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Recovery of biomass and merchantable timber volumes twenty years after conventional and reduced-impact logging in Amazonian Brazil

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ABSTRACT

Concerns about the sustainability of tropical forestry motivated this study on post-logging timber and carbon dynamics over a 20-year period in Paragominas, Pará, Brazil. Previously unlogged forest was subjected to conventional logging (CL), reduced-impact logging (RIL), or was set aside as an unlogged control. All trees $\geqslant$25 cm DBH and all trees of commercial species $\geqslant$10 cm DBH were monitored in a 24.5 ha plot in each treatment, with a 5.25 ha subplot in each for monitoring all trees $\geqslant$10 cm DBH. Above-ground biomass and bole volumes of merchantable species were tracked based on 10 inventories made between 1993 and 2014. Pre-logging biomass and bole volumes of commercial species were estimated as 237, 231, and 211 Mg ha^{-1}, and 78, 80, and 70 m^3 ha^{-1}, in the RIL, CL, and unlogged plots, respectively. One year after logging, biomass was reduced 14% by RIL and 24% by CL with corresponding merchantable species volume reductions of 21% and 31%. By 2014, biomass and bole volumes of commercial species had recovered 95% and 98% of their pre-logging stocks in the RIL plot but only 76% and 72% in the CL plot, respectively; timber volumes from large trees ($\geqslant$50 cm DBH) were only recovered to 81% in the RIL plot and to 53% in the CL plot. Over the first twenty years after logging, average volume increments from commercial species were substantially higher in the RIL plot (0.72 m^3 ha^{-1} year^{-1}) than in the CL plot (0.08 m^3 ha^{-1} year^{-1}). Recovery of both biomass and timber volumes were temporarily reversed between 2009 and 2014 due to a 4-fold increase in annual mortality rates in the RIL plot and a 5.5-fold increase in the CL plot (as well as a 3-fold increase in the control plot), all presumably related to the extreme drought of 2010. Our findings support the claim that use of RIL techniques accelerates rates of biomass and timber stock recovery after selective logging.

1. Introduction

Tropical forests are typically logged selectively because only a limited number of scattered trees provide merchantable timber (Dykstra, 2002; Schulze et al., 2008). Even where selective, logging can substantially alter forest structure and affect tree survival, growth, and recruitment rates for up to a decade post-harvest (Shenkin et al., 2015; Silva et al., 1995). Previous studies demonstrated that although biomass stocks can recover relatively rapidly after logging (Pinard and Cropper, 2000; West et al., 2014; Rutishauser et al., 2015), timber volume recovery reportedly requires substantially longer (e.g., MacPherson et al., 2010; Peña-Claros et al., 2008; Sist and Ferreira, 2007; Valle et al., 2007). While promotion of biomass recovery in production forests is a well-recognized climate change mitigation strategy (UN-REDD, 2011), timber volume recovery is essential to the financial attractiveness of forest management (Barreto et al., 1998; Putz et al., 2008a, 2008b). Based on 20-years of post-logging data from permanent sample plots, we compared the effects of conventional and reduced-impact logging (CL and RIL, respectively) on rates of recovery of above-ground biomass and merchantable timber volumes in a tropical rainforest in Amazonian Brazil.

RIL is a key to sustainable forest management insofar as it mitigates forest damage, which benefits biodiversity and reduces carbon emissions (e.g., Miller et al., 2011; Putz et al., 2012). Application of RIL techniques also reportedly increases the rates of recovery of biomass stocks and timber volumes (Putz et al., 2008a, 2008b). While RIL guidelines vary with location and context, common RIL techniques include pre-harvest mapping of crop trees, pre-harvest planning of roads and skid trails, pre-harvest liana cutting, directional felling, and cutting trees low to the

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ground to avoid waste (e.g., Dykstra, 2002). As opposed to RIL, CL typically causes unnecessary damage to soils and residual stands because all trees valuable enough to pay their extraction costs are felled, with minimal or no planning by workers with little training and supervision (Johns et al., 1996; Grogan et al., 2008). Due to lack of effective planning, CL operations often miss valuable trees that otherwise would be harvested but stimulates residual tree growth due to canopy opening (Johns et al., 1996; Pinard and Putz, 1996). Furthermore, CL operations recover less wood from the felled trees due to poor felling, bucking, and yarding operations (e.g., Barreto et al., 1998). West et al. (2014) reported that although individual trees grew faster after CL than RIL, the higher standing stocks of timber after RIL and lower post-logging mortality rates resulted in higher rates of stand-level aboveground biomass recovery. Here we extend that study in time from 16 to 21 years and include analysis of rates of bole volume recovery of merchantable species.

A meta-analysis of rates of commercial timber stock recovery based on 59 studies from around the tropics reported that if the same species continue to be harvested and the minimum cutting diameter is unchanged, then timber yields from the second and subsequent harvests will vary tremendously but average only 35% of those from primary forest (range 0–220%; Putz et al., 2012). Differences logging techniques (i.e., CL or RIL) were proposed by the authors as one explanation for the large variation in rates of recovery. But even where RIL was used, based on 10 years of data and a stand projection model for the plots used in the current study, Valle et al. (2007) concluded that with harvest cycles of 30 years, yields will decline from 30 $m^3\ ha^{-1}$ from the first harvest to 25 and 20 $m^3\ ha^{-1}$ for the second and third harvests, respectively. Similar results were reported for other Amazonian forests (Sist and Ferreira, 2007; van Gardingen et al., 2006). Motivated by these findings and using the same permanent sample plots, we expand on the studies of Johns et al. (1996), Barreto et al. (1998), Valle et al. (2007), and West et al. (2014) to evaluate the effects of CL and RIL on bole volume recovery of merchantable species recovery over a 20-year post-logging period.

2. Methods

The study site is on privately owned land in the eastern Brazilian Amazon (3°17′S, 47°34′W) at an elevation of about 200 m. The forest is evergreen with canopy heights of 25–40 m, the terrain is level to undulating, and the soils are predominately aluminum-rich yellow latosols. 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.

In 1993, 75 ha were subjected to CL and 105 to RIL; an additional plot of 30 ha was set aside as an unlogged control (Barreto et al., 1998; Johns et al., 1996). Although no direct indications of previous logging or fires were observed, the abundance of lianas may indicate anthropogenic disturbances many years before the experiment was implemented. Prior to logging, 24.5 ha plots (350×700 m) were established at random locations in areas to be subjected to RIL, CL, or reserved as an unlogged control. In those three plots all commercial trees $\geqslant$10 cm DBH (stem diameter at 1.3 m from the ground or above buttresses) and non-commercial trees $\geqslant$25 cm DBH were marked, mapped, and identified to species; all non-commercial trees $\geqslant$10 cm DBH were treated similarly in a 5.25 ha subplot within each 24.5 ha plot. All lianas $\geqslant$2 cm DBH on trees to be harvested in the RIL plot were cut two years prior to logging. Additional components of the RIL treatment included: directional felling by trained workers to lessen damage to juvenile commercial trees and to facilitate skidding; winches were used to clear logs from the felled boles to the skid trail to reduce yarding damage; a skid trail network was designed and flagged to mark the best path to the felled trees; log landings were built to accommodate the expected number of logs to be skidded to them; and, road constriction was minimized. All procedures followed a pre-designed logging plan that established the preferable felling direction, skidder path, boundaries of log landings, and road construction routes (Johns et al., 1996).

Different crews carried out the logging operations in each plot. In the CL area, logging was conducted by two independent teams of loggers with no formal training on RIL techniques. They were hired by a sawmill owner and each team consisted of one chainsaw operator, one bulldozer operator, and two assistants. In the RIL area, logging operation was carried out by one crew with RIL training that was composed of two sawyers, one skidder operator, one bulldozer operator, and two assistants (Johns et al., 1996). About one year post-logging, trees were re-measured and recorded as having suffered trunk or crown damage during logging (Johns et al., 1996). The same information was collected and new recruits were recorded during the ten subsequent measurements (1994–2014). Bole volumes of felled trees were similar in both treatments (39 $m^3\ ha^{-1}$ in RIL and 37 $m^3\ ha^{-1}$ in CL) but the extracted volume from the CL plot (29.7 $m^3\ ha^{-1}$) was lower than from the RIL plot (38.6 $m^3\ ha^{-1}$; Barreto et al., 1998).

We used the R v.3.2.2 (R Core Team, 2015; Wickham, 2011; Zeileis and Grothendieck, 2005) statistical software to develop algorithms to correct for potential biases in the permanent sample plot data (e.g., Talbot et al., 2014). First of all, for missing DBH measurements in our time-series dataset, we assumed that DBH increments proceeded at annual average rates between measurements. To correct for biased estimates of biomass and timber volumes due to time delays between the first record for a newly recruited trees and the date of their first entry into the $\geqslant$10 cm DBH class, we projected the DBH values of newly recruited trees backwards until they reached 10 cm DBH based on species-specific median growth rates for trees of all sizes over the 20-year monitored period. This correction represents a considerable departure from the method employed by West et al. (2014) in which non-commercial species were considered recruited only when they attained DBHs $\geqslant$25 cm and trees too large to have recruited between two measurements were considered to be present in the plots since the pre-logging measurement.

Above-ground biomass (Mg ha^{-1}) was estimated with the allometric equation developed by Chave et al. (2014; Eq. (1)):

$$\ln(\mathrm{AGB}) = -1.803 - 0.976 \times \mathrm{E} + 0.976 \times \ln(\rho) + 2.673 \times \ln(\mathrm{DBH}) - 0.299 \times \ln(\mathrm{DBH})^2 \quad (1)$$

in which AGB is the above-ground biomass (kg of dry matter), ρ the is species-specific wood density (kg m^{-3}) and E is a location-specific environmental variable. Species-specific wood densities were obtained from the Dryad Digital Repository (Chave et al., 2009) in accordance with the procedure recommended by Rifai et al. (2015). Due to lack of precise harvesting information, we assumed that trees from the harvested species (Annex S1) with $\geqslant$45 cm DBH that were present prior to logging (in 1993) but absent one year later were harvested. Bole volume from commercial species ($m^3\ ha^{-1}$) were estimated for all individuals of the merchantable species with the bole-volume equation developed for dense forests in central Amazonia by Nogueira et al. (2008):

$$\ln(\text{volume}) = \alpha + \beta \times \ln(\text{diameter}) \quad (2)$$

in which α and β are −9.008 and 2.579 for trees <40 cm DBH and −6.860 and 1.994 for larger trees. For trees larger than the maximum range of the volumetric equation (DBH $\geqslant$ 106 cm; 21 of the 7453 tree sampled from commercial species), timber volumes were estimated by linear extrapolation. We report results by 10 cm DBH