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Articles

Long-term impact of logging on tree mortality in managed forests: a case study from Paragominas, Pará, Brazil

Impacto da exploração madeireira sobre a mortalidade de árvores remanescentes em uma floresta manejada no município de Paragominas, Pará

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ABSTRACT

Even well-planned logging operations cause damage to remaining trees, which can lead to the mortality of some of them. Understanding the circumstances that influence the mortality of these trees can aid in planning exploratory activities. This study aimed to examine the effects of logging on the mortality of damaged remaining trees, according to the type and severity of damage sustained, over a ten-year monitoring period. The study was conducted in an experimental area located within a forest management unit on the Rio Capim Farm, municipality of Paragominas, state of Pará, Brazil. Eighteen permanent 1-hectare plots were established, where a census of trees with diameter at breast height (DBH) ≥ 20 cm was conducted. Seven measurements were taken: 2004 (before logging), 2005 (after logging), 2006, 2008, 2010, 2012, and 2014. The research found that the annual tree mortality rate was highest in the first two years after logging, with a reduction in mortality rates over the years, reaching approximately 2.3% in the tenth year after logging. A 95% confidence level mean comparison test showed that the mortality of damaged trees is more significant than that of undamaged trees and that from the fourth year after logging onward, the average mortality rates between them equalize. Based on the results, the hypothesis was accepted that the average mortality rate of damaged and undamaged trees becomes equal within ten years after logging.

Keywords: Timber operations; Damaged trees; Mortality

RESUMO

A exploração florestal, ainda que bem planejada, causa danos às árvores remanescentes, podendo levar à mortalidade de algumas delas, logo, o entendimento das circunstâncias que influenciam a mortalidade dessas árvores pode auxiliar no planejamento das atividades exploratórias. Neste contexto este trabalho objetivou estudar os efeitos da exploração madeireira na mortalidade das árvores remanescentes danificadas, de acordo com o tipo e severidade dos danos sofridos, ao longo de um período de dez anos de monitoramento. O estudo foi realizado em uma área experimental situada em uma unidade de manejo florestal na Fazenda Rio Capim, município de Paragominas, estado do Pará. Foram instaladas 18 parcelas permanentes de 1 ha cada, onde foi realizado um censo das árvores com diâmetro na altura do peito (DAP) ≥ 20 cm. Foram realizadas sete medições: 2004 (antes da exploração), 2005 (após a exploração), 2006, 2008, 2010, 2012 e 2014. Observou-se com a pesquisa que a taxa anual de mortalidade de árvores foi máxima nos dois primeiros anos após a colheita florestal, reduzindo nos anos seguintes e alcançando no décimo ano após a colheita o valor aproximado de 2,3%. Além disso, observou-se por teste de comparação de médias a 95% de nível de confiança que a mortalidade das árvores danificadas é mais expressiva que aquelas sem danos e que, a partir do quarto ano após a exploração, a taxa de mortalidade média entre elas se iguala.

Palavras-chave: Exploração madeireira; Árvores danificadas; Taxa de mortalidade

1 INTRODUCTION

The Brazilian Amazon holds a vast wealth of timber and non-timber resources (Ribeiro *et al*., 2018), making it significant in social, environmental, and economic dimensions. Consequently, there is constant national and international pressure to conserve its ecosystem services and biodiversity, aiming to develop practices that reconcile resource utilization with the forest's regenerative capacity (Becker, 2016). For the sustainable use of forest resources, it is necessary to employ reduced-impact logging (RIL) techniques, monitor forest dynamics, and apply silvicultural treatments to the remaining forest (Sabogal *et al*., 2000), thereby minimizing damage to residual trees (Figueiredo *et al*., 2016).

Even when planned, logging affects various ecological, biogeochemical, and micrometeorological processes in the forest (Asner *et al*., 2004). Its impact can persist for years as the canopy regenerates and fills gaps (Miller *et al*., 2008). Harvesting activities strongly alter the forest structure, being the primary cause of tree mortality during logging operations (Holmes *et al*., 2004). However, planned logging results

in lower vegetation impact compared to unplanned operations. Monitoring studies of managed forests have demonstrated that the intensity and method of logging lead to both short-term and long-term damage, increasing tree mortality rates and interfering with sustainable forest management (Alder; Silva, 2000; Phillips *et al*., 2003; Sist; Ferreira, 2007). For this reason, monitoring post-logging damage progression is essential, assessing its effects on the residual forest, and determining its impact on future production (Martins *et al*., 2003).

Despite the planned nature of logging, residual trees may suffer damage such as trunk and canopy breakage, trunk leaning, bark and trunk rupture, and uprooting (e.g., Sist; Ferreira, 2007). Damaged trees exhibit reduced wood quality (Cudzik *et al*., 2017), lower growth expectations compared to undamaged ones, and a higher risk of death. Such damage facilitates pathogen entry into the wood, leading to infections that make trees prone to breakage, uprooting, or immediate death (Hillis, 2012).

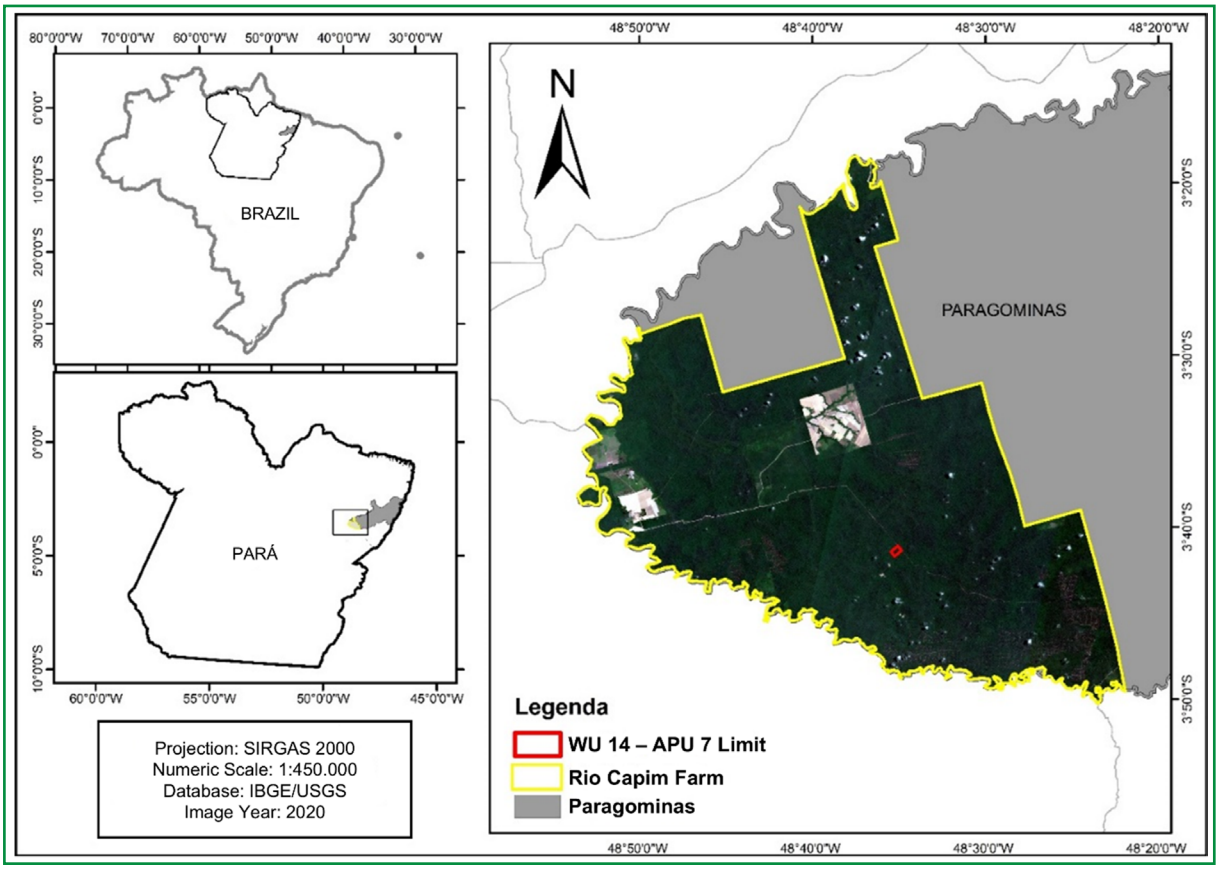
Several studies have addressed logging damage to residual trees, but few have focused on long-term monitoring, particularly the individual tracking of damaged trees and their mortality (Shenkin *et al*., 2015; Sist; Nguyen-Thé, 2002). Such analyses help understand how logging activities affect different diameter classes, the time required for forest recovery, and refine logging guidelines to ensure environmental and economic sustainability in forest management. In this context, this study aimed to evaluate the effects of logging on the mortality of damaged residual trees, based on the type and severity of damage sustained, over a ten-year monitoring period. Our main hypothesis is that the mortality of damaged and undamaged trees will not differ significantly after ten years of monitoring in a managed forest.

2 MATERIALS AND METHODS

2.1 Study area

The study was conducted in the municipality of Paragominas (3°18’ to 3°50’ S and 48°28’ to 48°54’ W), located in the southeastern region of the state of Pará, Brazil.

Figure 1 – Location map of WU 14 – APU 7 of the Rio Capim Farm, municipality of Paragominas, State of Pará, Brazil



Source: Authors (2025)

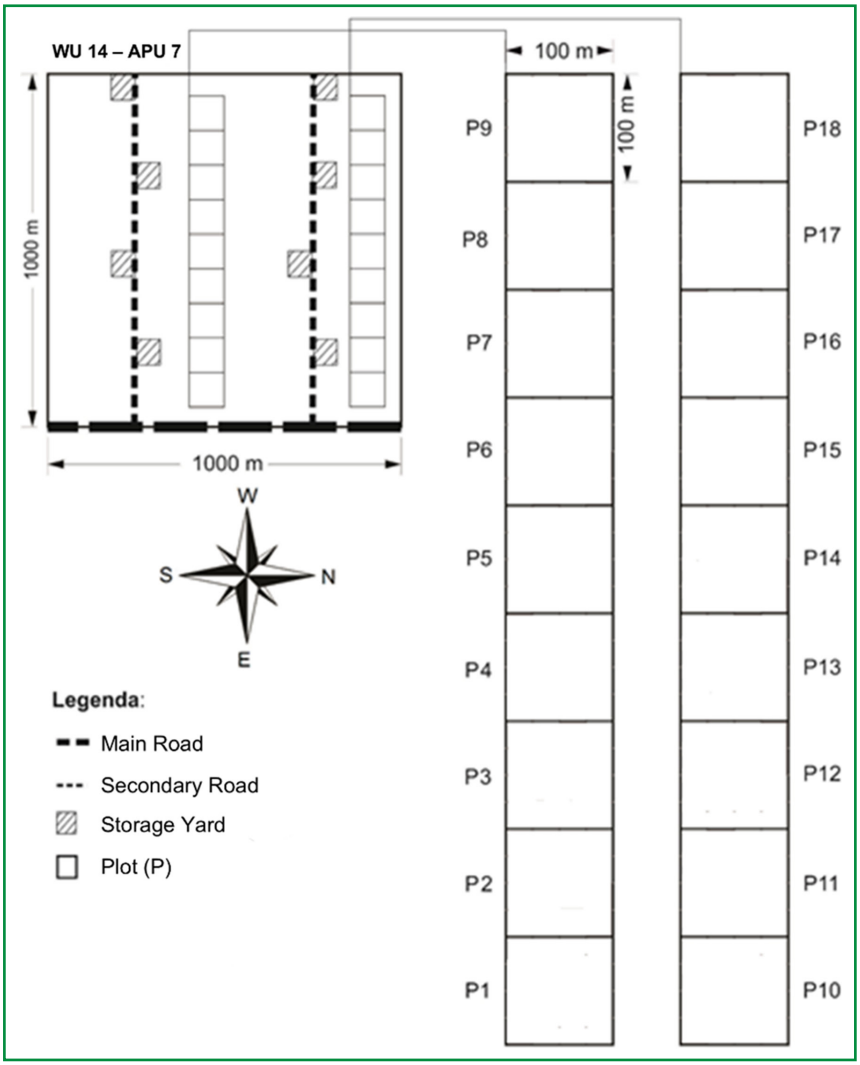
The topography is flat to gently undulating. Predominant soils in the region include Yellow Oxisols and Yellow Ultisols, with occasional occurrences of Plinthosols, Gleysols, and Neosols (Rodrigues *et al*., 2003). The vegetation is primarily classified as Dense Ombrophilous Forest (IBGE, 2019). According to Köppen's climatic classification, the climate type of the region is Aw, with an average annual precipitation of 1800 mm, average annual temperature of 26ºC, and relative humidity of 81% (Alvares *et al*., 2013).

The experiment was installed in the forest at Rio Capim farm, owned by Cikel Brasil Verde, in the southwestern part of the Paragominas municipality. The forest has been managed for timber production and FSC-certified since 2001. The silvicultural system applied in the forest management unit is a selective cutting system based on natural regeneration, with cutting cycles of 30 years and cutting intensity around 20 $m^3.ha^{-1}$ (Sist; Ferreira, 2007).

2.2 Data collection

The experiment was designed as illustrated in Figure 2 and described below. Two East-West strips were installed within the Work Unit (WU) 14 of Annual Production Unit (APU) 7, each measuring 900 m x 100 m. Thus, the experiment covered a sampled area of 18 ha, subdivided into 18 plots of 1 ha each (100 m x 100 m). The strips were installed at a minimum distance of 50 meters from the boundaries of the WU to avoid edge effects.

Figure 2 – Schematic design of the strips with the distribution of inventoried plots in WU 14 of APU 7, Rio Capim Farm, Paragominas, State of Pará, Brazil



Source: Authors (2025)

All trees within the plots with a diameter at breast height (DBH) ≥ 20 cm were measured, and their vernacular names were recorded. The scientific name was verified for some species through botanical samples, cross-checking against the IAN herbarium. Some trees were identified only by genus. The variables measured in the field were: (i) DBH, (ii) type of damage caused by logging, (iii) severity of damage, (iv) tree location (coordinates x and y) within the plots, and (v) commercial tree height, which was visually estimated during the first measurement.

This study utilized seven continuous inventories, with the first measurement taken in 2004 (before logging), the second in 2005 (after logging), the third in 2006, followed by measurements every two years (2008, 2010, 2012, and 2014). The type and severity of damage to residual trees were assessed in the logging year (2004), based on the classification used by Ferreira (2005), as detailed in Table 1.

Table 1 – Damage assessment protocol for experimental plots in WU 14 – APU 7, Rio Capim Farm, Paragominas, State of Pará, Brazil

Damage Category / Code	Description	Damage Level
Stem Damage		
S1	Broken stem at a height < 3m	4
S2	Broken stem at a height > 3m without sprouts	4
S3	Broken stem at a height > 3m and sprouted	3
Crown Damage		
C1	Only small branches broken	1
C2	Medium branches broken (less than half of the crown destroyed)	2
C3	Half or more of the crown destroyed	3
Leaning Trees		
L1	Tree leaning angle < 20°	1
L2	The tree leaning angle between 20° and 45°	2
L3	Tree leaning angle > 45°	3
Bark and Others		
BW1	Only bark removed	1
BW2	Small areas of bark and wood affected	2
BW3	Large areas of bark and wood affected	3
RR	Root torn off	4
MD	Tree with multiple damages	Non identified
ND	Trees without harvest damage	0

Source: Ferreira (2005)

In where: Damage Level: 0 - absent, 1- minimal, 2- medium, 3- severe and 4-extreme.

2.3 Data analisys

To characterize tree mortality dynamics over the 10-year monitoring period, the number of dead and recruited individuals during the period was recorded. Dead trees were distributed among plots, and the variables annual mortality rate (m_p) for each measurement interval, Equation (1), overall annual mortality rate (m), Equation (2), and the commercial volume (V) of the forest, Equation (3), were calculated using the following equations:

Annual mortality rate per plot (m_p) (SHEIL; MAY, 1996)

$$m_p = 1 - \left(\frac{N_{1p}}{N_{0p}}\right)^{\frac{1}{\Delta t}} \quad (1)$$

Annual mortality rate (m) for the forest (SHEIL; MAY, 1996)

$$m = 1 - \left(\frac{N_1}{N_0}\right)^{\frac{1}{\Delta t}} \quad (2)$$

Commercial volume of individuals, in $m^3.ha^{-1}$ (V)

$$V = \sum_{i=1}^{n} 10^{(1{,}93 * LogDBHi) - 2{,}96} \quad (3)$$

In where: Δt = interval between inventories, in years; N0 = number of individuals per hectare in the first inventory; N1 = number of surviving trees per hectare in the second inventory; N0p = number of trees per hectare in each plot, in the first inventory; N1p = number of surviving trees per hectare in each plot, in the second inventory; DBHi = Diameter at breast height, in cm, of the i-th measured tree; n = number of analyzed individuals in the forest.

The commercial volume of trees was calculated using the equation from the firm's Management Plan and was filed with the State Secretariat for Environment and Sustainability - SEMAS.

To characterize annual tree mortality dynamics, residual trees with DBH ≥ 20 cm were divided into two groups: (i) trees with damage caused by logging and (ii)

trees without apparent damage. For each group, the average annual mortality rate per hectare was calculated using data from the seven inventories, with the 18 plots considered sampling units, based on Sheil and May's Equation (1) (1996). To test our main hypothesis, annual mortality averages for damaged and undamaged trees were compared in post-logging years using Student's paired t-test, with a 95% confidence level (1 – α)

3. RESULTS AND DISCUSSIONS

3.1 Damaged trees from logging

The total volume of trees with a DBH ≥ 20 cm damaged by logging was approximately 30 $m^3.ha^{-1}$. On average, 6.3 trees per hectare or 33.34 $m^3.ha^{-1}$ were harvested. Thus, for every 1 m^3 of harvested trees, 0.9 m^3 of remaining trees with a DBH ≥ 20 cm were damaged. Additionally, for each harvested tree, an average of five residual trees were damaged (Table 2).

Table 2 – Density of live trees before logging, harvested trees, and damaged residual trees in Rio Capim Farm, municipality of Paragominas, Pará, Brazil

Trees with DBH ≥ 20 cm	*N* (trees.ha^{-1})	V (m^3. ha^{-1})
Alive pre-harvest (2004)	188,0	248,24
Harvested (H)	6,3	33,34
Damaged (D)	28,9	30,20
Ratio (D/H)	4,6	0,90
PD (%)	15,37	12,17

Source: Authors (2025)

In where: N is the density of individuals; V is the density in commercial volume of the forest; Alive pre-exploitation trees are the trees measured in 2004; Damaged trees (D) were counted for the year 2005; Percentage of damaged trees (PD) of alive trees in 2004.

Our results indicate a low impact of logging on residual vegetation compared to similar studies in the Amazon region. For example, in Jackson *et al*. (2002), 44 trees

(DBH ≥ 10 cm) were damaged for every harvested tree under a logging intensity of 12.1 $m^3.ha^{-1}$. In the analysis conducted by Verissimo *et al*. (1992), damage was lower for a higher logging intensity, with 23 trees (DBH ≥ 10 cm) damaged for a production of 38 $m^3.ha^{-1}$. Similarly, in Verissimo *et al*. (2002), 24 trees (DBH ≥ 10 cm) were damaged under a logging intensity of 16 $m^3.ha^{-1}$, and in Silva *et al*. (2001), 19 trees were damaged for a logging intensity of 23 $m^3.ha^{-1}$. These studies show significantly higher damage levels than observed in our study, even considering similar logging intensities.

One reason for these results may be the lack of reduced-impact logging (RIL) techniques in many of these studies, although Jackson *et al*. (2002) reported some measures being applied. This aligns our findings more closely with Oliveira *et al*. (2006), where approximately 4.3 trees (DBH ≥ 10 cm) were damaged for every harvested tree, under a logging intensity twice as high as in this study. Nonetheless, it is essential to emphasize that direct comparisons between our work and others are challenging due to varying forest characteristics and logging procedures.

Residual damage is inevitable in forest management activities, mainly due to trail preparation, felling, and tree dragging (Dey, 1994). However, measures such as planning roads and dragging trails, along with directional felling (Sabogal *et al*., 2000), and other RIL guidelines, can help reduce the negative effects of logging on residual vegetation (Pinto; West; Vidal, 2024) and soil (Lontsi *et al*., 2019). Moreover, adequate training and incentives are necessary for field workers to adopt RIL techniques effectively (Putz *et al*., 2008).

The analysis of the type and severity of damage caused by logging over a 10-year monitoring period indicates that trees with torn off roots (RR) and those with S1 damage (Broken stem at a height <3m) have the highest probability of dying after 10 years, with mortality rates of 99% and 93%, respectively (Table 3). The most frequent damage type is S2, Broken stem at a height >3m without sprouts, which affected 5.9 $trees.ha^{-1}$ (20% of damaged trees) and showed a high relative mortality of 48% after 10 years of monitoring. Trees with damage types C1, C2 (small or medium branches

broken in less than half the crown) and BW1 and BW2 (only bark or small areas of bark and wood affected) exhibited low relative mortality rates, ranging from 13% to 19%, which were lower than the relative mortality of undamaged trees, 21%. Considering all trees with some damage, 52% died after 10 years of monitoring.

Table 3 – Annual distribution and damage category of mortality of residual trees with DBH ≥ 20 cm, damaged and undamaged, in Rio Capim Farm, Paragominas, Pará, Brazil

Damage Category	Tree year of death						Rem. (2014)	Trees in 2004	Death Rate
	2005	2006	2008	2010	2012	2014			
S1	51	5	1	3	1	3	5	69	93%
S2	29	10	4		5	3	55	106	48%
S3	1			1	2		8	12	33%
C1	1						7	8	13%
C2	2	1	1				21	25	16%
C3	5		2	4		2	35	48	27%
L1			1		1		4	7	43%
L2	3			2			3	7	57%
L3							1	1	0%
BW1	2	3	3		1	2	47	58	19%
BW2	2	1	1	1		1	25	31	19%
BW3			1	1			3	5	40%
RR	83	3			1		1	88	99%
MD	11	4	1	3		2	35	56	38%
ND	135	96	64	75	115	88	2176	2749	21%
Total Damaged	190	27	15	15	11	13	250	521	52%

Source: Authors (2025)

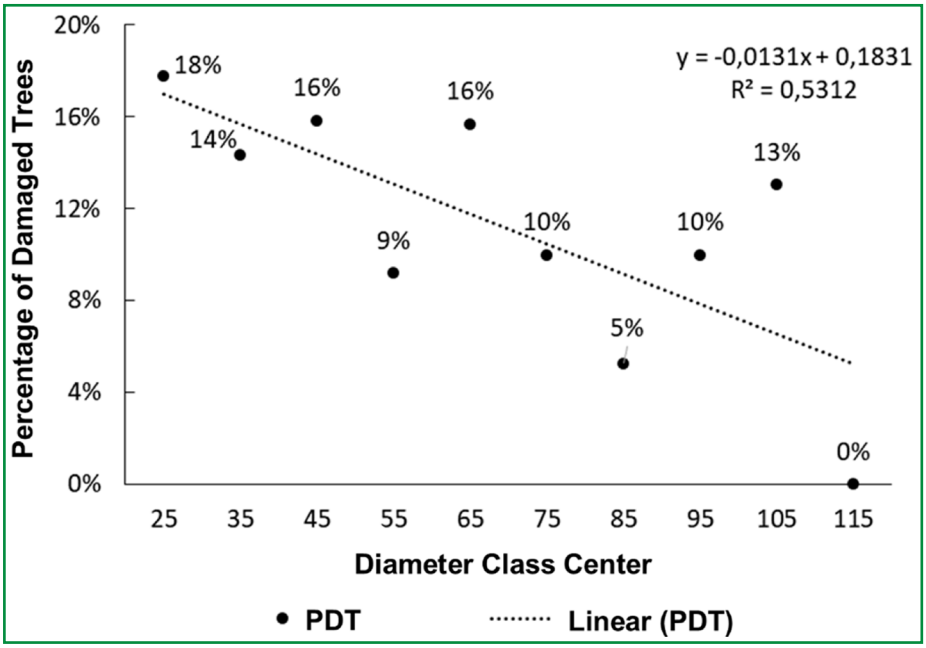
In where: S1 – Broken stem at a height <3 m; S2 – Broken stem at height a >3 m without sprouts; S3 – Broken stem at a height >3 m and sprouted; C1 – Only small branches broken; C2 – Medium branches broken (less than half of the crown destroyed); C3 – Half or more of the crown destroyed; L1 – Tree leaning angle <20°; L2 – Tree leaning angle between 20° and 45°; L3 – Tree leaning angle > 45°; BW1 – Only the bark removed; BW2 – Small areas of bark and wood affected; BW3 – Large areas of bark and wood affected; RR – Root torn off; MD – Trees with multiple damage; ND – No damage; Rem. (2014) are the trees remaining from exploitation, that is, those that remained alive from 2004 to 2014.

The results show that the impacts of logging extend beyond immediately dead trees and include damaged trees that may die in the subsequent years after logging. This aligns with findings by Shenkin *et al*. (2015), who reported a substantial increase

in mortality for trees with root, bark, crown, or inclined trunk damage. Damaged trees were found to be 2.5 times more likely to die than undamaged ones eight years after logging (Shenkin *et al*., 2015).

Figure 3 shows the percentages of trees inventoried in 2004 (census) damaged by logging, distributed by diameter classes with 10 cm intervals. Higher damage was noted in the 20 – 50 cm diameter classes, and a negative correlation between the number of damaged trees and tree size was observed. No individuals with a DBH above 110 cm were found to be damaged.

Figure 3 – Percentages of trees damaged by logging distributed by diameter class in Rio Capim Farm, Paragominas, Pará, Brazil



Source: Authors (2025)

In where: PDT represents the percentage of trees damaged in 2004. Linear (PDT) represents the linear trend curve of PDT vs. diameter class center.

Trees in the 20 – 50 cm diameter classes showed the highest percentage of damage (Figure 3), with similar concentrations of damage in intermediate-sized trees observed in other studies (Bertault; Sist, 1997; Alder; Silva, 2000). For trees with DBH < 20 cm, no conclusions were presented, but the literature suggests an all-or-nothing effect:

they are either destroyed or unaffected by management activities (Alder; Silva, 2000; Picard; Gourlet-Fleury; Forni, 2012). Large trees, on the other hand, are often avoided during road and trail construction as well as directional felling (van der Hout, 1999). These factors explain the higher percentage of damage to intermediate-sized trees.

Severe damage caused by logging can jeopardize the sustainability of forest management. For instance, studies by Verissimo *et al*. (1992) and Barreto *et al*. (1998), also conducted in the Paragominas region, showed that logging activities damaged 1.63 m^3 of trees for every 1 m^3 harvested, resulting in a second cutting cycle with approximately half the volume extracted during the first. However, a 30% reduction in damage, yielding 1.14 m^3 of residual trees damaged per 1 m^3 harvested, would allow for two cutting cycles with the same volumetric wood production (Barreto *et al*., 1998; Verissimo *et al*., 1992). Similar conclusions about damage reduction and logging sustainability have been reached by other studies (Pinard; Putz, 1996; Johns; Barreto; Uhl, 1996), though additional measures are needed to ensure stock recovery (Putz *et al*., 2022; Vidal; West; Putz, 2016).

We did not analyze the relationship between damage and the forest's future stock; however, a significant percentage of damaged trees were in the 30 – 50 cm diameter classes (Figure 3), which could become unavailable for the second cutting cycle due to the high mortality of damaged trees and the loss in wood quality of surviving ones (Namuene; Egbe, 2022). Furthermore, for a certain volume of harvested trees, a similar volume of residual trees is damaged (Table 2), which raises concerns about the sustainability of production, as forest growth rates may not compensate for all these losses.

3.2 Post-logging tree mortality

In the first year post-logging, 18.1 trees. ha-1 with a DBH ≥ 20 cm died, representing a loss of approximately 22 $m^3.ha^{-1}$ of standing timber (Table 4). During the second year, mortality decreased to 6.8 $trees.ha^{-1}$, corresponding to a timber volume loss of 8.3

$m^3.ha^{-1}$ (Table 4). Together, these losses over two years amount to approximately 30 $m^3.ha^{-1}$ of standing timber, equivalent to the maximum volume allowed for extraction in managed areas under current legislation.

Table 4 – Observed mortality and recruitment of trees with DBH ≥ 20 cm in Rio Capim Farm, Paragominas, Pará, Brazil

Measurement Years	Trees with DBH ≥ 20 cm				
	Live.ha^{-1}	Dead.ha^{-1}	Rec.h^{a-1}	V_{Dead}.ha^{-1}	m (%)
2004	188,0	-	-		
2005	166,5	18,1	2,9	22,0	9,9
2006	164,4	6,8	4,8	8,3	4,2
2008	164,6	4,6	4,7	5,7	1,5
2010	168,7	5,4	9,6	6,5	1,8
2012	172,7	7,3	11,3	7,5	2,5
2014	176,8	6,3	10,5	6,4	2,3

Source: Authors (2025)

In where: Live.ha^{-1} is the density of live trees; Dead.ha^{-1} is the density of dead trees; Rec.ha^{-1} density of recruited trees; V_{Dead}.ha^{-1} is the volume of dead trees by hectare; m (%) is the annual mortality rate.

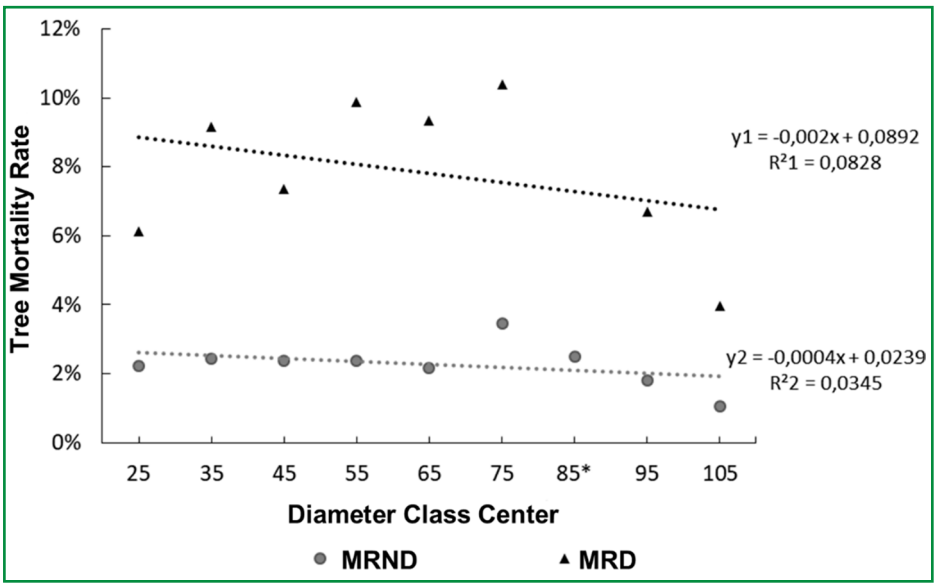
From the second year onward, mortality rates stabilized, with losses ranging between 4.6 and 7.3 trees.ha^{-1} every two years, corresponding to standing timber volumes of 5.7 to 7.5 $m^3.ha^{-1}$. These findings align with expected dynamics for logged tropical forests, where mortality rates decline following logging activities. By the tenth year, mortality rates stabilized at approximately 2.3%, similar to those observed in unlogged tropical forests, which typically range from 1 to 2% annually (Teixeira *et al*., 2007).

The mortality pattern observed reflects an expected trajectory for tropical logged forests, corroborating findings by Shenkin *et al*. (2015) and Amaral *et al*. (2019), with elevated mortality in the initial years and a decline in subsequent years. Such patterns highlight the importance of monitoring and adapting forest management practices over time to mitigate long-term ecological impacts.

3.3 Mortality of damaged trees and undamaged trees due to logging

The annual mortality rate of undamaged trees ranged from 1% to 3.5% from 2004 to 2014, while the annual mortality rate of damaged trees was higher, varying between 4% and 11%. However, there was no relationship between the annual mortality rate and diameter classes, whether for the population of damaged trees or undamaged ones (Figure 4). This result corroborates the findings of Shenkin *et al*. (2015), who noted that tree size has little influence on mortality, with factors such as the type and severity of damage being more significant.

Figure 4 – Annual mortality rates of trees damaged by logging and undamaged trees, by diameter class, from 2004 to 2014 in a managed forest in Paragominas, Pará, Brazil



Source: Authors (2025)

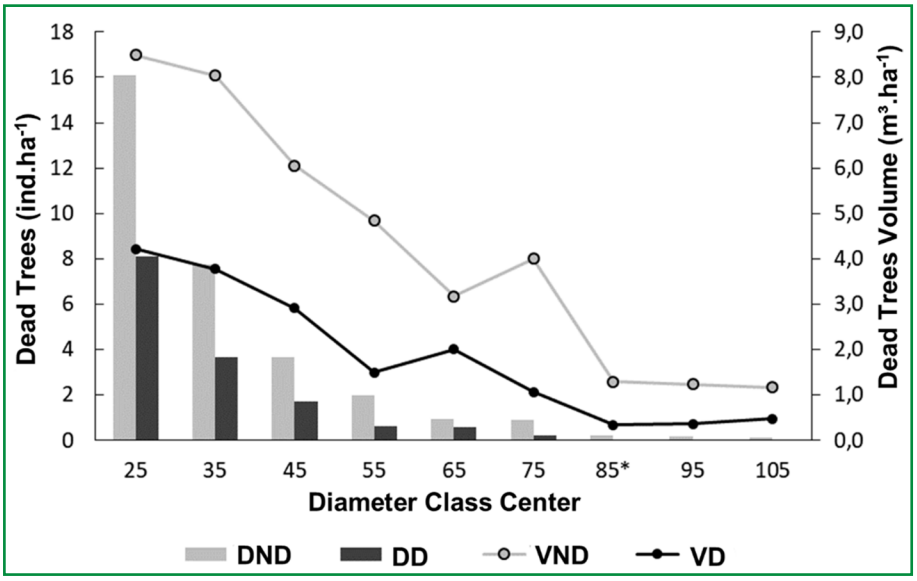
In where: MRND represents the undamaged trees' annual mortality rate; MRD represents the damaged trees' annual mortality rate. *Center of class with 100% mortality for damaged trees.

When analyzing the density and volume of dead trees, it is noted that smaller diameter classes exhibit higher absolute values (Figure 5). So, the loss of individuals and volume is more pronounced in smaller diameter classes, which was also observed by Appolinário *et al*. (2005). They reported that additional stress factors, such as sudden

canopy opening or increased competition for resources, might increase the mortality of smaller trees. Thus, the absolute number of dead trees is expected to be greater in smaller diameter classes (Figure 5), as absolute mortality rises with tree abundance (Rossi *et al*., 2007).

Although the mortality rates are similar across all diameter classes of damaged trees (Figure 4), it is important to highlight that a higher number of damaged trees were found in smaller diameter classes (Figure 5). Consequently, there is a negative correlation between the quantity of damaged trees and tree size.

Figure 5 – Diameter distribution of density and volume of residual dead trees, damaged and undamaged by logging, from 2004 to 2014 in a managed forest in Paragominas, Pará, Brazil



Source: Authors (2025)

In where: DND represents the number of dead undamaged trees per hectare; DD represents the number of dead damaged trees per hectare; VND represents the volume of dead undamaged trees per hectare; VD represents the volume of dead damaged trees per hectare.

Upon analyzing the average annual mortality rate separately for the groups— (I) undamaged trees and (II) trees damaged by logging—there was a significant difference in mortality between the groups in the first and second years post-logging (Table 5). The average mortality rates in the first two years post-logging were 5% and 4% for

undamaged trees and 36% and 8% for damaged ones (Table 5). These higher mortality rates occur due to the severe structural damage and physiological stress trees experience in the first few years after harvesting (Shenkin *et al*., 2015; Sist; Nguyen-Thé, 2002).

Subsequently, there is a reduction in mortality rates in the following years. In our study, starting from the fourth year post-logging, mortality rates between trees with and without damage showed no statistical difference (Table 5). The literature indicates that approximately ten years are required for the mortality rates of a logged forest to equal those of an unlogged forest (de Graaf, 1986; Dionisio *et al*., 2018; Madron, 1994).

Some exceptions include the work of Shenkin *et al*. (2015), where eight years were required for stabilization, though a sharp increase in mortality occurred in the sixth year due to a severe drought, affecting the results. Another study by Sist and Nguyen-Thé (2002) found stabilization within four years; however, numerous damaged trees were cut or poisoned in the first two years post-harvest, significantly reducing mortality in the following years and complicating direct comparison of results. Other explanations for the rapid stabilization of mortality in our study include the comparison of mortality between damaged and undamaged trees within the same area, whereas most other studies compared damaged trees with undamaged ones in forests or plots unaffected by logging operations; or due to the low impact of logging on residual trees observed in our study.

Table 5 – Average annual mortality rate per plot and Student's T-test for residual trees damaged and undamaged with DBH ≥ 20 cm in Rio Capim Farm, municipality of Paragominas, Pará, Brazil

Measurement Year	MEAN-MND	MEAN-MD	T-test (p-value)
2005	4,9%	36,4%	0,0000000001
2006	3,6%	7,7%	0,0437105147
2008	1,3%	2,8%	0,1168510198
2010	1,5%	2,7%	0,2700577914
2012	2,5%	2,2%	0,6751734407
2014	2,1%	2,7%	0,5687735610

Source: Authors (2025)

In where: MEAN-MND represents the mean mortality of undamaged trees, and MEAN-MD is the mean mortality of damaged trees. Student's t-test was applied at a 95% confidence level (1 – α). Mortality was calculated based on the formula of Sheil and May (1996).

4 CONCLUSIONS

We concluded that even using the current RIL guidelines, the logging operation resulted in significant damage to residual vegetation, with a nearly 1:1 ratio between harvested and damaged volumes. This could jeopardize the continuity of timber harvesting activities, although the damage observed in our analyses was lower than most studies conducted in the Amazon. Solutions to this scenario primarily involve reducing the volume of harvested timber, with the trade-off of reducing logging profits. This effect could be mitigated by utilizing damaged trees as energy residues within the initial years post-logging.

We also concluded that tree size influences the absolute number of trees likely to be damaged, though it is a weak indicator of mortality, which is more dependent on the type of damage sustained by the tree. These aspects should be considered when refining harvesting techniques to avoid damage to trees intended for use in the next cutting cycle and reduce severe damage to vegetation. Regarding forest recovery, mortality rates between damaged and undamaged trees quickly equalized, which may indicate that the logging impact was low in terms of mortality.

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