Carbon sequestration potential in the Amazon rainforest using best management practices

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Abstract

The objective of this study was to verify the potential that public areas in the Brazilian Amazon have for sequestering carbon, if better management techniques were applied. The data came from the municipality of Paragominas-PA, three treatments were applied, (i) area without logging (Control), (ii) conventional logging (CL) and reduced impact logging (RIL), totaling 15.75 ha measured. All trees with a diameter at 1.3 m above the ground (dbh) greater than 10 cm were measured on 12 occasions between the years 1993 and 2023. The Gompertz biological model was applied to predict aboveground biomass stocks. After 30 years, the biomass balance was 40.1, -20.3 and 20.8 $Mg.ha^{-1}$ for the RIL, CL and control treatments, respectively. RIL (328.85 $Mg.ha^{-1}$) presented maximum stocks adjusted by the Gompertz model that were statistically higher than CL (241.59 $Mg.ha^{-1}$) and control (198.41 $Mg.ha^{-1}$). By managing the forest with RIL, the gains in biomass stock were 18.2%. If these gains were applied to public forests in the Amazon, it would be possible to absorb 21.4% of the total Brazilian emissions between 1993 and 2023, totaling the removal of 15.1 billion tons of CO_2e.

Keywords: Reduced Impact Logging, Conventional Logging, Gompertz model, Tropical Forest.

1 Introduction

Forests account for approximately 90% of terrestrial carbon (C) storage and sequester about 7.6 billion tons of carbon dioxide equivalents (CO_2e) from the atmosphere annually (Pan et al., 2013; Harris et al., 2021). They play a pivotal role in the global

terrestrial C cycle. A substantial share of this sink originates from old-growth tropical forests, such as the Amazon, which harbors an estimated 175 ± 25 PgC in aboveground biomass (AGB) (Saatchi et al., 2007; Malhi et al., 2009; Marques et al., 2017; Baccini et al., 2017)—one of Earth's largest carbon reservoirs (McKay et al., 2022). Yet, accelerated C release from these forests could exacerbate global warming (Harris et al., 2021).

The Amazon holds 49% of global tropical biomass C (Saatchi et al., 2011) and spans one-third of South America's land area (Goulding et al., 2003). Increasing fragmentation and degradation threaten its stability, potentially altering global C dynamics. Despite remaining a net sink (~430 Tg C yr^{-1}) (Phillips et al., 2017), long-term studies (~30 years) in permanent plots reveal declining sequestration rates (Brienen et al., 2015; Hubau et al., 2020). Much of the absorbed C recirculates rapidly via respiration (10-20 years) (Chanca et al., 2025), risking a shift to net emissions driven by degradation (~0.36 Pg C yr^{-1}), deforestation (~0.13 Pg C yr^{-1}), and heightened tree mortality from droughts (Gatti et al., 2021).

Sustainable forest management emerges as a key strategy to bolster C sequestration and storage (e.g., Putz et al., 2008; West et al., 2014; Chazdon et al., 2016; Vidal et al., 2016; Pinto et al., 2024, 2025). In Brazil, regulations mandate cutting cycles of 25-35 years and harvest limits of 21-35 m^3 ha^{-1}, with minimum cutting diameters (MCD) for trees ≥ 50 cm DBH (Brazil, 2006, 2009; Vidal et al., 2020). Reduced Impact Logging (RIL) excels by minimizing damage through pre-planned roads, vine removal, and directional felling, preserving regeneration and structure (Putz et al., 2012; West et al., 2014; Vidal et al., 2016).

Permanent plots in the Brazilian Amazon, established since the 1950s (Sist et al., 2007; Putz et al., 2012), underpin efforts to enhance management beyond timber, including C sequestration (243 Tg C yr^{-1}) (Phillips et al., 2016). Programs like REDD+ and Improved Forest Management (IFM) underscore these priorities.

Accurate C stock estimates are vital for tracking deforestation/degradation losses, regeneration gains, and sequestration potential (Pinto et al., 2024, 2025), informing conservation policies (Harris et al., 2021). Long-term monitoring in permanent plots is essential, with large trees (DBH > 110 cm) critical for post-logging AGB recovery (Sist et al., 2014).

This study addresses four key questions: (i) Biomass and C sequestration under conventional vs. RIL logging; (ii) CO_2e removal potential in Brazilian public forests; (iii) Large trees' contribution to biomass balance; (iv) Time for managed forests to surpass unlogged C levels post-harvest. These insights support policies balancing productivity and mitigation.

With most tropical forests outside reserves facing selective logging, enhancing sequestration is crucial for climate goals. Hypotheses: (i) RIL-logged forests sequester more C than conventionally logged ones; (ii) RIL positions public forests as C sinks. We modeled biomass and C dynamics 30 years post-logging to assess sequestration potential in eastern Brazilian Amazon public forests under improved management. Results from permanent plots evaluate medium-term sustainable management effects under two scenarios.

2 Materials and methods

This study utilized data from a forest management area established in 1993, located in the municipality of Paragominas, Pará, Brazil (Figure 1), spanning coordinates 2°25'–4°09' S and 46°25'–48°54' W. The regional climate is classified as Am (Köppen), featuring mean annual temperatures exceeding 26°C and precipitation ranging from 1,600 to 2,200 mm (Alvares et al., 2013). Topography is predominantly flat to gently undulating, with soils mainly dystrophic Yellow Latosols (Pinto et al., 2009). The vegetation is characterized as Dense Tropical Forest (IBGE, 2012).

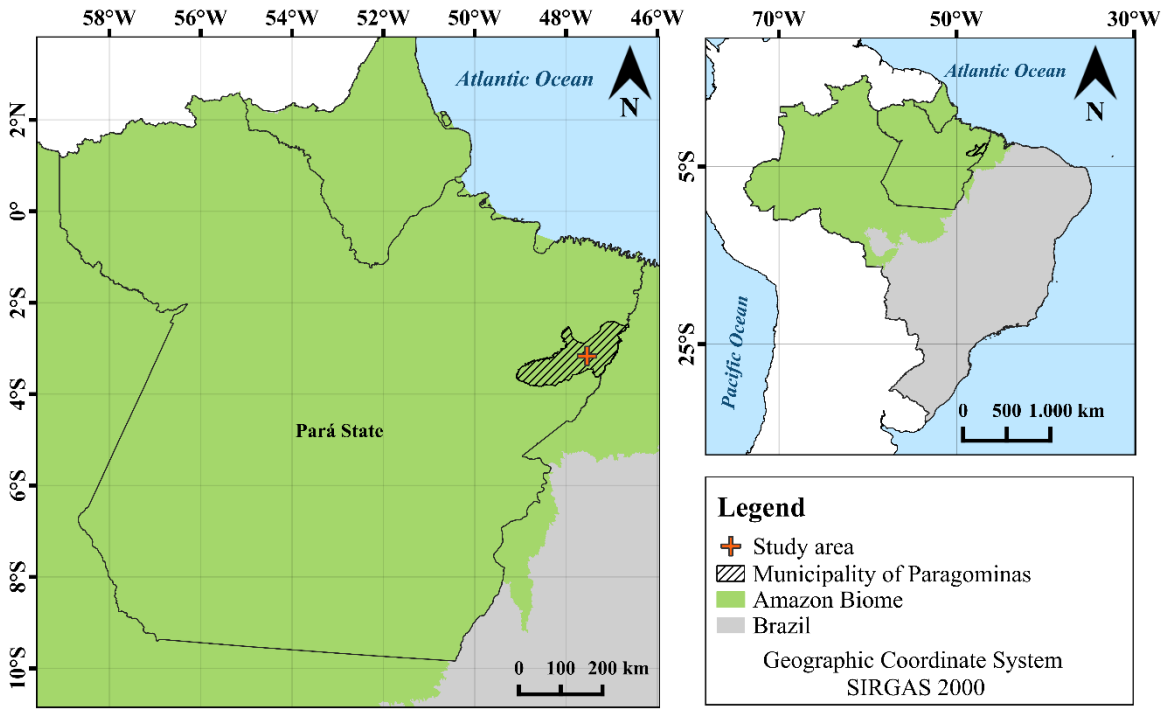

Figure 1: Location of the study area in the Amazon biome, Brazil. Source: The authors.

Data were collected from three treatments across 15.75 ha: an unlogged control and two logging systems—conventional logging (CL) and reduced-impact logging (RIL)—each in 75 × 700 m permanent plots (5.25 ha total per treatment). All trees with dbh ≥ 10 cm (measured at 1.3 m) were censused pre-logging (1993) and post-logging (1994, 1995, 1996, 1998, 2000, 2003, 2006, 2009, 2014, 2017, 2023), spanning 30 years of dynamics.

Harvest volumes were comparable between systems, but extracted timber differed by ~30% (38.6 m^3 ha^{-1} for RIL vs. 29.7 m^3 ha^{-1} for CL; Barreto et al., 1998). Felled biomass was 48.8 Mg ha^{-1} (RIL) and 71.4 Mg ha^{-1} (CL; Table 1). RIL minimized damage via planning, directional felling, and skilled crews, reducing stump waste and cracks. Full details on methods and management are in Barreto et al. (1998), West et al. (2012), Vidal et al. (2016), and Pinto et al. (2024).

Table 1. Details of the logging intensities of the two management systems (reduced-impact logging-RIL and conventional logging-CL) applied in the study area in the Eastern Amazon, in Paragominas, Pará State, Brazil. Source: adapted from Barreto et al. (1998).

Characteristics of Logging	RIL	CL

Volume extracted ($m^3.ha^{-1}$)	38.6	29.7
Trees extracted ($Tree.ha^{-1}$)	4.5	5.6
Basal area extracted ($m^2.ha^{-1}$)	2.2	2.3
Biomass extracted ($Mg.ha^{-1}$)	48.8	71.4

Once the data was in hand, modeling began with biomass calculations. The BIOMASS package (Rejou-Mechain et al., 2017) of the R software (R Core Team, 2025) was used to estimate the tree biomass of each tree. This package uses the equation $y = e^{(-2.024-0.896 \cdot E+0.920 \cdot ln(\rho)+2.795 \cdot ln(DBH)-0.0461 \cdot ln[ln(DBH)^2])} + \varepsilon$, to estimate biomass. There are three predictor variables in the equation: (i) E is a measure of environmental stress (calculated with the forest coordinates). E varies as a function of temperature seasonality, climatic water deficit, and precipitation seasonality (Chave et al., 2014), (ii) ρ is the wood density of each tree (in $g.cm^{-3}$) and, (iii) dbh is the diameter at 1.3 meters above the soil (in cm). The ρ can be assigned to a tree according to its species, genus, family or forest (Chave et al., 2009).

The biomass data for each tree were converted to carbon per tree using a conversion factor of 0.47 (IPCC, 2006). These data were subsequently converted to biomass and carbon per hectare ($Mg.ha^{-1}$). Then, the Gompertz biological model (01) was adjusted to the different treatments tested (Tjørve and Tjørve, 2017; Kruchelski et al., 2022; Vidal et al., 2026). These adjustments were made for the biomass variable in $Mg.ha^{-1}$.

$$y = \beta_0 \cdot e^{(-e^{(\beta_1 - \beta_2 \cdot I)})} + \varepsilon \quad (01)$$

Where: y is the total aboveground biomass (in $Mg.ha^{-1}$), β_i are the coefficients of the non-linear regression models, I is the post-logging age (in years), ε is the residual in the adjusted model.

The equations were evaluated by R^2, Akaike Information Criterion (AIC – Akaike, 1974) and RMSE% as shown in (02) to (04).

$$R^2 = Cor(y_i, \hat{y}_i)^2 \quad (02)$$

$$AIC = 2p - 2\ln(\hat{L}) \quad (03)$$

$$RMSE\% = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}}{\bar{y}} \cdot 100 \quad (04)$$

Where: Cor is the correlation between the actual values (y_i) and those estimated by the model ($\hat{y}_i$); $RMSE$ is the root mean square error, in Mg.ha^{-1}; y_i is the biomass of year i, in Mg.ha^{-1}; $\hat{y}_i$ is the estimated biomass for year i, in Mg.ha^{-1}; $\bar{y}$ is the estimated mean biomass for each treatment, in Mg.ha^{-1}; n is the number of observations in years for each treatment.

The likelihood ratio test (Regazzi, 2003; Kruchelski et al., 2022) was applied to test whether the equations and their coefficients (H_0) generated for all treatments were statistically equal. This test is the ratio of the maximum likelihood of the full model, all different coefficients for each treatment, and the maximum likelihood of the reduced model, which is with one or more equal coefficients. If the restriction is applied to all coefficients, the test represents identity between the evaluated treatments. Otherwise, the test assesses whether the restricted coefficients are equivalent.

For large samples, the test statistic follows a chi-square distribution (05) with $\nu = k_\Omega - k_w$ degrees of freedom, where k_Ω and k_w are the number of coefficients of the full and reduced model, respectively, and can be calculated as follows (Regazzi, 2003):

$$\chi^2_{calc} = -nln\left(\frac{SQR_\Omega}{SQR_w}\right) \quad (05)$$

Where: SQR is the sum of squares of the residuals, Ω denotes the full model, w indicates the reduced model (under coefficient restriction), n is the number of observations, and ln is the natural logarithm.

If the calculated value is greater than the tabulated value ($\alpha = 0.05$), the null hypothesis is rejected and it is concluded that there is no equality between the coefficients under restriction. With the identification of a difference between the coefficients, a paired comparison was carried out between the different managements. If the coefficients showed differences between the managements, the model presented in (01) was adjusted for each management.

The forest structure assessment was carried out by applying two indices presented by Machado et al. (2025), which use biomass as an ecological indicator. The first index presented in (06) provided the degree of evolution of the forest structure, while the second index (07) represented the forest's potential to increase biomass stocks. As a reference, we used the estimates provided by Mazzei et al. (2010) and Sist et al. (2014), which mention

average stocks of 409 Mg.ha^{-1} for AGB, for Dense Tropical Forests in the study region. This reference was chosen due to its proximity to the present study area and because it represents a climax forest stock in the region.

$$Index_1 = \frac{K}{T} \quad (06)$$

$$Index_2 = \frac{B}{L} \quad (07)$$

Where: K is the biomass of trees over 40 cm dbh in Mg, T is the total tree biomass in Mg, B is the total tree biomass per hectare in Mg.ha^{-1} and L is the potential tree biomass for tropical forests in Mg.ha^{-1}.

$Index_1$ provides an analysis of biomass allocation and forest structure (Machado et al., 2025). The closer it is to a value, the greater the biomass stock in large trees and the closer the forest is to climax. $Index_2$ shows the area's stock potential, that is, how much the forest can increase its biomass stock. $Index_2$ represents a relationship between the forest's regeneration stage and the biomass stock of a climax forest. The actual values found in the area were used for the structure calculations, not the Gompertz model estimates.

3 Results

3.1 Modeling and potential of biomass and carbon stocks in the forest

At the end of the first logging cycle, RIL showed faster biomass and tree carbon recovery (Figure 2) compared to CL. When evaluating the dynamics through the generated equations, the biomass balance after 30 years of evaluation (compared to the original stocks) was 40.1, -20.3, and 20.8 Mg.ha^{-1} for the RIL, CL, and control treatments, respectively. Biomass removal at logging was 71.4 and 48.8 Mg.ha^{-1} for CL and RIL, respectively. Final stocks estimated by the Gompertz equations were 261.2, 221.9, and 198.1 Mg.ha^{-1} for RIL, CL, and control, respectively. The annual biomass increase rates estimated by the equations were 3.03, 1.84, and 0.78 Mg.ha^{-1}.year^{-1} for RIL, CL, and control, respectively.

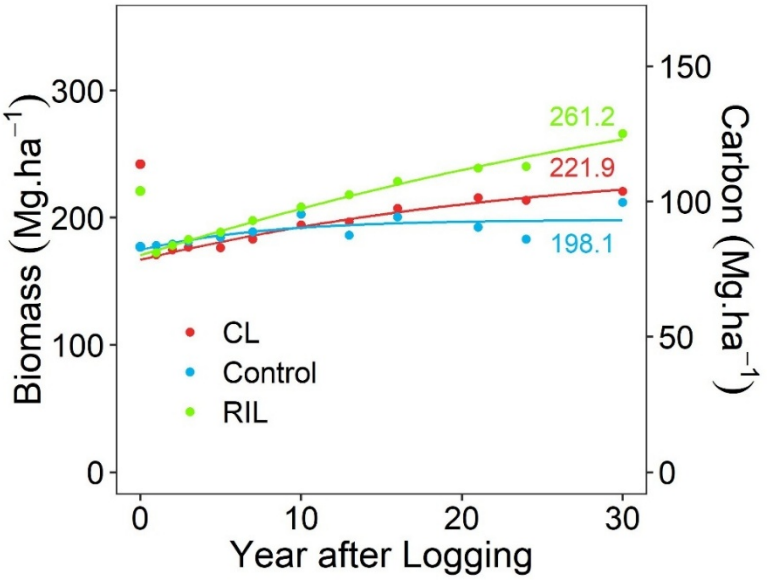

Figure 2: Biomass and carbon dynamics for the forest 30 years after harvest, the biomass values in the figure represent the value estimated by the Gompertz model, data collected in the Amazon rainforest area, Paragominas - PA. Source: The authors.

The RIL presented (328.85 Mg.ha^{-1}) asymptotic maximum stocks (Table 2) adjusted by the Gompertz model statistically superior (Tables 3 and 4) to the CL (241.59 Mg.ha^{-1}) and control (198.41 Mg.ha^{-1}). When evaluating the statistics, it was observed that the Gompertz model obtained adherence to the three treatments, however, with superior statistics for the RIL compared to the CL and control.

Table 2. Estimated coefficients and fit statistics of the Gompertz model applied to the different treatments, Control, Conventional Logging (CL) and Reduced Impact Logging (RIL), 30 years (I) after logging in a dense tropical forest area in the eastern Amazon, in Paragominas-PA, Brazil. Source: The authors.

Treatments	Equation	RMSE (Mg.ha^{-1})	RMSE (%)	AIC	R^2
Control	$y = 198.41 \cdot e^{(-e^{(-2.0546-0.1367.I)})}$	8.868	4.67	83.73	0.47
CL	$y = 241.59 \cdot e^{(-e^{(-0.9932-0.0493.I)})}$	2.993	1.54	59.83	0.98
RIL	$y = 328.85 \cdot e^{(-e^{(-0.4189-0.0351.I)})}$	3.459	1.64	63.01	0.99

Table 3. Calculated values of the likelihood ratio test (χ^2_{calc}) for all combinations between the control, Conventional Logging (CL) and Reduced Impact Logging (RIL) treatments, together with the coefficient constraints of the Gompertz model, for the dense tropical

forest area in the eastern Amazon 30 years after logging, in Paragominas-PA, Brazil. Source: The authors.

Treatments	Restriction						
	$\beta_0, \beta_1, \beta_2(H_0)$	$\beta_0, \beta_1(H_1)$	$\beta_0, \beta_2(H_2)$	$\beta_1, \beta_2(H_3)$	$\beta_0(H_4)$	$\beta_1(H_5)$	$\beta_2(H_6)$
Todos	67.40	11.54	46.71	43.10	5.82	13.53	4.69
Control, CL	14.91	7.42	14.91	13.08	0.66	7.29	0.38
Control, RIL	45.48	4.76	31.75	30.20	3.50	8.97	0.48
CL, RIL	59.62	5.35	38.38	29.69	5.35	5.35	0.90

Marked values (gray cells) indicate non-rejection of the null hypothesis (α=0.05), configuring equivalence between the coefficient for the tested treatment. β_i, model coefficient; and H_i, tested coefficient restriction hypotheses.

Table 4. Relationship (Restriction) between the asymptotes (β_0 (H_4) in Mg.ha^{-1}) of the Gompertz model to compare the treatments, Control, Conventional Logging (CL) and Reduced Impact Logging (RIL) for the dense tropical forest area in the eastern Amazon 30 years after logging, in Paragominas-PA, Brazil. Source: The authors.

Treatments	Asymptote (Mg.ha^{-1})
Control	198.41 b
CL	241.59 b
RIL	328.84 a

Equal letters in the same column represent statistical equality, based on the equality between coefficients of the maximum likelihood test (Table 3).

The identity of the fitted equations for the three treatments was not observed (Table 3), that is, with the restriction on the three coefficients, all fitted curves presented statistical differences. When evaluating the identity of the fitted equations for only one coefficient, equality of coefficients was observed when the treatments were evaluated in pairs. As in the evaluation of the equality of the control equations with conventional exploration, in which the coefficient restrictions H_4 and H_6 presented statistically equal coefficients.

3.2 Structural recovery responses in cutting cycles

In the evaluation of the forest structure ($Index_1$), it was observed that for CL and control there was a reduction in the estimated values from 0.555 to 0.511 and 0.540 to 0.486, respectively (Table 5). When evaluated for the RIL, an increase in the value for

$Index_1$ from 0.513 to 0.518 was observed, evidencing the benefits of applying better management practices. As observed by the biomass stock balance, CL was the only treatment that decreased its biomass stock. $Index_2$ showed a reduction in the potential biomass stock from 0.592 to 0.543 in the CL. For the control and RIL areas, there was an increase in the potential biomass stock from 0.436 to 0.484 and from 0.541 to 0.639, respectively. All these trends are for 30 years after logging.

Table 5: Ecological indicators based on tree biomass for the control area of conventional logging (CL) and reduced impact logging (RIL) treatments in eastern Amazonian forests 30 years after logging in Paragominas, Pará, Brazil. Source: The authors.

Treatment	$Index_1$		$Index_2$	
	Forest age based on logging			
	0	30	0	30
Control	0.540	0.486	0.436	0.484
CL	0.555	0.511	0.592	0.543
RIL	0.513	0.518	0.541	0.639

4 Discussion

4.1 Modeling and potential of biomass and carbon stocks in the forest

RIL presented the largest biomass and carbon stocks 30 years after logging (Figure 2). This is due to the best practices of the exploration maids, mainly due to the lesser damage caused to the remaining trees, a vast literature highlights all the gains of the RIL system (Pinard and Putz, 1997; Putz et al., 2008; Mazzei et al., 2010; Miller et al., 2011; Putz et al., 2012; Bicknell et al., 2014; Burivalova et al., 2014; West et al., 2014; Bedrij et al., 2022; Sullivan et al., 2022; d'Oliveira et al., 2024; Pinto et al. 2024). Among these benefits are, as the maintenance of carbon and water cycles (Longo et al., 2020), associated with pre-logging practices such as mapping and selective cutting of trees of commercial interest, liana management through cutting, planning of trails and skid roads (Pinard e Putz, 1997, Miller et al., 2011) as well as directional cutting (Putz et al., 2008). RIL practices have a lower impact on forest structure (Sullivan et al., 2022; d'Oliveira et al., 2024), enabling the maintenance of species diversity (Bicknell et al., 2015) and biomass stocks (Pinto et al., 2024). CL is not based on maximizing the protection of remaining trees,

whether during felling or timber removal. Thus, the damage caused to the forest is greater and harms the forest; the biomass removed during logging (Figure 2) reflects these negative effects on the forest structure (Table 5). Conversely, RIL substantially mitigates these effects by minimizing canopy opening and understory disturbance (d'Oliveira et al., 2024). As a consequence, RIL reduces structural degradation that typically leads to increased light penetration, increased grass cover, and the establishment of fast-growing, low-wood-density pioneer species (Barlow et al., 2016; Both et al., 2019).

The application of the Gompertz biological model proved efficient, with RMSE below 5% for all treatments (Table 2). The literature mentions that errors below ~10% indicate robust estimates of aboveground biomass (AGB). However, when estimates are obtained through models based on individual trees, errors tend to be higher, ranging from approximately 20% to 50% (Chave et al., 2014; Balbinot et al., 2019; Trautenmüller et al., 2021; 2023; Machado et al., 2025). This demonstrates that modeling per unit area is one way to reduce errors in biomass and carbon estimates.

Biological models have fundamental structural properties for evaluating forests, among which the asymptote stands out, representing the maximum average that the treatment can reach over time. This characteristic is essential for interpreting growth potential and forest response in long-term scenarios. The RIL presented a higher asymptote (Tables 2 and 3), demonstrating its full potential to increase biomass and carbon stocks in managed areas. The asymptotic value for the RIL treatment was 26.5% (328.85 $Mg.ha^{-1}$) higher than that for the CL treatment (241.59 $Mg.ha^{-1}$). The area logged with "best management practices" (RIL) returned its carbon stocks within 30 years after logging and exceeded the initial stocks of the CL, which was the area with the largest stocks before logging. Although the aforementioned vast literature portrays the benefits of applying RIL for sustainability, maintaining biodiversity, and providing ecosystem services, RIL has emerged as a way to mitigate the effects of climate change by transforming managed forests from CO_2 emitters to CO_2 sinks.

Based on this information, what would be the climate mitigation benefits of applying RIL in Amazon forests? What would be the carbon sequestration potential with these best management practices? The scientific community agrees that applying RIL offers several benefits for forests and climate change mitigation. However, the potential for

carbon sequestration is not yet unanimous. This study performed a simple simulation based on the data presented.

In 2020, public areas in the Brazilian Amazon totaled approximately 276,587,070 ha (Salomão et al. 2021), classified as Indigenous lands, conservation units, and non-designated lands. The implementation of Reduced Impact Logging (RIL) in these forests resulted in an 18.2% increase in biomass stocks, highlighting its potential as an effective approach to promote the sustainable use of forest resources and, simultaneously, strengthen carbon stocks on a large scale.

Through a simple simulation, by applying the average biomass gains obtained with Reduced Impact Logging (RIL) to the public forests of the Amazon, it is estimated that it would be possible to offset approximately 21.4% of Brazil's total emissions between 1993 and 2023. This percentage represents a potential and depends heavily on: (i) the fraction of area actually eligible for management, (ii) the transferability of the +18.2% gain to the entire public Amazon, and (iii) the time horizon, that is, the permanence of the additional stock. This would correspond to the removal of approximately 15.1 $GtCO_2e$, according to data from the Greenhouse Gas Emissions and Removals Estimation System (SEEG) (https://seeg.eco.br/). When using the potential annual gains (501.8 $MtCO_2e$) and an average value of US$ 30.00 per ton, these areas would have the potential to generate US$ 15 billion per year in Brazil.

Reduced Impact Logging (RIL) represents a strategic alternative to curb the advance of deforestation in the Amazon. Between 2019 and 2020, approximately 44% of forest loss occurred on public lands. From 1997 to 2020, more than 21 million hectares were deforested around ~8% of the public forests in the Brazilian Amazon, an area larger than the state of Paraná, Brazil. The resulting emissions total 10.2 $GtCO_2$ (Salomão, 2021), equivalent to five years of Brazil's national greenhouse gas emissions (Albuquerque et al. 2020).

We know that commercial logging is not permitted in some of these areas. In-depth studies must be conducted to quantify the areas of public forests suitable for forest management. Simulations like this should be conducted for the planet's tropical forests. Biomass and carbon dynamics models must be adjusted with data from other regions of the

Amazon rainforest to confirm the potential gains in CO_2 accumulation with the application of RIL.

4.2 Structural recovery responses in cutting cycles

In the evaluation of the forest structure of the three treatments of the present study, the biomass stocks were 221.1, 242.2 and 178.3 $Mg.ha^{-1}$ for RIL, CL and Control (values before logging), respectively. We can verify that all biomass values found were lower than the average of 409 $Mg.ha^{-1}$ cited by Mazzei et al. (2010) and Sist et al. (2014). To explain the lower values found in the present study, there are three possibilities: (i) the area has already been exploited in the past, of which there are no records and not all exploitation was found in the first inventory in the area in 1993, but there was a high index of liana infestation; (ii) the productive capacity of the area studied by Mazzei et al. (2010) and Sist et al. (2014) was higher and; (iii) the literature mentions that plot size directly influences biomass estimates (Balbinot et al., 2017; 2019; Trautenmüller et al., 2021; 2023). The sample areas of the present study were 52,500 m^2 (No repetition), while the samples of Mazzei et al. (2010) and Sist et al. (2014) were 10,000 m^2, for each repetition. However, the biomass values found in the present study are close to values cited in the literature as average values for tropical forests. Pan et al. (2013) cited 221.8 $Mg.ha^{-1}$ and Ometto et al. (2023) cited 174.0 $Mg.ha^{-1}$ for tropical forests and the Amazon rainforest, respectively.

Before discussing forest structure indices, it is worth noting that the estimated values for 30 years after logging used biomass stocks estimated by adjusted Gompertz equations. The $Index_1$ revealed that the RIL (from 0.513 to 0.518) was the only treatment that maintained a stable forest successional stage. In anthropized areas, Machado et al. (2025) found a value of 0.404 for this same index in one of the best-preserved areas of the Brazilian Atlantic Forest. This evidence shows that the RIL preserves unharvested medium-sized trees and reduces competition from remaining individuals. Reduced competition and greater availability of resources (water, light, and nutrients) lead to gains in growth and faster passage through the diameter classes of regenerating trees.

Despite the greater biomass removal and increased data on the remaining medium-sized trees, the CL showed a smaller reduction in $Index_1$ (0.540 – 0.511) than the control area. The largest decrease was found in the control area, which dropped from 0.540 to

0.486, indicating that some environmental factor was more important for the reduction in biomass in larger trees. One hypothesis is that climate extremes are more important in destabilizing a forest's structure than logging. In this study, logging with good practices proved beneficial for forest dynamics and maintenance of its structure.

Due to climate change, the occurrence of extreme weather events has been increasing in frequency and intensity (Machado et al., 2025). Old-growth tropical forests, such as the Amazon rainforest, are not adapting as quickly as climate change intensifies. This may be one explanation for the change in forest structure ($Index_1$) in the control area. Droughts are the main climatic event that can influence the dynamics of tropical forests. These extreme weather events, which would normally occur two or three times per century, are occurring more frequently and their intensity is increasing, reflecting climate change. Over the 30 years of monitoring the study area, at least five severe drought events have occurred, including some of the most intense ever recorded since meteorological measurements began in the Brazilian Amazon (beginning in the 1970s). For example, intense El Niño events recorded in 2005, 2010, and 2016, characterized by severe droughts, may have negatively affected the control plots, causing them to release carbon instead of accumulating it. Overall, the results of this study indicate that the application of RIL represents an effective strategy for increasing the resilience and resistance of tropical forests to extreme weather events.

The $Index_2$ provides insight into the biomass stock potential of the studied forest in relation to a climax forest. Only CL decreased the estimated value of the index 30 years after logging, going from 0.592 to 0.543. The largest increase was for the RIL, which went from 0.541 to 0.639, showing that the forest increased its tree biomass and carbon stocks. For the control area, the values of $Index_2$ increased from 0.436 to 0.484, demonstrating a general increase in biomass and carbon stocks in this treatment. Machado et al. (2025) reported an $Index_2$ of 0.316, this forest being one of the best preserved in the Atlantic Forest, located in the Serra do Mar in the state of Paraná-BR, with an area of approximately 4,000 km². This index clearly shows that logging with good practices provides gains in structure and increases in biomass and carbon stocks in managed forests.

The results of this study demonstrate that the application of RIL provides biological gains and maintains forest dynamics, benefiting forest resilience to climate change. These

findings reinforce the need for expanded research on the effects of forest management on carbon stocks and forest dynamics in different regions of the Amazon. Furthermore, it is crucial to advance studies that quantify the extent of areas with potential for sustainable forest management in order to more accurately estimate the potential gains in carbon sequestration resulting from the application of RIL. The improvement and expansion of payment for ecosystem services mechanisms, such as Reducing Emissions from Deforestation and Forest Degradation (REDD+) and Improved Forest Management (IFM), are also essential to encourage the adoption of these practices by tropical forest owners.

There is still uncertainty as to whether the Amazon region will be adequately rewarded for the global value of its ecosystem services in the coming years. To this end, it is crucial to deepen our understanding of how atmospheric CO_2, climate, and indirect anthropogenic factors influence these forests and, conversely, how forests modulate these factors. This progress requires significant and integrated investments in forest monitoring, combining field measurements, remote sensing, and appropriate modeling. Coordination between national and international actions will be essential to ensure that the Amazon's unique contribution to global climate stability is recognized and promoted. Continued encouragement of good management practices is essential to ensure the maintenance of these ecological and socioeconomic benefits in the long term.

Final considerations

The RIL presents a faster recovery of initial stocks of tree biomass and carbon. The RIL presents the greatest future potential for storing biomass and carbon through the asymptote of the Gompertz model.

Forest management in public areas of the Amazon, if carried out with best practices (RIL), has the potential to sequester up to 21.4% of the total greenhouse gas emissions emitted by Brazil between 1993 and 2023.

Despite all the indications of gains from applying reduced-impact management (RIL), some considerations must be made: (i) This work represents a simulation of potential gains; it does not represent actual gains; (ii) Further studies on RIL gains should be conducted in other *terra firme* forests across the eastern and western Amazon, the predominant type used for sustainable management. This study was conducted in situ in

terra firme forests of the eastern Amazon. Expanding assessments to other regions will improve understanding of spatial variability in forest dynamics and carbon stock responses to RIL; (iii) New studies should be conducted to quantify the total public areas of the Amazon that can effectively be managed. (iv) Studies on areas suitable for management should be conducted for private areas, as approximately 25% of the areas are privately owned.

The complexity of future studies on the actual gains in biomass and carbon stocks that management can provide for tropical forests is evident. Studies to quantify the true areas where management can be applied are also highly complex. However, they are necessary, as developed countries must allocate resources for these studies and maintain the sustainability of tropical forests. Forest management generates income from timber sales and conserves nature by keeping forests standing, meaning they maintain their natural resources without changing land use and occupation. It also provides social benefits, enabling a better quality of life for forest producers and reducing forest exodus.

Thus, RIL is not merely a technical forest management tool, but also a strategic instrument for climate-change mitigation, contributing directly to achieving the targets of the Paris Agreement and supporting the global transition toward a low-carbon economy.

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