recover aboveground carbon lost to emissions (Nepstad et al. 2006). Nonetheless, we believe our results support a continued debate regarding the conservation value of management strategies that include selective logging.

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## APPENDIX A

Detailed site description (*Ecological Archives* A019-058-A1).

## APPENDIX B

Carbon bookkeeping model (*Ecological Archives* A019-058-A2).