Trees, Forests and People 18 (2024) 100717

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

Forest biomass recovery twenty-four years after conventional and reduced-impact logging in Eastern Amazon

Rodrigo Costa Pinto [a], Thales A.P. West [b,*], Edson Vidal [a]

[a] Department of Forest Sciences, "Luiz de Queiroz" College of Agriculture, University of São Paulo, Av. Pádua Dias, 11, 13418-900 Piracicaba, São Paulo, Brazil
[b] Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands

ARTICLE INFO

Keywords:
Above-ground biomass
Forest management
Forest recovery
REDD+

ABSTRACT

Given the mounting global concerns about mitigating climate change and curbing greenhouse gas emissions, it becomes increasingly crucial to comprehend the effects of logging techniques on biomass dynamics in tropical forests. This understanding is essential for fostering greater carbon retention and sequestration, aligning with the objectives of initiatives like REDD+ (Reducing Emissions from Deforestation and forest Degradation plus sustainable forest management and the conservation and enhancement of forest carbon stocks) and other conservation goals. In this context, this study investigated the effects of two wood harvesting methods, reduced-impact logging (RIL) and conventional logging (CL), on above-ground biomass (AGB) recovery rates 24 years after harvesting. The experimental design was based on three treatments: RIL, CL, and an unlogged control plot, situated in the municipality of Paragominas, State of Pará, in the Eastern Amazon region of Brazil. All trees with diameter at breast height (DBH) ≥25 cm, as well as all trees of commercial species with a DBH ≥10 cm, were monitored in a 24.5 ha plot within each treatment. Additionally, a 5.25 ha subplot within each treatment was designated for the monitoring of all trees with DBH ≥10 cm. The biomass data were generated from 11 measurements carried out from 1993 to 2017 (24-year period). Pre-logging AGB stocks were estimated at 181 Mg ha^{-1} in the RIL plot, 187 Mg ha^{-1} in the CL plot, and 174 Mg ha^{-1} in the control plot. One year after logging, AGB decreased by 19 % under RIL and 30 % under CL, while the control forest remained unchanged. By 13 years after harvest, the RIL plot achieved 102 % AGB recovery, while the CL plot recovered 86 % of the original pre-harvest stock. Over the 24-year post-logging period, AGB stocks recovered to 128 % in the RIL plot compared to only 90 % in the CL plot, while the control forest maintained 93 % of its original stock. The average annual ABG increment rates were 3.56 Mg ha^{-1} $year^{-1}$ after RIL and 2.33 Mg ha^{-1} $year^{-1}$ after CL. Our findings demonstrate that implementing RIL is a more effective strategy for maintaining post-logging AGB stocks and accelerating AGB recovery rates, serving as a significant mitigation measure against climate change.

1. Introduction

The Amazon tropical forest plays a fundamental role as a significant sink for greenhouse gases (GHGs), storing 86 Pg C (Saatchi et al., 2007), or 10 % of all carbon stock stored in forests worldwide (861 ± 66 Pg C; Pan et al., 2011). Despite its global importance, the rainforest continues to experience high rates of deforestation and environmental degradation, leading to the loss of carbon stocks (Keenan et al., 2015). The dynamics of forest conversion in the Amazon are typically linked to livestock and agricultural activities (Betts et al., 2008; Wright, 2010). However, degradation due to logging often precedes the loss of forest cover, which usually occurs without proper planning and results in a reduction and damage to the remaining forest stock (Asner et al., 2005; Nepstad et al., 1999). In 2015, selective logging in the tropics was estimated to emit approximately 834 Tg CO_2 into the atmosphere, representing 6 % of the total tropical greenhouse gas emissions (Ellis et al., 2019).

The impacts of timber harvesting rank among the primary causes of anthropogenic disturbances affecting the carbon stock and structure of tropical forests (Putz et al., 2022; Verissimo et al., 1992). Despite the vast diversity of species in the Amazon rainforest, timber harvesting primarily targets a small group of commercial species (Piponiot et al., 2019). While the overall impact of harvesting on woody biomass may be relatively low, the damage inflicted per cubic meter on certain species

* Corresponding author.
E-mail addresses: rodrigopinto@usp.br (R.C. Pinto), t.a.pupowest@vu.nl (T.A.P. West), edson.vidal@usp.br (E. Vidal).

https://doi.org/10.1016/j.tfp.2024.100717

Available online 31 October 2024

can be considerable (Barreto et al., 1998). For this reason, the use of reduced-impact logging (RIL) techniques has been promoted as a strategy to reduce collateral damage from harvesting in these environments and foster greater post-harvesting recovery of biomass and forest carbon stocks (Piponiot et al., 2016; Vidal et al., 2016). However, a common phenomenon observed in many tropical forests is the prevalence of unplanned logging practices, which can cause considerable damage to the remaining forest stand (Putz et al., 2022, 2000). This form of exploitation is commonly referred to as conventional logging (CL).

Following logging activities, biomass losses can persist for several years due to heightened mortality rates among remaining trees during harvesting operations (Shenkin et al., 2015). Logged forests have the potential to restore their above-ground biomass (AGB) through the accelerated growth of surviving trees and newly recruited individuals (Blanc et al., 2009). The complete recovery of post-harvest biomass stocks depends on the intensity of timber harvesting, and the time frame can vary significantly. Some studies indicate recovery occurring as early as 16 years after RIL, while others estimate it may take up to 125 years (Rutishauser et al., 2015; Vidal et al., 2016; West et al., 2014). For CL, studies estimate that it may take up to 86 years for post-harvest biomass stocks to fully recover (Rutishauser et al., 2015). Still, recovery processes, including tree mortality, growth, and recruitment, are expected to vary across the Amazon Basin and the Guiana Shield due to distinct geographical patterns in forest structure and dynamics (Piponiot et al., 2016).

RIL stands as a cornerstone of sustainable forest management, mitigating forest damage, promoting biodiversity, and curbing carbon emissions (Putz et al., 2022, 2012). The significant carbon benefits arising from enhancements in tropical forest management warrant recognition and compensation through climate change mitigation programs aimed at decreasing emissions from forest degradation while augmenting forest carbon stocks (Angelsen, 2008). Over the past decades, REDD+ (Reducing Emissions from Deforestation and Forest Degradation plus the role of conservation, sustainable forest management, and enhancement of forest carbon stocks), a mechanism developed to reward efforts leading to avoided deforestation and the promotion of sustainable forest management, has gained significant traction across the tropics (UN-REDD, 2023). Performance-based REDD+ payments are envisioned to foster the continuous provision of social, economic, and environmental benefits to local forest stakeholders associated with the sustainable use of natural resources and conservation. Furthermore, well-managed forests are more resistant to fire and resilient to climate change compared to unsustainably managed forests (Putz et al., 2012).

To shed further light on the climate benefits of sustainable forest management, this study reports on the long-term monitoring of the recovery dynamics of above-ground biomass (AGB) in a managed forest site in eastern Pará state, Brazil, subjected to RIL and CL, 24 years after harvesting.

2. Material and methods

2.1. Study area

This study was conducted at Agrosete farm, located 30 km from the center of the town of Paragominas, Northeast of Pará State, Brazil, between the coordinates 2° 25′ e 4° 09′ S e 46° 25′ e 48° 54′ W (Fig. 1). In this region, the climate is hot and humid, with an average annual rainfall of 1700 mm from January to May and <50 mm from June to November (Alvares et al., 2013). The relief of the region varies from flat to slightly undulating and the typology of soils is mostly classified as Dystrophic Yellow Latosol (Pinto et al., 2009). The forests in the region are

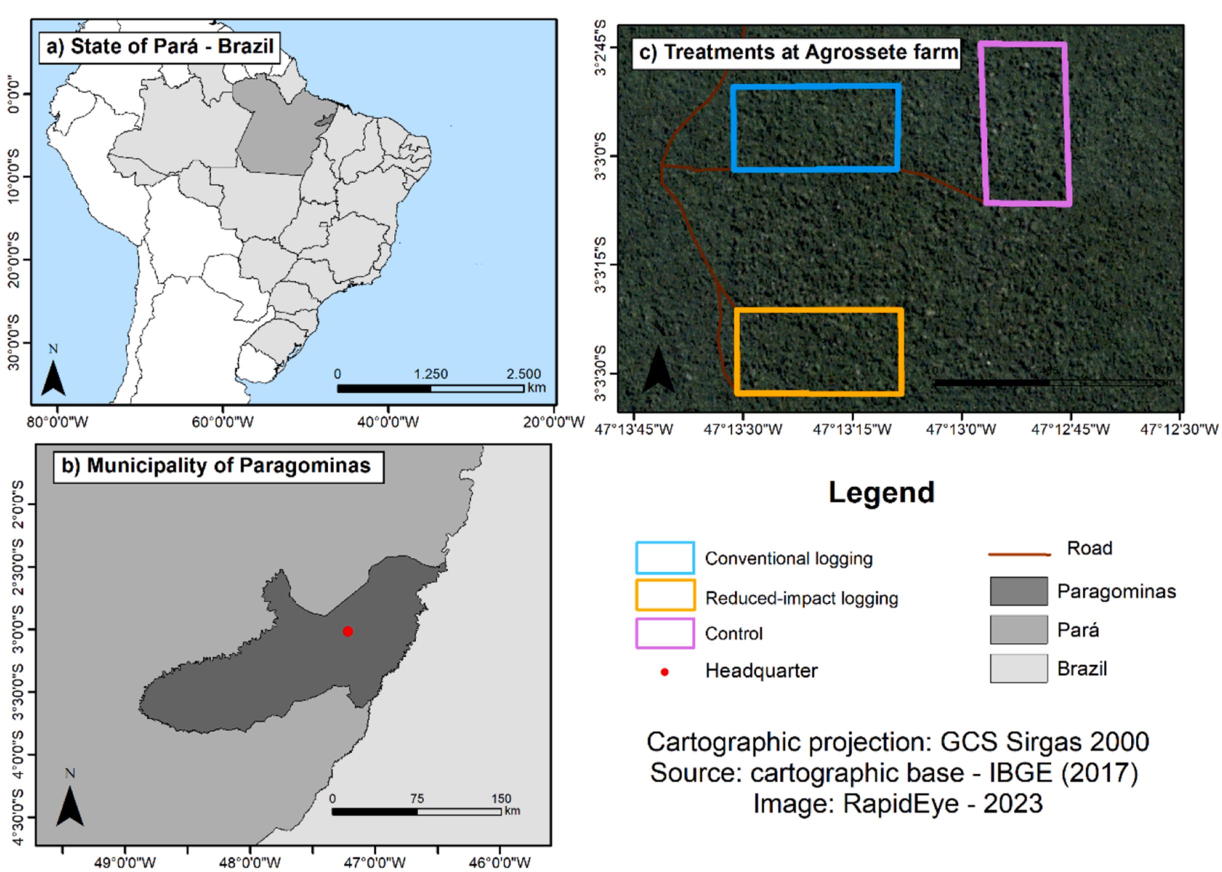

Fig. 1. Location of the Agrossete Farm in the municipality of Paragominas, State of Pará, Brazil (a, b), forest dynamics monitored in 24.5 ha plots submitted to reduced-impact logging (RIL) (Orange), conventional logging (CL) (Blue) and unlogged control plot (Purple) (c).

classified as Ombrophilous Dense Evergreen with canopy heights ranging from 29 to 40 m (IBGE, 2012; Pinto et al., 2009).

2.2. Experimental design

In 1993, 105 ha and 75 ha of the forest were subjected to CL and RIL, respectively. Another 30 hectares of the same stand were preserved as a control area, totaling 210 hectares under the experiment. Two years before harvesting, one permanent plot of 24.5 ha (350 × 700 m) was established in each of the three treatments. The forest dynamic within each plot was monitored for 24 years, from 1993 to 2017 (Vidal et al., 2016; Naves et al., 2020; Fig. 1). Although there is no evidence of logging or fires prior to the experiment, the abundance of lianas suggests that the forest may have been exposed to some level of degradation many decades ago (Vidal et al., 2016).

Within each 24.5-ha plot, where all individuals of commercial species with a diameter at breast height (DBH) >10 cm and non-commercial species with DBH ≥ 25 cm were monitored, a single additional rectangular subplot of 5.25 ha (75 × 700 m) was established to measure all individuals with DBH >10. The plots underwent sequential forest inventories in 1994, 1995, 1996, 1998, 2000, 2003, 2006, 2009, 2014, and 2017. During each inventory, all newly appearing individuals were identified based on the inclusion criteria. Due to the shortcomings of the experimental design, with no replication of each treatment within the plots, standard statistical comparisons among the treatments are compromised. In response to this limitation, West et al. (2014), investigated the validity of the experiment based on: (1) a comparison of pre-logging forest characteristics among the treatment plots; (2) geostatistical analyses of pre-logging aboveground biomass; and (3) a comparison of post-logging growth rates. The authors found no evidence of differences in pre-existing conditions among the experimental plots that could influence the effects of logging treatments.

Based on standard RIL practices, the following techniques were applied in the RIL plot: the removal of lianas with DBH ≥2 cm from the trees to be extracted two years before harvest; the planning of felling direction, skidder path, stockyards, and road routes; and harvesting executed by a trained logging crew from the Amazon Institute of People and the Environment (Imazon; Portugues acronym), in Brazil. In contrast, the CL plot was subjected to unplanned logging practices carried out by untrained staff, resulting in substantial collateral damage to the remaining forest (Barreto et al., 1998; Johns et al., 1996).

In both treatments, felled volumes were similar (39 m^3 ha^{-1} e 37 m^3 ha^{-1}) and the harvested species overlapped substantially (Table S1); however, the volume harvested and evtually processed in the sawmill was much lower under the CL treatment than in under RIL due to losses during the unplanned felling of the trees, including (1) wood left behind on the stump, (2) log splitting due to poor felling technique, and (3) wood left behind on the bole due to improper bucking (Barreto et al., 1998; Table 1).

Several studies were carried out based on the data from the Agrosete farm to understand the dynamics of forest management in tropical native forests (Vidal et al., 2016; Naves et al., 2020). Furthermore, the permanent plots used in this study are part of global monitoring networks of forest biomass and related climate change effects (Schepaschenko et al., 2019; Sist et al., 2015).

Table 1
Logging intensities of the reduced-impact logging (RIL) and conventional logging (CL) treatments implemented in 1993 at Agrossete farm, Paragominas, State of Pará, Brazil (adapted from Barreto et al., 1998).

Logging intensities	RIL	CL
Mean felled volume (m^3 ha^{-1})	38.9	37.4
Harvested volume	38.6	29.7
Bole wood volume abandoned after felling (%)	1	26
Harvested 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 harvested (sd;n)	8.2(6.22;138)	5.3(3.83;279)
Mean diameter (cm) at the base of harvested trees (SD; n)	79.0 (23.9;138)	71.8 (17.8;279)

2.3. Data analysis

To estimate the AGB for each measured tree, as well as for the entire forest, we employed the BIOMASS package (v. 2.1.11). This R package, developed for estimating AGB, was developed to standardize calculations and evaluate the uncertainties from forest plot measurement based on a Bayesian inference procedure (Réjou-Méchain et al., 2017). Using a modified allometric equation from Chave et al. (2014), the package estimates the AGB based on DBH, wood density, and spatial coordinates, has the following expression:

$$AGB = \exp(-2.024 - 0.896\ x\ E + 0.920\ x\ln(WD) \quad (1)$$

$$+2.795\ x\ln(DBH) - 0.0461\ x\ \ln\left[\ln(DBH)^2\right])$$

where E refers to a location-specific environmental variable (site coordinates), and WD is the density of wood (kg m^{-3}). Wood-specific densities of tree species were obtained from the Global Wood Density Database (GWDD). These densities were estimated using a function that estimates WD based on taxonomy or congeners, utilizing the GWDD or any additional dataset. WD can be assigned to an individual at the species, genus, family, or stand level (Chave et al., 2009). AGB stocks were calculated for each 24.5-ha plot in each treatment. For those plots, the AGB stocks from unmeasured trees with 10–25 cm DBH were extrapolated from the 5.25 ha subplots. In addition, we separated the annual AGB stocks into diameter classes to examine changes in the forest structure. Version 4.2.3 of the R software was used for the analysis (R Core Team, 2024).

3. Results

3.1. AGB responses after harvest

Pre-logging (1993) AGB stocks were estimated at 181, 187, and 174 Mg ha^{-1}, in the RIL, CL, and control plots, respectively. One year after logging, the AGB was reduced by 19 % and 30 % in the RIL and CL areas, respectively, while the control plot remained unchanged. In 2006, 13 years post-harvest, the RIL plot had recovered far more of its pre-logging biomass (102 %) than the CL plot (86 %). Particularly in the period from 13 to 24 years after harvest, the RIL areas had a significant ABG increase of 19.2 %, against only 4.7 % in the CL plot (Fig. 2).

During the first 13 years post-harvest, annual increments in AGB (i. e., recruitment plus residual tree growth minus mortality) averaged 3.16 Mg ha^{-1} $year^{-1}$ in the RIL plot and 2.5 Mg ha^{-1} $year^{-1}$ in the CL plot. In contrast, between 13 and 24 years after harvest, the RIL plot recovered 5.5 times more biomass than the CL plot (4.4 Mg ha^{-1} $year^{-1}$, versus 0.8 Mg ha^{-1} $year^{-1}$, respectively). As a result, the average annual AGB increment rates for the 24-year period were 3.56 Mg ha^{-1} $year^{-1}$ and 1.65 Mg ha^{-1} $year^{-1}$ for the RIL and CL plots, respectively. During the same period, the control plot experienced biomass loss of 1.1 Mg ha^{-1} $year^{-1}$, potentially as a result of three strong El Niño (extreme drought) events, in 2005, 2010, and 2016.

By the year the RIL plot had recovered 100 % of its biomass stock (i. e., 13 years after harvest), newly recruited individuals represented about 15 % of the standing stock. In contrast, in the CL plot, newly recruited trees represented about 25 % of the AGB stock 13 years after logging, when 86 % of its pre-harvest AGB stock was restored. After 24 years post-harvest, the RIL plot recovered 128 % of its original biomass (232 Mg ha^{-1}), with new individuals accounting for approximately 28 % of the total standing stock. Notably, the newly recruited individuals in the CL plot also contributed 28 % of the total 90 % AGB (161 Mg ha^{-1}) 24 years after logging. The control plot maintained 93 % of its original

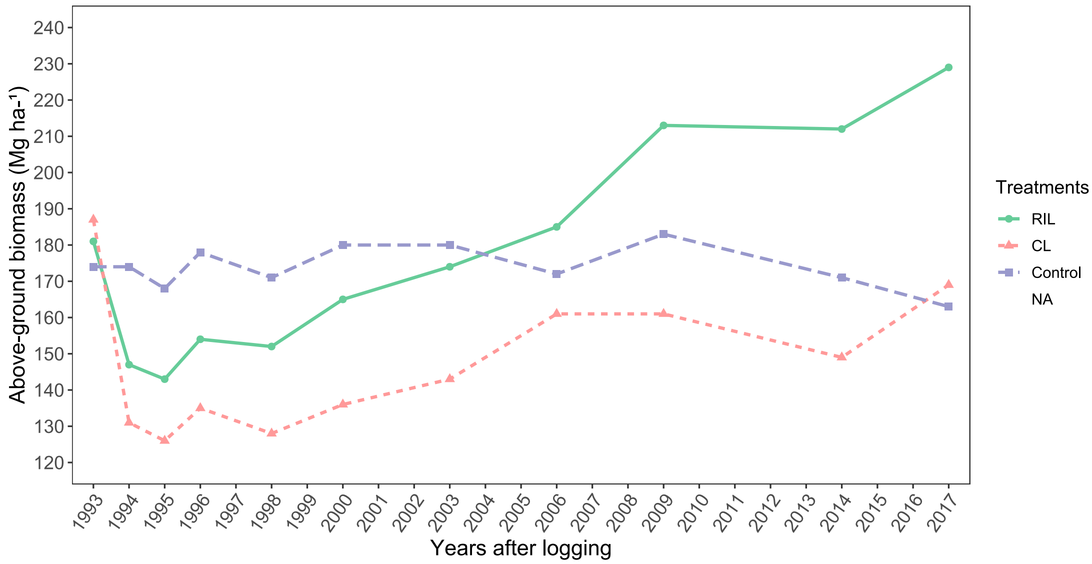

Fig. 2. Above-ground biomass dynamics in 24.5 ha plots subjected to reduced-impact logging (RIL), conventional logging (CL), and unlogged control plots.

stock 24 years after the start of the experiment, with newly recruited trees since then representing 19 % of the AGB (Figs. 2 & 3).

3.2. AGB dynamics by diameter class

By the time the AGB stock reached its pre-harvest levels in the RIL plot (around 2006), recovery was mainly due to residual stock growth. In 1993, the ≥20–50 cm DBH class represented 45 % of the original stock in this treatment (82 Mg ha^{-1}), whereas in 2006, it increased to 55 % of the AGB (102 Mg ha^{-1}) (Fig. 3). There was an AGB reduction in the 10–20 cm class in 2006, presumably from the 2005 extreme drought.

In 2017, 24 years after the harvest, all diameter classes showed an increase in AGB stocks in the RIL plot compared to pre-harvesting levels. In contrast, for the same period, both CL and control areas experienced a decrease in AGB stocks in most diameter classes. The exceptions were for the classes of 10–20 cm in both CL and control plots, and 20–30 cm only in the control plot. (Fig. 3). In addition to the effects of logging on the CL plot, it is likely that the general decrease in stocks observed in those plots also resulted from the extreme drought events of 2005, 2010, and 2016.

In 1993, before harvest, 37 % of the AGB stocks were stored in trees with DBH ≥60 cm in the RIL plot, 36 % in the CL plot, and 42 % in the control plot. After 24 years post-harvest, the proportion of AGB contribution from trees in the ≥60 cm class decreased in all three treatments (32.3 % for RIL, 29.6 % for CL, and 37 % for the control plot, respectively; Fig. 3).

4. Discussion

4.1. Aboveground biomass stocks before harvest

The pre-harvest AGB estimates for the experimental plots were lower (174–187 Mg ha^{-1}) than the values found in two previous studies in the same area (211–264 Mg ha^{-1}) (Vidal et al., 2016; West et al., 2014). On

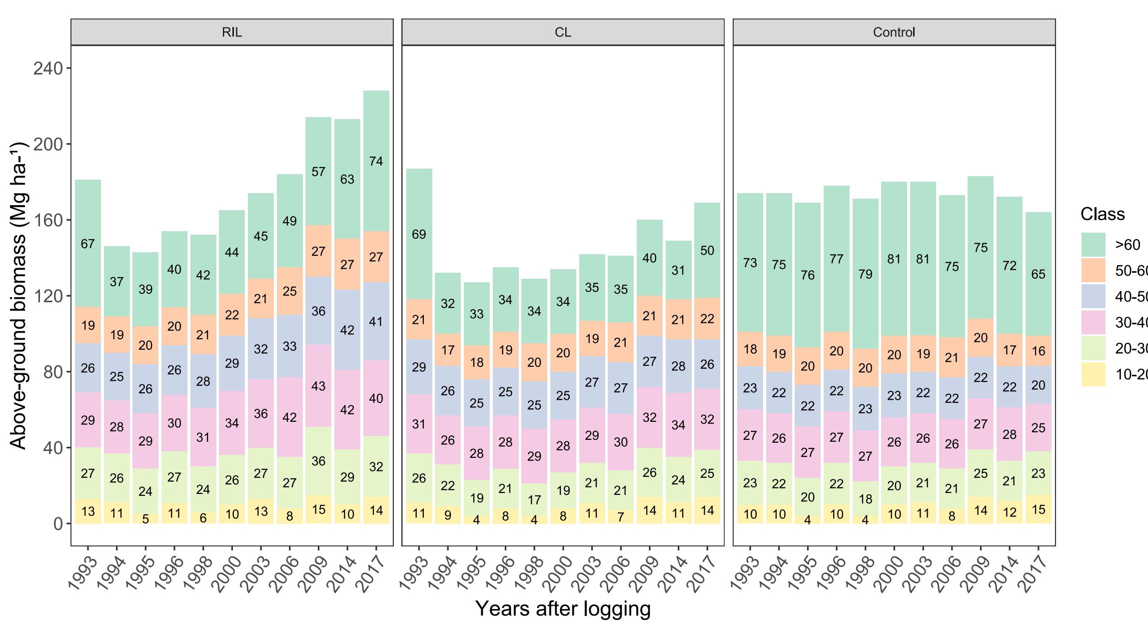

Fig. 3. Changes in above-ground biomass by diameter class compared to pre-logging (1993) values after reduced-impact logging (RIL), conventional logging (CL), and in the unlogged control plot. AGB-class stocks per hectare are reported inside the histogram bars.

average, the biomass stocks were 57 Mg ha^{-1} (24 %) smaller than those reported by Vidal et al. (2016) and West et al. (2014), and also smaller than the estimates by Mazzei et al. (2010; 410 Mg ha^{-1}) and Uhl et al. (1988; 300 Mg ha^{-1}) for areas close to our study site, as well as the average value reported by the Intergovernmental Panel on Climate Change (IPCC, 2019; 307 Mg ha^{-1}) for tropical rainforests. Although there were no signs of wood harvesting prior to the experiment, the somewhat lower biomass estimates compared to those reported by Vidal et al. (2016) and West et al. (2014), could be further evidence of previous disturbances in the study site. Vidal et al. (2016) attributed the differences found by West et al. (2014) to adjustments in the selected allometric equation. Similarily, we believe the source of the differences we found was also due to an allometric equation refinement, from Réjou-Méchain et al. (2017). Such a refinement was based on the correction proposed by Baskerville (2011), drawing from a Bayesian inference procedure and the spatial distribution of the forest plots, designed to reduce the uncertainty of the AGB estimates.

4.2. Aboveground biomass recovery in logged forest

One year after harvest, the effects of selective logging on AGB stocks were reductions of 19 % in the RIL and 30 % in the CL plots, respectively, values similar to those reported by Vidal et al. (2016) and West et al. (2014) in both RIL and CL plots, as well as by Mazzei et al. (2010), for a forest located 200 km from our study area, exposed to RIL (23 %). In contrast to the previous studies by Vidal et al. (2016) and West et al. (2014), our findings suggest that 100 % of the pre-harvest AGB stocks had already recovered in the RIL plot 13 years after RIL (as opposed to 16 years). Our estimates for the AGB recovery in the RIL treatment were two years shorter than the 15-year simulated AGB recovery time by Mazzei et al. (2010). We suspect that the estimated shorter recovery time may have been influenced by the involvement of a trained logging team from Imazon, as well as by the refinement of the allometric research applied in this study. This assumption is also supported by the observation that growth rates decreased by 24 % to 14 % with increasing liana levels, and by 13 % to 23 % with increasing collateral damage in the RIL and control plots, respectively, compared to the CL plot (Erdmann, 2019). For the latter area, our updated estimates indicate that 86 % of the pre-logging volume had been recovered after 13 years (versus 74 % and 81 % estimated by the previous two studies, respectively). Yet, the former numbers increased only slightly after 16 years post-harvesting (to 77 % and 82 %, respectively).

The annual rate of AGB recovery in the RIL plot over the 13-year post-harvest period (3.16 Mg ha^{-1} year^{-1}) was 13 % and 34 % higher than reported by West et al. (2014; 2.8 Mg ha^{-1}year^{-1}) and Vidal et al. (2016; 2.36 Mg ha^{-1} year^{-1}), respectively. For the same period, the rate of recovery in the CL plot (2.5 Mg ha^{-1} year^{-1}) was faster than reported in previous studies (0.5 Mg ha^{-1} year^{-1} in West et al., 2014, and 0.99 Mg ha^{-1} year^{-1} in Vidal et al., 2016). In the control plot, during the same period, we observed a significant change in biomass (loss) at a rate of −1.1 of Mg ha^{-1} year^{-1}, which was lower than values reported in previous studies (−0.6 Mg ha^{-1} year^{-1} in West et al., 2014, and −0.93 Mg ha^{-1} year^{-1} in Vidal et al., 2016). Throughout the entire monitoring period in the control plot, the reduction was only noticed due to the extreme drought event, as observed by West et al. (2014) and Vidal et al. (2016). Again, we attribute the estimated reductions in biomass in the control plot to the 2005, 2010, and 2016 droughts (Marengo et al., 2011; Phillips et al., 2009; Smith et al., 2019). Among them, the 2016 drought was particularly severe, leading to the loss of thousands of trees across the Amazon forest.

4.3. Aboveground biomass dynamics responses by class diameter

In 2006, when the RIL plot reached pre-harvest biomass levels, recruited trees represented 15 % of the total stock. In comparison, although the CL plot had a higher proportion of new trees (25 %), its biomass stock had not yet recovered. By 2017, 24 years after harvest, both plots had the same recruitment proportion (28 %), with the AGB stock still not yet fully recovered in the CL plot. The recruitment rates estimated in this study were higher than those observed by West et al. (2014), who reported values of 9 % and 11 % for RIL and CL, respectively, after 16 years of harvest.

In 1993, a significant portion of the biomass stock (38.7 % on average across all plots) was stored in large trees (DBH ≥60 cm). By 2017, both the CL and Control plots exhibited a reduction in biomass stock within this diameter class, with levels of reduction similar to those reported by Vidal et al. (2016). We believe that the effects of harvesting still persist in this diameter class within the CL plot, unlike in the RIL plot (which showed an increase) and in the control plot. Over the monitored periods (2003–2006, 2009–2014, and 2014–2017), the severity of the El Niño drought contributed to reductions in biomass stocks within this class. These reductions could be attributed to the susceptibility of large trees to severe drought (Bennett et al., 2015).

4.4. Implications for sustainable forest management and REDD+

The literature widely acknowledges the significant positive impacts of adopting RIL techniques on the rates of biomass recoveries (Putz et al., 2022, 2012), which is corroborated by the analysis of the long-term monitoring data reported in this study. The adoption of RIL can result in measurable reductions in carbon emissions, which could be financially rewarded through the REDD+ mechanism (Ellis et al., 2019). It is also noteworthy that after RIL, forests may recover their carbon and timber stocks more rapidly than after conventional logging (Vidal et al., 2016). Despite these advances in RIL practices, compensatory payments for sustainable forest management practices that reduce carbon emissions and increase carbon sequestration as a form of climate change mitigation remain rare, even after 30 years of discussions (Putz et al., 2022).

Arguably, RIL operations can only benefit from potential REDD+ funds if their positive impacts on forest recovery and damage reduction are not reversed over time. Extreme droughts are becoming increasingly common in the Amazon. In the past 15 years, the region, including our study site, has experienced three such events. Climate change has significantly affected post-harvest biomass recovery and ABG stocks in our forest plots, especially those related to large trees, which are more vulnerable than others (Flores et al., 2024; Marengo et al., 2011). Yet, the trees under the RIL treatment seemed to be more resilient than those in the CL plot. Therefore, promoting more sustainable forest management practices seems critical to achieving climate change mitigation.

Improving allometric equations for biomass estimation is also crucial for enhancing carbon sequestration calculations and better understanding forest carbon dynamics in selectively managed tropical forest, particularly for REDD+ activities. Our results suggest that the RIL treatment contributed even more climate change mitigation than previously estimated (Mazzei et al., 2010; Vidal et al., 2016; West et al., 2014).

5. Conclusions

Our findings suggest that the implementation of RIL is an effective strategy for accelerating post-logging AGB recovery rates, serving as a mitigation measure against climate change. The utilization of RIL resulted in the least impact on residual biomass at the plot level and expedited AGB recovery to over 100 % within 13 years of harvesting. In contrast, the CL plot remained 14 % below the original pre-harvest stock. After 24 years post logging, AGB stocks recovered to 128 % in the RIL plot, contrasting with only 86 % in the CL plot, whereas the control forest retained at 93 % of its original stock. Hence, this study reaffirms previous research advocating for the transition from CL to RIL, as well as the still untapped potential of RIL activities to mitigate greenhouse gas emissions from forest degradation under the REDD+

mechanism.

CRediT authorship contribution statement

Rodrigo Costa Pinto: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Thales A.P. West:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Edson Vidal:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by the State of São Paulo Research Foundation (FAPESP; grants 2024/04038-7, 2022/09047-9, 2009/132775, 2019/25820-7, 2022/10454-8). E. V. thanks the National Council for Scientific and Technological Development (CNPq) for a productivity grant (311416/2022-5). T.A.P.W. thanks the CNPq for grant 201138/2012-3 (01300.004770/2024-95). The first author extends gratitude to the International Tropical Timber Organization (ITTO) for the 2021 Autumn Cycle Fellowship Awardees (084/21A), whose support propelled the development of this work.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100717.

Data availability

The authors are unable or have chosen not to specify which data has been used.

References

Alvares, C.A., Stape, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorol. Zeitschrift 22, 711–728. https://doi.org/10.1127/0941-2948/2013/0507.

Angelsen, A., 2008. REDD models and baselines. Int. For. Rev. 10, 465–475. https://doi.org/10.1505/IFOR.10.3.465.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N., 2005. Ecology: selective logging in the Brazilian Amazon. Science 310 (80–), 480–482. https://doi.org/10.1126/science.1118051.

Barreto, P., Amaral, P., Vidal, E., Uhl, C., 1998. Costs and benefits of forest management for timber production in eastern Amazonia. For. Ecol. Manage. 108, 9–26. https://doi.org/10.1016/S0378-1127(97)00251-X.

Baskerville, G.L., 2011. Use of Logarithmic Regression in the Estimation of Plant Biomass. 2, 49–53. 10.1139/X72-009.

Bennett, A.C., Mcdowell, N.G., Allen, C.D., Anderson-Teixeira, K.J., 2015. Larger trees suffer most during drought in forests worldwide. Nat. Plants 2015 110 (1), 1–5. https://doi.org/10.1038/nplants.2015.139.

Betts, R.A., Malhi, Y., Roberts, J.T., 2008. The future of the Amazon: new perspectives from climate, ecosystem and social sciences. Philos. Trans. R. Soc. B Biol. Sci. 363, 1729–1735. https://doi.org/10.1098/RSTB.2008.0011.

Blanc, L., Echard, M., Herault, B., Bonal, D., Marcon, E., Chave, J., Baraloto, C., 2009. Dynamics of aboveground carbon stocks in a selectively logged tropical forest. Ecol. Appl. 19, 1397–1404. https://doi.org/10.1890/08-1572.1.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G., Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. Ecol. Lett. 12, 351–366. https://doi.org/10.1111/J.1461-0248.2009.01285.X.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Chang. Biol. 20, 3177–3190. https://doi.org/10.1111/GCB.12629.

Ellis, P.W., Gopalakrishna, T., Goodman, R.C., Putz, F.E., Roopsind, A., Umunay, P.M., Zalman, J., Ellis, E.A., Mo, K., Gregoire, T.G., Griscom, B.W., 2019. Reduced-impact logging for climate change mitigation (RIL-C) can halve selective logging emissions from tropical forests. For. Ecol. Manage. 438, 255–266. https://doi.org/10.1016/J.FORECO.2019.02.004/REDUCED_IMPACT_LOGGING_FOR_CLIMATE_CHANGE_MITIGATION_RIL_C_CAN_HALVE_SELECTIVE_LOGGING_EMISSIONS_FROM_TROPICAL_FORESTS.PDF.

Erdmann, A.A., 2019. Fatores Que Influenciam a Dinâmica Florestal Após Exploração De Madeira Na Amazônia brasileira. Universidade de São Paulo, Piracicaba. https://doi.org/10.11606/T.11.2019.tde-02092019-095634.

Flores, B.M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R.A., Levis, C., Lapola, D.M., Esquível-Muelbert, A., Jakovac, C., Nobre, C.A., Oliveira, R. S., Borma, L.S., Nian, D., Boers, N., Hecht, S.B., ter Steege, H., Arieira, J., Lucas, I.L., Berenguer, E., Marengo, J.A., Gatti, L.V., Mattos, C.R.C., Hirota, M., 2024. Critical transitions in the Amazon forest system. Nat. 626, 555–564. https://doi.org/10.1038/s41586-023-06970-0, 2024 6267999.

Johns, J.S., Barreto, P., Uhl, C., 1996. Logging damage during planned and unplanned logging operations in the eastern Amazon. For. Ecol. Manage. 89, 59–77. https://doi.org/10.1016/S0378-1127(96)03869-8.

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: results from the FAO Global Forest Resources Assessment 2015. For. Ecol. Manage. 352, 9–20. https://doi.org/10.1016/J.FORECO.2015.06.014.

Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., Rodriguez, D.A., 2011. The drought of 2010 in the context of historical droughts in the Amazon region. Geophys. Res. Lett. 38. https://doi.org/10.1029/2011GL047436.

Mazzei, L., Sist, P., Ruschel, A., Putz, F.E., Marco, P., Pena, W., Ferreira, J.E.R., 2010. Above-ground biomass dynamics after reduced-impact logging in the Eastern Amazon. For. Ecol. Manage. 259, 367–373. https://doi.org/10.1016/J.FORECO.2009.10.031.

Nepstad, D.C., Veríssimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., Brooks, V., 1999. Large-scale impoverishment of amazonian forests by logging and fire. Nature 398, 505–508. https://doi.org/10.1038/19066.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333 (80–), 988–993. https://doi.org/10.1126/SCIENCE.1201609/SUPPL_FILE/PAPV2.PDF.

Phillips, O.L., Aragão, L.E.O.C., Lewis, S.L., Fisher, J.B., Lloyd, J., López-González, G., Malhi, Y., Monteagudo, A., Peacock, J., Quesada, C.A., Van Der Heijden, G., Almeida, S., Amaral, I., Arroyo, L., Aymard, G., Baker, T.R., Bánki, O., Blanc, L., Bonal, D., Brando, P., Chave, J., De Oliveira, Á.C.A., Cardozo, N.D., Czimczik, C.I., Feldpausch, T.R., Freitas, M.A., Gloor, E., Higuchi, N., Jiménez, E., Lloyd, G., Meir, P., Mendoza, C., Morel, A., Neill, D.A., Nepstad, D., Patiño, S., Peñuela, M.C., Prieto, A., Ramírez, F., Schwarz, M., Silva, J., Silveira, M., Thomas, A.S., Steege, H. Ter, Stropp, J., Vásquez, R., Zelazowski, P., Dávila, E.A., Andelman, S., Andrade, A., Chao, K.J., Erwin, T., Di Fiore, A., Honorio, E.C., Keeling, H., Killeen, T.J., Laurance, W.F., Cruz, A.P., Pitman, N.C.A., Vargas, P.N., Ramírez-Angulo, H., Rudas, A., Salamão, R., Silva, N., Terborgh, J., Torres-Lezama, A., 2009. Drought sensitivity of the amazon rainforest. Science 323 (80–), 1344–1347. https://doi.org/10.1126/SCIENCE.1164033/SUPPL_FILE/PHILLIPS.SOM.PDF.

Piponiot, C., Rutishauser, E., Derroire, G., Putz, F.E., Sist, P., West, T.A.P., Descroix, L., Guedes, M.C., Coronado, E.N.H., Kanashiro, M., Mazzei, L., D'Oliveira, M.V.N., Peña-Claros, M., Rodney, K., Ruschel, A.R., Souza, C.R.de, Vidal, E., Wortel, V., Hérault, B., 2019. Optimal strategies for ecosystem services provision in Amazonian production forests. Environ. Res. Lett. 14, 124090. https://doi.org/10.1088/1748-9326/ab5eb1.

Piponiot, C., Sist, P., Mazzei, L., Peña-Claros, M., Putz, F.E., Rutishauser, E., Shenkin, A., Ascarrunz, N., de Azevedo, C.P., Baraloto, C., França, M., Guedes, M., Coronado, E.N. H., d'Oliveira, M.V.N., Ruschel, A.R., da Silva, K.E., Sotta, E.D., de Souza, C.R., Vidal, E., West, T.A.P., Hérault, B., 2016. Carbon recovery dynamics following disturbance by selective logging in amazonian forests. Elife 5. https://doi.org/10.7554/eLife.21394.

Putz, F.E., Dykstra, D.P., Heinrich, R., 2000. Why Poor Logging Practices Persist in the TropicsPorque Persisten las Prácticas Madereras Deficientes en los Trópicos. Conserv. Biol. 14, 951–956. https://doi.org/10.1046/J.1523-1739.2000.99137.X.

Putz, F.E., Romero, C., Sist, P., Schwartz, G., Thompson, I., Roopsind, A., Medjibe, V., Ellis, P., 2022. Sustained timber yield claims, considerations, and tradeoffs for selectively logged forests. PNAS Nexus 1, 1–7. https://doi.org/10.1093/pnasnexus/pgac102.

Putz, F.E., Zuidema, P.A., Synnott, T., Peña-Claros, M., Pinard, M.A., Sheil, D., Vanclay, J.K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., Zagt, R., 2012. Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. Conserv. Lett. 5, 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x.

R Core Team, 2024. A Language and Environment For Statistical Computing [WWW Document]. R Found. Stat. Comput. Vienna. URL. https://www.r-project.org/ (accessed 3.4.24).

Réjou-Méchain, M., Tanguy, A., Piponiot, C., Chave, J., Hérault, B., 2017. <scp>biomass</scp> : an <scp>r</scp>package for estimating above-ground biomass and its uncertainty in tropical forests. Methods Ecol. Evol. 8, 1163–1167. https://doi.org/10.1111/2041-210X.12753.

Rutishauser, E., Hérault, B., Baraloto, C., Blanc, L., Descroix, L., Sotta, D., Ferreira, J., Kanashiro, M., Mazzei, L., D'oliveira, M.V.N., De Oliveira, L.C., Peña-Claros, M., Putz, F.E., Ruschel, A.R., Rodney, K., Roopsind, A., Shenkin, A., Da Silva, K.E., De Souza, C.R., Toledo, M., Vidal, E., West, T.A.P., Wortel, V., Sist, P., 2015. Current

Biology Rapid tree carbon stock recovery in managed Amazonian forests. Curr. Biol. 25, 775–792. https://doi.org/10.1016/j.
Saatchi, S., Houghton, R.A., Dos Santos Alvalá, R.C., Soares, J.V., Yu, Y., 2007. Distribution of aboveground live biomass in the Amazon basin. Glob. Chang. Biol. 13, 816–837. https://doi.org/10.1111/J.1365-2486.2007.01323.X.
Schepaschenko, D., Chave, J., Phillips, O.L., Lewis, S.L., Davies, S.J., 2019. The Forest Observation System, building a global reference dataset for remote sensing of forest biomass. Sci. Data 6, 198. https://doi.org/10.1038/s41597-019-0196-1.
Shenkin, A., Bolker, B., Peña-Claros, M., Licona, J.C., Putz, F.E., 2015. Fates of trees damaged by logging in Amazonian Bolivia. For. Ecol. Manage. 357, 50–59. https://doi.org/10.1016/j.foreco.2015.08.009.
Sist, P., Rutishauser, E., Peña-Claros, M., Shenkin, A., Hérault, B., Blanc, L., Baraloto, C., Baya, F., Benedet, F., da Silva, K.E., Descroix, L., Ferreira, J.N., Gourlet-Fleury, S., Guedes, M.C., Bin Harun, I., Jalonen, R., Kanashiro, M., Krisnawati, H., Kshatriya, M., Lincoln, P., Mazzei, L., Medjibé, V., Nasi, R., d'Oliveira, M.V.N., de Oliveira, L.C., Picard, N., Pietsch, S., Pinard, M., Priyadi, H., Putz, F.E., Rodney, K., Rossi, V., Roopsind, A., Ruschel, A.R., Shari, N.H.Z., Rodrigues de Souza, C., Susanty, F.H., Sotta, E.D., Toledo, M., Vidal, E., West, T.A.P., Wortel, V., Yamada, T., 2015. The Tropical managed forests Observatory: a research network addressing the future of tropical logged forests. Appl. Veg. Sci. 18, 171–174. https://doi.org/10.1111/avsc.12125.
Smith, M.N., Stark, S.C., Taylor, T.C., Ferreira, M.L., de Oliveira, E., Restrepo-Coupe, N., Chen, S., Woodcock, T., dos Santos, D.B., Alves, L.F., Figueira, M., de Camargo, P.B., de Oliveira, R.C., Aragão, L.E.O.C., Falk, D.A., McMahon, S.M., Huxman, T.E., Saleska, S.R., 2019. Seasonal and drought-related changes in leaf area profiles depend on height and light environment in an Amazon forest. New Phytol 222, 1284–1297. https://doi.org/10.1111/NPH.15726.
Uhl, C., Buschbacher, R., Serrao, E.A.S., 1988. Abandoned Pastures in Eastern Amazonia. I. Patterns of Plant Succession. J. Ecol. 76, 663. https://doi.org/10.2307/2260566.
UN-REDD, 2023. PRICING FOREST CARBON. Geneva, Switzerland.
Verissimo, A., Barreto, P., Mattos, M., Tarifa, R., Uhl, C., 1992. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. For. Ecol. Manage. 55, 169–199.
Vidal, E., West, T.A.P., Putz, F.E., 2016. Recovery of biomass and merchantable timber volumes twenty years after conventional and reduced-impact logging in Amazonian Brazil. For. Ecol. Manage. 376, 1–8. https://doi.org/10.1016/j.foreco.2016.06.003.
West, T.A.P., Vidal, E., Putz, F.E., 2014. Forest biomass recovery after conventional and reduced-impact logging in Amazonian Brazil. For. Ecol. Manage. 314, 59–63. https://doi.org/10.1016/j.foreco.2013.11.022.
Wright, S.J., 2010. The future of tropical forests. Ann. N. Y. Acad. Sci. 1195, 1–27. https://doi.org/10.1111/J.1749-6632.2010.05455.X.

Further reading

Baskerville, G.L., 1972. Use of Logarithmic Regression in the Estimation of Plant Biomass. Can. J. For. Res. 2, 49–53. https://doi.org/10.1139/x72-009.