



INTERTEMPORAL BIOMASS AND CARBON STOCK DYNAMICS IN A MANAGED AMAZONIAN FOREST

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ABSTRACT

Context: Managed tropical forests play a crucial role in climate regulation and in maintaining carbon stocks; however, integrated assessments that treat biomass and carbon as environmental assets remain limited. **Originality/Contribution:** This study integrates IPCC methodological approaches with the System of Environmental-Economic Accounting (SEEA) Central Framework to organize biomass and carbon stocks and flows as forest environmental assets under sustainable management. **Objective:** To evaluate the intertemporal dynamics of forest volume, biomass, and carbon stocks in a managed Amazonian forest. **Methodology:** Trees with a DBH ≥ 20 cm were analyzed in Annual Production Unit 4 of the Tapajós National Forest, from 2009 to 2022. Stem volume was converted into biomass, carbon, and CO₂ equivalents using conversion factors consistent with IPCC guidelines and regional references. Stock changes were estimated using the Gain–Loss and Stock–Difference methods, and exploratory multivariate analyses were performed to assess the structural and temporal coherence of forest variables. **Results:** Gross increment reached 87.38 m³ ha⁻¹, while total reductions amounted to 88.47 m³ ha⁻¹, i.e., forest volume was stable over the study period. After conversions, stability of biomass and carbon stocks was also observed, with minimal net emissions. Multivariate analysis revealed a temporal trajectory characterized by post-harvest structural reorganization followed by biomass accumulation within the monitored forest component. **Conclusions:** The results indicate that biomass and carbon stocks remained approximately stable in the monitored area throughout the study period. Environmental-economic accounting provided a consistent framework for organizing biomass and carbon stocks and flows, supporting the assessment of stock changes in managed Amazonian forests.

Keywords: Forest carbon, Forest biomass, Natural capital

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DINÂMICA INTERTEMPORAL DA BIOMASSA E DOS ESTOQUES DE CARBONO EM FLORESTA AMAZÔNICA MANEJADA

RESUMO Contexto: Florestas tropicais manejadas desempenham papel crucial na regulação climática e na manutenção dos estoques de carbono, mas avaliações integradas que tratem biomassa e carbono como ativos ambientais permanecem limitadas. Originalidade/Contribuição: Este estudo integra abordagens metodológicas do IPCC com a Estrutura Central do Sistema de Contabilidade Ambiental-Econômica (SEEA) para organizar estoques e fluxos de biomassa e carbono como ativos ambientais florestais sob manejo sustentável. Objetivo: Avaliar a dinâmica intertemporal do volume florestal, da biomassa e dos estoques de carbono em uma floresta amazônica manejada. Metodologia: Foram analisadas árvores com DAP ≥ 20 cm na Unidade de Produção Anual 4 da Floresta Nacional do Tapajós (2009–2022). O volume do fuste foi convertido em biomassa, carbono e CO₂ equivalente com fatores compatíveis com as diretrizes do IPCC e referências regionais. As mudanças nos estoques foram estimadas pelos métodos Gain–Loss e Stock–Difference, e análises multivariadas exploratórias avaliaram a coerência estrutural e temporal das variáveis florestais. Resultados: O incremento bruto atingiu 87,38 m³ ha⁻¹ e as reduções totais 88,47 m³ ha⁻¹, resultando em estabilidade do volume ao longo do período. Após as conversões, os estoques de biomassa e carbono permaneceram estáveis, com emissões líquidas mínimas. A análise multivariada revelou uma trajetória temporal de reorganização estrutural pós-colheita, seguida por acúmulo de biomassa no componente monitorado. Conclusões: Os resultados indicam estabilidade aproximada dos estoques de biomassa e carbono na área monitorada durante o período analisado. A contabilidade ambiental-econômica forneceu uma estrutura consistente para organizar estoques e fluxos de biomassa e carbono,

contribuindo para o monitoramento mais transparente de florestas amazônicas manejadas.

Palavras-Chave: Carbono florestal, Biomassa florestal, Capital natural

1. INTRODUCTION

Tropical forests regulate climate, sustain biodiversity and support the livelihoods of millions of people. They store large amounts of carbon in living biomass and soils and therefore influence the global carbon cycle and stability of the Earth system (Bonan, 2008; Pan et al., 2011). Maintaining the ecological integrity of these forests is increasingly recognized as essential for climate regulation and the provision of ecosystem services that support human well-being (Bonan, 2008; Pan et al., 2011).

Sustainable forest management seeks to reconcile timber production with the maintenance of ecological processes and long-term ecosystem stability. Selective logging modifies forest structure, alters species composition and redistributes biomass among diameter classes, thereby influencing dynamics and carbon storage capacity (Putz et al., 2008; Sist & Ferreira, 2007). Recruitment, growth, and mortality drive forest recovery and determine whether biomass and carbon stocks remain stable over time (Putz et al., 2008; Sist & Ferreira, 2007).

Permanent forest inventories provide detailed information on tree populations, forest structure and growth dynamics, enabling long-term assessments of forest recovery and biomass accumulation (Phillips et al., 2009; Chave et al., 2014). These measurements support the evaluation of ecosystem stability and carbon storage following disturbance and management interventions (Phillips et al., 2009; Chave et al., 2014). However, conventional forest inventories often prioritize timber volume while giving limited attention to forests as environmental assets with measurable stocks and flows (United Nations, 2014; Obst et al., 2016).

Environmental accounting frameworks provide a structured approach for tracking stocks and flows of natural resources and evaluating changes in ecosystem assets over



time. The System of Environmental-Economic Accounting (SEEA) provides standardized methods that integrate biophysical information with economic and policy frameworks, thereby supporting the assessment of natural capital and ecosystem services (United Nations, 2014; Obst et al., 2016). When forest inventory data are linked to environmental accounting indicators, ecosystem condition and sustainability can be assessed more comprehensively (United Nations, 2014; Obst et al., 2016).

In spite of the considerable advances in sustainable forest management and carbon accounting, relatively few studies have integrated long-term forest inventory data with environmental asset accounting and carbon metrics to evaluate the stability of forest natural capital under managed conditions. This gap limits the ability to assess whether managed tropical forests maintain structural integrity, carbon storage capacity, and climate regulation functions over time (Putz et al., 2008; United Nations, 2014).

At the international level, the Intergovernmental Panel on Climate Change provides methodological guidance for estimating greenhouse gas emissions and removals using the Stock-Difference and Gain-Loss approaches. These methods provide strong methodological consistency and national greenhouse gas inventories, but little guidance for management-scale decision making (IPCC, 2006; IPCC, 2019). In parallel, the SEEA offers an internationally accepted framework for organizing physical environmental assets and flows and for integrating environmental information into economic analysis and policy evaluation (United Nations, 2014). Although these frameworks are conceptually complementary, few applied studies have integrated them, particularly in managed tropical forests (IPCC, 2019; United Nations, 2014).

Environmental-economic accounting increasingly supports decision-making by linking ecological conditions to management outcomes. Applied studies have shown that natural capital accounting can improve planning, governance, and the evaluation of environmental assets, when implemented at appropriate spatial and temporal scales

(Bateman et al., 2013; Obst et al., 2016; Ramihangihajason et al., 2025). Within the United Kingdom National Ecosystem Assessment, Bateman et al. (2013) demonstrated that integrating ecosystem information into economic decision-making increases transparency and supports more efficient resource allocation (Bateman et al., 2013).

Long-term forest inventories enable the application of environmental-economic accounting at the management-unit scale. By organizing intertemporal information on biomass and carbon into sequential physical accounts, researchers can evaluate the stability, resilience, and performance of forest assets beyond conventional short-term production indicators (United Nations, 2014; Obst et al., 2016). This approach treats forest biomass and carbon stocks as measurable environmental assets, strengthening their integration into climate governance, forest management planning, certification processes, and environmental market mechanisms (United Nations, 2014; IPCC, 2019).

Previous studies have generally treated continuous forest inventories, biomass and carbon estimation, and environmental accounting as separate analytical domains. In the integrated framework used here, the forest inventory identifies growth, recruitment, mortality, and harvesting; IPCC procedures convert these observations into standardized biomass and carbon indicators; and the SEEA framework organizes opening stocks, additions, reductions, and closing stocks. To our knowledge, no previous study has combined continuous forest inventory data, IPCC conversion procedures, and SEEA-compatible intertemporal accounts for a monitored production unit in the Tapajós National Forest.

Using long-term permanent forest inventory data from the Tapajós National Forest, we combined physical environmental accounts with exploratory multivariate analyses to assess biomass and carbon dynamics under the applied forest management regime (Chave et al., 2014; Obst et al., 2016). Specifically, this study evaluates the intertemporal dynamics of forest volume, biomass, and carbon stocks in a managed Amazonian forest by integrating

IPCC methodological approaches with the environmental-economic accounting framework of the System of Environmental-Economic Accounting (IPCC, 2006; United Nations, 2014).

2. MATERIAL AND METHODS

2.1 Data source and study area

This study used forest volume data derived from the Forest Monitoring System (MFT), a database designed to store, organize, and process data from temporary and continuous forest inventories. The Brazilian Agricultural Research Corporation (Embrapa) developed the MFT to support forest monitoring and management in tropical forest environments (Silva et al., 2008).

The analysis focused on Annual Production Unit 4 (APU 4), managed by the Cooperativa Mista da Floresta Nacional do Tapajós (COOMFLONA). The unit covers 700 ha and is located within the Tapajós National Forest, in the municipality of Belterra, Pará State, eastern Amazonia, Brazil.

Forest dynamics were monitored for all trees with diameter at breast height (DBH) ≥ 20 cm.

Seven permanent plots measuring 50×50 m (0.25 ha each) were randomly established across the managed area, totaling 1.75 ha of sampled area. This sampling design follows recommendations for permanent plot representativeness in Annual Production Units (APUs) in eastern

Amazonia, which propose one permanent plot per 100 ha for APUs smaller than 1,000 ha (Silva et al., 2005).

2.2 Forest volume estimates

Forest volume was estimated within the Forest Monitoring System using allometric equations developed and validated for APU 4. These equations incorporate diameter classes and were applied consistently across the four forest inventory campaigns conducted from July 2009 to August 2022. The stem volume data for trees with DBH ≥ 20 cm, grouped by diameter class and monitoring campaign, are summarized in Table 1.

Total merchantable volume per hectare was calculated separately for live trees, harvested trees, and trees lost to natural mortality. Net volume increment was estimated as the difference in live tree volume between consecutive monitoring periods (t_2-t_1 , t_3-t_2 , and t_4-t_3), following standard procedures for forest growth and yield assessment (IPCC, 2006; Silva et al., 2008).

2.3 Volume expansion factor

The volume expansion factor accounts for stem volume from diameter classes not included in the primary inventory and is commonly applied to reduce underestimation of forest biomass stocks (Brown & Lugo, 1992; Nogueira et al., 2008). Its application requires compatibility between the diameter range represented by the reference factor and

Table 1. Trunk volume ($\text{m}^3 \text{ha}^{-1}$) of trees with DBH ≥ 20 cm, grouped by diameter class, in Annual Production Unit 4 (APU 4), Tapajós National Forest, based on Forest Monitoring System records

Tabela 1. Volume do fuste ($\text{m}^3 \text{ha}^{-1}$) de árvores com DAP ≥ 20 cm, agrupadas por classe diamétrica, na Unidade de Produção Anual 4, Floresta Nacional do Tapajós, com base nos relatórios do Sistema de Monitoramento Florestal

Timber resource inventoried by diameter class	jul/09 (T1) Total ($\text{m}^3 \text{ha}^{-1}$)	jul/11 (T2) Total ($\text{m}^3 \text{ha}^{-1}$)	jun/15 (T3) Total ($\text{m}^3 \text{ha}^{-1}$)	Aug/22 (T4) Total ($\text{m}^3 \text{ha}^{-1}$)
Trees with DBH ≥ 45 cm	176.99	180.28	172.60	187.56
Harvested	-	17.20	-	-
Dead	-	7.85	13.37	23.18
Live	176.99	155.23	159.22	164.38
Trees with $20 \text{ cm} \leq \text{DBH} < 45$ cm	82.63	91.28	92.36	102.37
Dead	-	8.36	10.30	8.22
Live	82.63	82.92	82.06	94.16
Grand total	259.62	271.56	264.95	289.93

the diameter range omitted from the inventory.

Because the available expansion factors were developed for diameter ranges that did not correspond exactly to the unmonitored trees in this inventory, we set the volume expansion factor to unity. This conservative decision avoided introducing an unsupported correction into the intertemporal series, but it also means that total volume, biomass, and carbon refer only to trees with DBH ≥ 20 cm and may underestimate whole-stand stocks. Total volume was calculated according to Eq. 1:

$$V_t = V \times VEF \quad (\text{Eq. 1})$$

in which V_t is total volume ($\text{m}^3 \text{ ha}^{-1}$), V the monitored volume ($\text{m}^3 \text{ ha}^{-1}$), and VEF the volume expansion factor.

2.4 Aboveground biomass estimation

We estimated aboveground biomass by converting merchantable stem volume into dry biomass using wood basic density and biomass expansion factors. This approach follows the Tier 1 recommendations of the Intergovernmental Panel on Climate Change and has been widely applied in tropical forest carbon assessments (Brown & Lugo, 1984; Brown & Lugo, 1992; IPCC, 2006; Sanquetta et al., 2019).

Wood basic density was not measured directly for each species in the permanent plots. We therefore adopted a mean value of 0.63 t m^{-3} based on regional empirical measurements for Amazonian species (Carneiro et al., 2020). This regional value supports a Tier 1 estimate when species-specific measurements are unavailable, but it does not capture the full variation in wood properties within a highly diverse forest.

Reported basic density values range from approximately 0.51 to 0.83 g cm^{-3} , equivalent to 0.51 to 0.83 t m^{-3} . High-density species such as *Dipteryx odorata* may exceed 0.80 g cm^{-3} , whereas *Bertholletia excelsa* and *Khaya grandifoliola* commonly exhibit wood densities from approximately 0.50 to 0.65 g cm^{-3} (Santos et al., 2025). Thus, the adopted mean may overestimate biomass for species with lighter wood and underestimate it for those with denser wood. Applying the same value to all inventories preserves

temporal consistency, but it does not remove uncertainty from the absolute stock estimates.

To account for non-commercial aboveground components, including large branches, twigs, leaves, and fruits, we applied a biomass expansion factor of 1.58 (Brown & Lugo, 1992; Sanquetta et al., 2019). Crown architecture, tree size, species composition, and disturbance history can alter the relation between stem biomass and total aboveground biomass. Therefore, this mean factor provides a standardized estimate rather than a direct measurement of each component. Aboveground biomass was calculated according to Eq. 2:

$$AGB = V \times D \times BEF \quad (\text{Eq. 2})$$

which AGB is aboveground biomass (t ha^{-1}), V the stem volume ($\text{m}^3 \text{ ha}^{-1}$), D wood basic density (t m^{-3}), and BEF the biomass expansion factor.

2.5 Belowground biomass estimation

We estimated belowground biomass using a root-to-shoot ratio of 0.25, consistent with IPCC default values and the reference adopted by Sanquetta et al. (2019). Root biomass allocation varies with species, tree size, soil conditions, water availability, and disturbance. The fixed ratio therefore introduces additional uncertainty into total biomass estimates, particularly in a floristically diverse Amazonian forest. Total biomass was calculated as:

$$TB = AGB + (AGB \times R) \quad (\text{Eq. 3})$$

in which TB is total biomass (t ha^{-1}), AGB the aboveground biomass (t ha^{-1}), and R the root-to-shoot ratio.

2.6 Carbon stock and carbon dioxide equivalent ($\text{CO}_2 \text{ eq}$)

Carbon stock was estimated by applying a carbon fraction of 0.47 to total biomass, consistent with IPCC guidelines (IPCC, 2006, 2019):

$$C = TB \times CF \quad (\text{Eq. 4})$$

Carbon stock was converted to carbon dioxide equivalent using the molecular weight ratio between CO_2 and carbon:

$$CO_2 eq = C \times 3.67 \quad (\text{Eq. 5})$$

in which C is carbon stock ($t\ C\ ha^{-1}$) and CF the carbon fraction.

2.7 Treatment of dead wood and litter

Following the IPCC Tier 1 approach, carbon transferred to dead wood and litter was assumed to be released to the atmosphere within the same year. This assumption maintains the focus on living biomass dynamics and ensures methodological consistency (IPCC, 2006).

2.8 Carbon stock change methods

Changes in carbon stocks were quantified using both the Gain–Loss and Stock–Difference methods (IPCC, 2006).

Gain–Loss method: G (gains) → carbon gains resulting from growth and recruitment and L (losses) → carbon losses resulting from mortality, harvesting, and disturbances

$$\Delta C = G - L \quad (\text{Eq. 6})$$

Stock–Difference method:

$$\Delta C = \frac{Ct_2 - Ct_1}{(t_2 - t_1)} \quad (\text{Eq. 7})$$

2.9 Analytical scope and boundaries

This analysis focused on trees with $DBH \geq 20\ cm$ monitored in permanent plots. Trees below this threshold contribute to stand density, recruitment, biomass, and carbon storage, especially through numerous small stems. Their exclusion narrows the accounting boundary and likely underestimates total stand stocks. It may also delay the representation of regeneration because individuals enter the accounting system only after reaching 20 cm DBH. The consistent threshold across all inventories supports comparison of changes within the monitored component, but the resulting values should not be interpreted as complete ecosystem biomass or carbon stocks (Brown & Lugo, 1992; Nogueira et al., 2008).

Deadwood decomposition, litter turnover, and soil organic carbon were not measured or modeled. Under the Tier 1 accounting assumption adopted here, carbon

transferred from living biomass to dead organic matter was treated as released within the same accounting year. This boundary supports a consistent account of live-tree stocks, but it does not quantify carbon retained temporarily in necromass and litter or stored in soils.

2.10 Statistical analyses

Exploratory multivariate analyses evaluated structural coherence and intertemporal dynamics of forest biomass and carbon stocks organized within the environmental asset accounting framework.

Correlation matrices were constructed using standardized values of tree density (individuals ha^{-1}), basal area, stem volume, biomass, and carbon dioxide equivalent.

Principal Component Analysis (PCA) was used to summarize multivariate information and to identify dominant structural and carbon storage gradients among accounting components. PCA ordination visualized temporal trajectories and the relative influence of growth and mortality processes on standing stock dynamics.

Hierarchical cluster analysis, using Euclidean distance and Ward's method, evaluated similarity among accounting components and monitoring periods. This procedure identified functional groupings of structural and carbon storage variables, revealing organizational patterns within the forest carbon system.

All variables were standardized prior to analysis to ensure comparability. Statistical analyses were conducted using R software. Table 2 summarizes the conversion factors adopted, and Figure 1 illustrates the methodological framework and analytical workflow.

3. RESULTS

3.1 Structural, biomass, and carbon dynamics of trees $\geq 20\ cm\ DBH$ (2009–2022)

The long-term assessment of trees $\geq 20\ cm\ DBH$ revealed contrasting dynamics between commercial and non-commercial components, with implications for forest structure, resource availability, and ecosystem functioning. Total standing volume remained approximately stable over

Table 2. Expansion and conversion factors applied for biomass and carbon estimation
Tabela 2. Fatores de expansão e conversão aplicados à estimativa de biomassa e carbono

Factor	Values used in this research*	Unit	Reference values	Reference	Function
Volume expansion factor (VEF)	1.00	dimensionless	1.25 (DBH of 10 to 30 cm) and, 1.22 (DBH 10 to 25 cm) 1.283 dense forest (DBH <25 cm) and, 1.506 open forest (DBH 10 to 31.7 cm)	Brown & Lugo (1992) Nogueira et al. (2008)	In the absence of an allometric equation, it is used to expand the stem volume for trees and saplings with DBH below the diameter classes monitored with volumetry.
Basic wood density (D)	0.63	t m ⁻³	0.69 0.63 - Tapajós National Forest	Brown & Lugo (1992) Carneiro et al. (2020)	Convert volume to trunk dry mass or stem biomass.
Biomass Expansion Factor (BEF) - Total Aboveground Biomass	1.58	dimensionless	1.58 1.58 - Recovering Forest	Brown & Lugo (1992) Sanquetta et al. (2019)	Expand the stem biomass into total aboveground biomass, including non-commercial parts of the trees such as large branches, twigs, leaves, and fruits.
Ratio (R) Root/aerial part - Belowground biomass	0.25	dimensionless	0.25 - Recovering Forest 0.25 - 0.37	Sanquetta et al. (2019) IPCC (2006)	To estimate belowground biomass from aboveground biomass.
Carbon Fraction (CF) in biomass	0.47	dimensionless	0.47 - 0.50	IPCC (2006) Tito et al. (2009)	Convert total biomass into carbon.
CO ₂ conversion factor (44/12)	3.67	dimensionless	3.67	IPCC (2006) Tito et al. (2009)	Convert carbon into carbon dioxide equivalent.

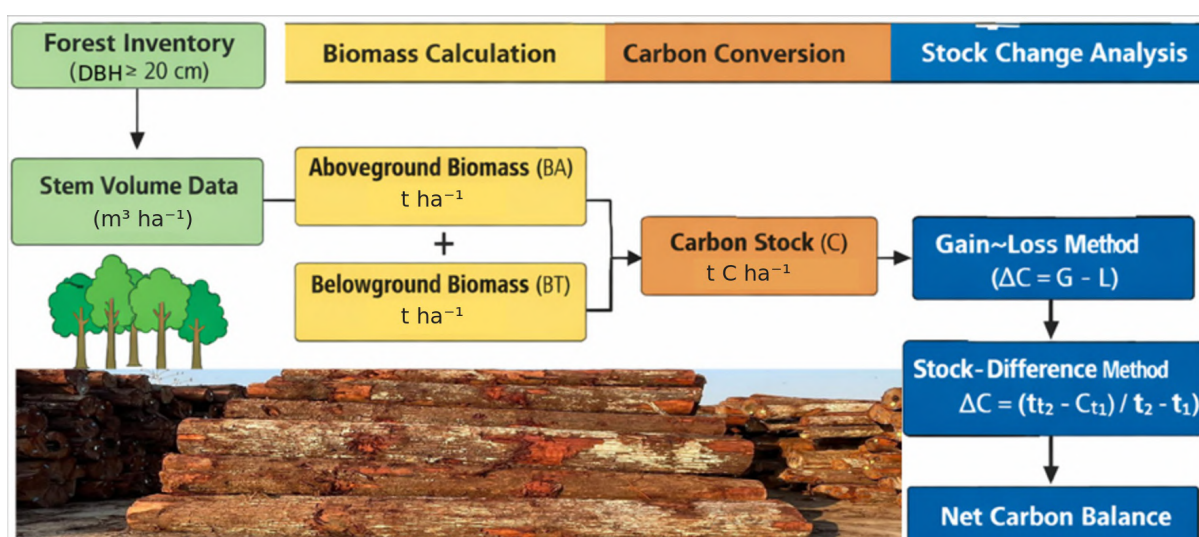


Figure 1. Diagram of the intertemporal assessment of biomass and carbon stock dynamics in a managed Amazonian forest

Figura 1. Diagrama da avaliação intertemporal da dinâmica da biomassa e dos estoques de carbono em uma floresta amazônica manejada

the 13-year period within the monitored component. However, this apparent stability masks divergent trends between resource components (Figure 2).

The commercial component exhibited a net decline in structural and functional metrics. Standing volume decreased by $11.22 \text{ m}^3 \text{ ha}^{-1}$, accompanied by reductions in total biomass (-13.96 t ha^{-1}) and carbon stock (-6.56 t ha^{-1}). These declines reflect the combined effects of harvesting and natural mortality, indicating that recruitment and growth of commercially valuable species were insufficient to fully compensate for removals. This pattern suggests increasing pressure on timber resources and highlights the slow recovery dynamics of commercially valuable species compared to the broader forest community.

In contrast, the non-commercial component showed positive gains across all structural and functional variables. Standing volume increased by $10.14 \text{ m}^3 \text{ ha}^{-1}$, accompanied by gains in total biomass ($+12.61 \text{ t ha}^{-1}$) and carbon stock ($+5.93 \text{ t ha}^{-1}$). These increases indicate biomass accumulation and structural change within the non-commercial component. The expansion of the non-commercial component reflects recruitment and growth processes that contributed to the observed stock recovery.

Declines in the commercial component were offset by increases in non-commercial biomass, resulting in overall structural stability. This compensation maintained the total monitored standing stock, although it did not restore the original commercial composition.

Although carbon stocks declined within the commercial component, gains in non-commercial biomass compensated for these losses. Consequently, the live-tree carbon stock monitored in this study remained approximately stable over time. These results identify the non-commercial component as the main source of compensation for losses in commercial trees.

Hierarchical clustering separated closely related structural and accounting components. Stem volume and biomass remained strongly associated because stem dimensions constitute the empirical basis of biomass estimation. Aboveground biomass,

total biomass, carbon, and CO_2 equivalent also formed close associations because these variables represent successive conversions of the same live-tree stock. Root biomass occupied a related position but represented a distinct allocation compartment. Ecologically, this organization indicates that changes in large-tree structure govern most of the monitored carbon variation. Statistically, part of the proximity among variables also results from their deterministic conversion relationships, so the groups should be interpreted as coherent accounting compartments rather than independent ecological processes.

3.2 Structural and functional basis of carbon accumulation and forest resilience

The first two principal components explained 97.2% of the total variation, with PC1 accounting for 62.1% and PC2 for 35.1% (Figure 2). PC1 represented the main gradient of biomass turnover and stock accumulation. The vectors associated with growth, mortality, final standing stock, and net stock change were oriented toward positive PC1 scores, indicating that this axis differentiated periods according to the magnitude of the recorded gains and losses. The similar orientation of the growth and mortality vectors does not imply equivalent ecological effects. It indicates that both processes contributed to the intensity of forest turnover during the monitoring intervals.

PC2 distinguished the temporal stages of post-harvest structural reorganization. The 2009–2011 interval occupied the negative portion of both axes and corresponded to the period of selective harvesting, elevated losses, and a negative stock balance. The 2011–2015 interval was positioned closer to the origin, indicating an intermediate condition in which gains and losses approached equilibrium. The 2015–2022 interval shifted toward positive PC2 scores and was associated with the recovery of standing stock and the expansion of the non-commercial component. The consolidated 2009–2022 balance was located in the positive portion of PC1, reflecting the cumulative magnitude of growth, recruitment, mortality, and harvesting over the entire monitoring period.

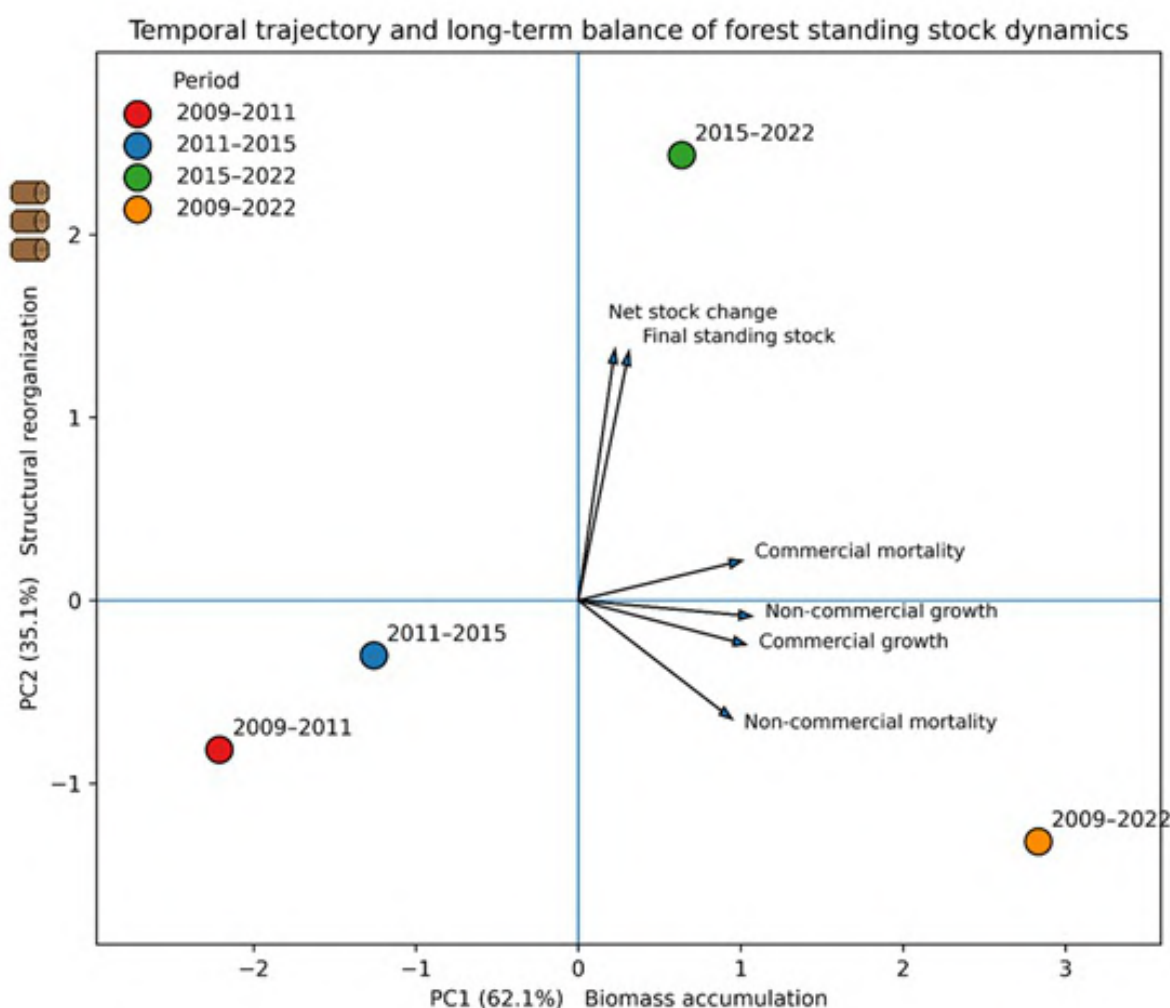


Figure 2. Temporal trajectory and long-term balance of forest standing stock dynamics revealed by principal component analysis (PCA)

Figura 2. Trajetória temporal e balanço de longo prazo da dinâmica do estoque florestal em pé, identificados por meio da análise de componentes principais (PCA)

The ordination therefore indicates that the recovery trajectory did not result from uniform restoration of all forest components. The commercial component remained below its initial volume, biomass, and carbon stocks, whereas gains in non-commercial trees compensated for most of these losses. The PCA therefore indicates evidence of structural redistribution rather than complete recovery of the pre-harvest commercial composition.

The hierarchical clustering complemented the temporal ordination by identifying close associations among stem volume, biomass, carbon stock, and CO₂ equivalent (Figure 3). These associations reflect the dependence of carbon storage on live-tree structure and the

sequential conversion of stem volume into biomass and carbon. Root biomass formed a related but distinct compartment because it was estimated from aboveground biomass through a fixed root-to-shoot ratio. Since several variables were mathematically derived from the same stem-volume data, the resulting clusters primarily indicate internal coherence in the accounting chain and should not be interpreted as independent ecological processes.

Together, the PCA and hierarchical clustering suggested that the approximate stability of total carbon stocks arose from compensation among forest components. Growth and recruitment in non-commercial trees offset much of the reduction in the

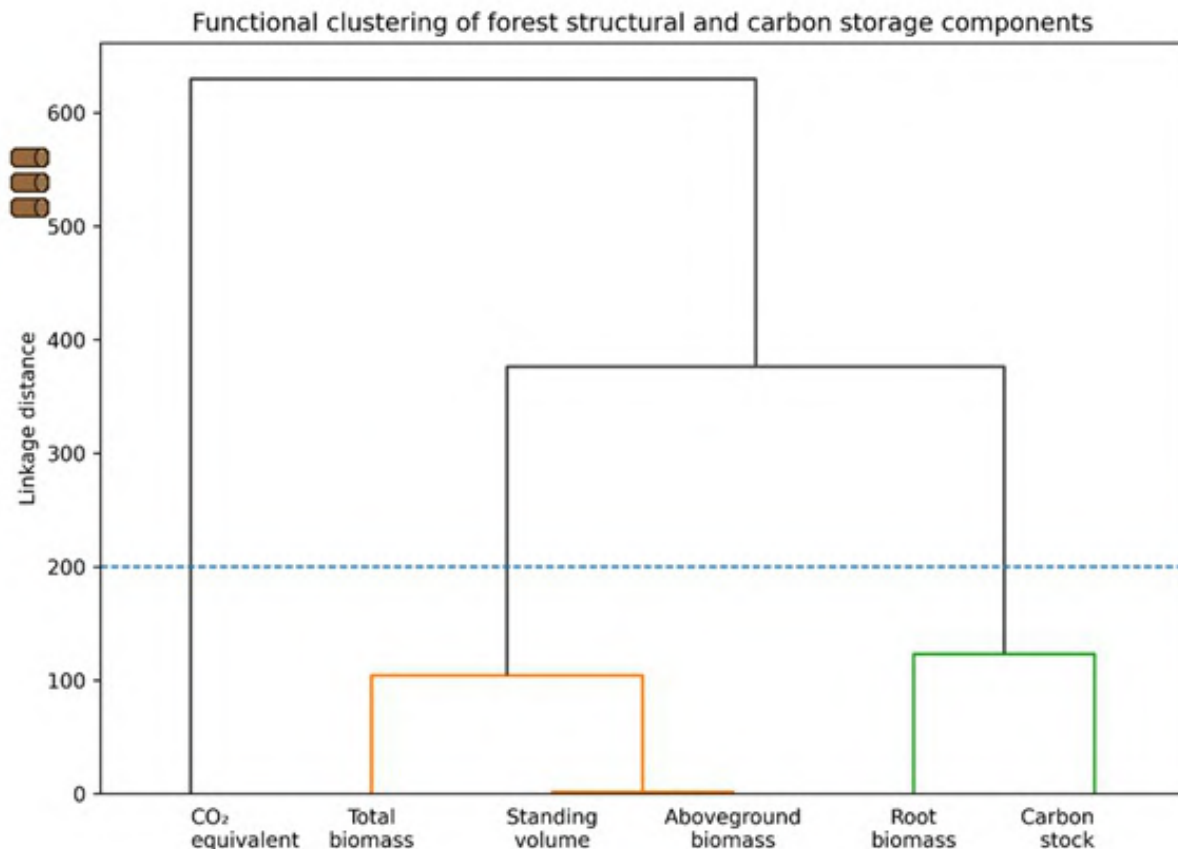


Figure 3. Hierarchical clustering (Ward's method) of forest structural and carbon components for trees ≥ 20 cm DBH (2009–2022)

Figura 3. Agrupamento hierárquico, pelo método de Ward, dos componentes estruturais da floresta e dos estoques de carbono para árvores com DAP ≥ 20 cm, no período de 2009 a 2022

commercial component, while mortality remained the principal source of biomass loss. Consequently, stable total carbon stocks coexisted with changes in forest structure, commercial composition, and future timber availability.

The sequential physical accounts provided the quantitative basis for this multivariate interpretation. After organizing the opening stocks and the additions and reductions associated with growth, recruitment, mortality, and harvesting, the accounting intervals revealed progressively improving balances following the initial post-harvest reduction (Table 3).

The initial accounting period from July 2009 to July 2011 recorded an opening live-tree volume stock of $259.62 \text{ m}^3 \text{ ha}^{-1}$. During this interval, recruitment and growth added $11.94 \text{ m}^3 \text{ ha}^{-1}$, while mortality reduced the stock by $16.20 \text{ m}^3 \text{ ha}^{-1}$ and selective harvesting removed $17.20 \text{ m}^3 \text{ ha}^{-1}$. These combined outflows exceeded gains, resulting

in a net reduction of $21.47 \text{ m}^3 \text{ ha}^{-1}$ and a closing stock of $238.15 \text{ m}^3 \text{ ha}^{-1}$.

From 2011 onward, no harvesting activities were recorded. Recruitment and growth consistently exceeded mortality losses, producing positive net balances of $3.13 \text{ m}^3 \text{ ha}^{-1}$ between 2011 and 2015 and $17.25 \text{ m}^3 \text{ ha}^{-1}$ between 2015 and 2022. This pattern indicates recovery of forest volume through natural dynamics following the initial harvest event. In accordance with environmental-economic accounting principles, the closing stock of each period was carried forward as the opening stock of the subsequent period, enabling consistent intertemporal tracking of physical assets and flows (United Nations, 2014).

3.3 Intertemporal variation of volume, biomass, and carbon stocks

Over the 13.1-year monitoring period, the initial stem volume of living trees was $259.62 \text{ m}^3 \text{ ha}^{-1}$ (Table 4). Total recruitment

Table 3. Sequential physical account of timber volume in Annual Production Unit 4, Tapajós National Forest

Tabela 3. Conta física sequencial do volume de madeira na Unidade de Produção Anual 4 da Floresta Nacional do Tapajós

Timber resource inventory	Volume V (m ³ ha ⁻¹)		
	July 2009 to July 2011	July 2011 to June 2015	June 2015 to August 2022
1. Initial stock of live trees	259.62	238.15	241.29
2. (Recruitment + growth)	11.94	26.80	48.64
Reductions			
3.1 Dead trees (standing and fallen)	-16.20	-23.67	-31.40
3.2 Harvest of live trees	-17.20	-	-
3. Total reductions	-33.40	-23.67	-31.40
4. Final live-tree stock (1+2-3)	238.15	241.29	258.53
5. Net balance for the period (4-1)	-21.47	3.13	17.25

Source: Research data derived from MFT reports.

Fonte: Dados derivados dos relatórios do MFT.

and growth amounted to 87.38 m³ ha⁻¹, while total reductions from mortality (71.27 m³ ha⁻¹) and harvesting (17.20 m³ ha⁻¹) summed to 88.47 m³ ha⁻¹. This balance resulted in a final stem volume of 258.54 m³ ha⁻¹, corresponding to a small net decrease of 1.09 m³ ha⁻¹, or 0.42% relative to the initial stock.

After applying expansion and conversion factors, the initial total biomass

stock was estimated at 323.03 t ha⁻¹. Recruitment and growth added 108.72 t ha⁻¹, while total reductions reached 110.07 t ha⁻¹, yielding a final biomass stock of 321.68 t ha⁻¹. This represents a net decrease of 1.35 t ha⁻¹ over the monitoring period, equivalent to an average annual change of -0.10 t ha⁻¹ yr⁻¹.

The initial carbon stock in living biomass was 151.83 t C ha⁻¹, corresponding

Table 4. Movement of stem volume, biomass, and carbon stocks between July 2009 and August 2022 (13.1 years)

Tabela 4. Movimentação do volume do fuste, da biomassa e dos estoques de carbono entre julho de 2009 e agosto de 2022, período correspondente a 13,1 anos

Resource	Timber Resource V (m ³ ha ⁻¹)			Biomass (t ha ⁻¹)		Carbon Stock (t ha ⁻¹)		
	1. Bole volume - Vf (DBH≥20 cm)	2. Total volume - Vt (Vf *FEV)	3. Biomass - B (Vt *D)	4. Aboveground biomass (AGB) Ba (B*BEF)	5. Belowground biomass (BGB) (Ba*R)	6. Total biomass (4+5)	C(Bt *FC)	CO ₂ eq (C*3.67)
1. Initial stock of live trees	259.62	259.62	163.56	258.43	64.61	323.03	151.83	557.20
2. (Recruitment + growth)	87.38	87.38	55.05	86.98	21.74	108.72	51.10	187.54
Reductions								
3.1 Dead trees (standing and fallen)	71.27	71.27	44.90	70.94	17.73	88.67	41.68	152.95
3.2 Harvest of live trees	17.20	17.20	10.84	17.12	4.28	21.40	10.06	36.92
3. Total reductions	88.47	88.47	55.73	88.06	22.01	110.07	51.73	189.87
4. Final live-tree stock (1+2-3)	258.54	258.54	162.88	257.35	64.34	321.68	151.19	554.87
5. Final balance for the period (4-1)	-1.09	-1.09	-0.68	-1.08	-0.27	-1.35	-0.64	-2.33

to 557.20 t CO₂ eq ha⁻¹. The final stock was 151.19 t C ha⁻¹ (554.87 t CO₂ eq ha⁻¹), resulting in a net reduction of 0.64 t C ha⁻¹ (2.33 t CO₂ eq ha⁻¹) over 13.1 years. This corresponds to a very low mean annual net emission of 0.049 t C ha⁻¹ yr⁻¹ (0.18 t CO₂ eq ha⁻¹ yr⁻¹).

3.4 Net balances and resilience of managed forest stocks

Over the monitoring period, the long-term physical accounts indicate that natural forest growth nearly offset total removals and mortality. Recruitment and growth accounted for 33.66 % of the initial stem volume stock, while mortality losses represented 27.45 % of the initial stock over the full period. This balance resulted in the near stabilization of timber volume, biomass, and carbon stocks.

The net annual stem volume increment averaged -0.08 m³ ha⁻¹ year⁻¹ over the 13.1-year period, corresponding to a relative growth rate of -0.03% per year. Gross annual increment reached 6.67 m³ ha⁻¹ year⁻¹, reflecting the high productivity of the managed forest system.

When post-harvest biomass losses were expanded using biomass conversion factors, the combined mortality and harvesting losses during the 2009–2011 interval totaled approximately 25 t ha⁻¹ of biomass, equivalent to 7.74 % of the biomass stock of live trees at that time.

Within the monitored component and the 13.1-year period, the physical accounts indicate that gains from growth and recruitment nearly compensated for mortality and harvest losses. The intertemporal accounting structure allowed consistent tracking of stocks and flows across volume, biomass, and carbon pools, providing a quantitative basis for evaluating stock changes under the applied management regime.

4. DISCUSSION

Dead biomass, composed of litter and necromass, plays a central role in forest carbon dynamics by functioning both as a temporary carbon reservoir and as a delayed source of atmospheric emissions through decomposition (Higa et al., 2014; IPCC, 2006). Litter includes leaves, fruits, flowers, bark fragments and fine branches smaller

than 2 cm in diameter, whereas necromass comprises coarse woody debris with diameters greater than 2 cm. These components differ markedly in residence time, decomposition rates and contributions to carbon fluxes, directly influencing estimates of ecosystem carbon balance.

More advanced accounting approaches, particularly those associated with IPCC Tier 2 and Tier 3, explicitly model transfers of biomass from living vegetation to dead organic matter pools and subsequent decomposition dynamics. These approaches allow estimation of carbon fluxes using Stock-Difference or Gain-Loss methods combined with empirically derived decomposition constants, providing a more realistic representation of ecosystem carbon turnover (IPCC, 2006).

Decomposition rates vary according to wood density, diameter, chemical composition and degree of soil contact. Low-resistance species may exhibit decomposition constants around 0.145, corresponding to half-lives of approximately 4.8 years. Moderately resistant species show constants near 0.077 and half-lives close to 9 years, whereas highly resistant species can retain carbon for several decades, with constants as low as 0.017 and half-lives exceeding 40 years (Summers, 1988). This heterogeneity strongly influences carbon persistence within forest systems and must be considered when interpreting net emission estimates.

In eastern Amazonia, litter production and accumulation exhibit substantial spatial variability. In a dense ombrophilous forest in Parauapebas, annual litterfall reached 5.73 t ha⁻¹ yr⁻¹, with a mean carbon content of 47.58%, and values ranging from 3.1 to 16.5 t ha⁻¹ yr⁻¹, depending on forest structure, successional stage, and edaphoclimatic conditions (Paiva et al., 2020). In the Jaru Biological Reserve, Rondônia, litter production reached 14.13 t ha⁻¹ yr⁻¹, with a decomposition coefficient of 1.37 and mean residence time of only 0.73 years, indicating a rapid turnover under favorable climatic conditions (Freire et al., 2020).

Decomposition dynamics strongly influence carbon transfers between forest pools and the atmosphere. Although this study adopted a Tier 1 approach, which assumes immediate release of carbon from



dead biomass, incorporating dead biomass dynamics in future assessments would reduce uncertainty and improve ecological realism in carbon accounting for managed Amazonian forests (IPCC, 2006). Over the 13.1-year monitoring period, natural ingrowth and tree growth exceeded reductions caused by mortality, resulting in a cumulative gross increment of $87.38 \text{ m}^3 \text{ ha}^{-1}$, equivalent to 33.66% of the initial standing volume. Despite the relatively high mortality rates, the gross volumetric balance remained positive.

The organization of physical accounts following the SEEA framework enabled evaluation of stock dynamics using both Gain-Loss and Stock-Difference approaches recommended by the IPCC (2006). The net annual volumetric increment reached $1.23 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, corresponding to a relative growth rate of 0.47% per year. This value falls within the range reported for dense ombrophilous forests in eastern Amazonia. In a secondary

forest in southeastern Pará, for example, the mean annual periodic increment was $6.71 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$, closely matching the gross increment observed in this study ($6.67 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) (Paiva et al., 2020).

The evidence summarized in Table 5 indicates that the approximate stability of total biomass and carbon in APU 4 was driven by interacting and compensatory processes. Mortality was the largest source of biomass reduction, selective harvesting intensified initial loss, and growth and recruitment in non-commercial trees compensated for most of the decline in the commercial component. The final balance therefore represents a period-specific outcome of the harvesting intensity, residual stand condition, demographic processes, and accounting boundary. It should not be interpreted as absence of post-harvest change or as complete recovery of the pre-harvest forest structure.

Table 5. Scientific findings supporting the interpretation of biomass and carbon stock dynamics in APU 4, Tapajós National Forest

Tabela 5. Evidências científicas que fundamentam a interpretação da dinâmica da biomassa e dos estoques de carbono na Unidade de Produção Anual 4 da Floresta Nacional do Tapajós

Reference and study context	Key finding	APU 4 result and interpretation
Sist et al. (2014), Eastern Amazon	Large trees represented a small proportion of stem density but approximately half of aboveground biomass. Their delayed post-logging mortality controlled net biomass change and could maintain a negative carbon balance for several years.	Mortality removed $71.27 \text{ m}^3 \text{ ha}^{-1}$, equivalent to 88.67 t ha^{-1} of total biomass and $41.68 \text{ t C ha}^{-1}$. Mortality was therefore the main reduction pathway, highlighting that structural recovery cannot be assessed from growth alone.
Putz et al. (2008), tropical managed forests	Reduced-impact logging decreases collateral damage and carbon emissions, but recovery depends on harvest intensity, residual damage, mortality, and cutting-cycle length.	Growth and recruitment added 108.72 t ha^{-1} of biomass, whereas mortality and harvesting removed 110.07 t ha^{-1} . The near balance depended on the applied management regime and monitoring horizon.
Condé et al. (2022), northern Brazilian Amazon	Timber volume and forest carbon stocks may remain approximately stable under specific management intensities, although long-term permanent-plot monitoring remains essential.	Carbon declined from 151.83 to $151.19 \text{ t C ha}^{-1}$, a net change of $-0.64 \text{ t C ha}^{-1}$ over 13.1 years. This convergence supports approximate stock stability, not complete structural recovery.
Heinrich et al. (2023), pantropical recovering forests	Secondary and degraded humid tropical forests accumulate substantial aboveground carbon, but recovery rates vary among regions and according to disturbance history and environmental conditions.	The non-commercial component gained 12.61 t ha^{-1} of biomass and 5.93 t C ha^{-1} , compensating most losses in commercial trees. Recovery therefore occurred through structural redistribution rather than restoration of the original commercial composition.
Chave et al. (2014), pantropical biomass allometry	Tree diameter, height, and wood density are major controls of aboveground biomass; species and structural variation must be represented to reduce estimation error.	The use of mean wood density (0.63 t m^{-3}), a biomass expansion factor of 1.58, and a root-to-shoot ratio of 0.25 preserves intertemporal consistency but introduces uncertainty into absolute stocks.
Nogueira et al. (2008), Brazilian Amazon biomass estimates	Inventory diameter limits, wood density, and volume-expansion procedures influence Amazonian biomass estimates and can create systematic differences among studies.	Trees with $\text{DBH} < 20 \text{ cm}$ were excluded and the volume expansion factor was set to 1.00. The final biomass stock of 321.68 t ha^{-1} therefore represents the monitored component and provides a conservative estimate of whole-stand biomass

The estimated initial biomass stock of 323.03 t ha⁻¹ and carbon stock of 557.20 t CO₂ eq ha⁻¹ fall within the range reported for terra firme forests in eastern Amazonia when expansion and conversion factors are applied (IPCC, 2006; Nogueira et al., 2008; Sanquetta et al., 2019). However, three sources of uncertainty affect the absolute values. First, a single mean wood density does not represent the wide interspecific variation in Amazonian forests and may shift estimates upward or downward, according to the abundance of light- or dense-wood species. Second, a fixed biomass expansion factor does not capture differences in crown architecture and allocation among species and diameter classes. Third, a constant root-to-shoot ratio simplifies belowground allocation, which varies with species and site conditions. Using the same factors in all four inventories strengthens temporal comparability, but it does not make the estimates species-specific or eliminate propagated uncertainty. The results therefore support inference about intertemporal direction and magnitude within the defined accounting boundary, while absolute whole-forest stocks require cautious interpretation (IPCC, 2006; Chave et al., 2014; Nogueira et al., 2008).

The DBH threshold introduces a separate and directional limitation. Individuals below 20 cm DBH were absent from the monitored stock even though small trees can represent a large share of stem density and a non-negligible fraction of biomass and carbon. Their omission likely reduced the estimated opening and closing stocks and excluded part of the regeneration pool until trees crossed the 20 cm threshold. Comparisons with inventories that include trees from 10 cm DBH, such as the study by Pimentel et al. (2024), must therefore consider different population boundaries. The fixed threshold remains suitable for evaluating changes in the monitored tree component, but the reported estimates should not be generalized to total ecosystem carbon.

Direct comparisons among Amazonian studies require caution due to differences in accounting boundaries, time horizons, inventory thresholds, and measurement technologies (Fearnside, 2008). Accordingly, the comparisons presented here provide

contextual interpretation rather than strict methodological equivalence.

Integrating IPCC methods with the SEEA accounting structure converts repeated forest inventories into sequential physical accounts that distinguish opening stocks, biological additions, natural losses, harvest removals, and closing stocks. At the management-unit scale, these accounts can support harvest planning, carbon certification and chain-of-custody systems, as well as the monitoring and valuation of forest carbon stocks, providing information that supports forest management and economic decision-making (Gorain et al., 2025). They can also provide auditable time series for forest certification and chain-of-custody systems, where verified stock changes and monitoring continuity strengthen evidence of environmental performance. For carbon monitoring, the same structure improves traceability between field measurements, conversion parameters, and reported CO₂-equivalent balances. At the policy level, standardized physical accounts can support management regulations, climate reporting, concession oversight, payment and incentive programs, and environmental statistics, provided that the inventory boundaries and associated uncertainties are maintained for each estimate (IPCC, 2019; United Nations, 2014; Obst et al., 2016; Ramihangihajason et al., 2025).

Selective logging removed 17.20 m³ ha⁻¹, equivalent to 6.63% of the initial standing volume, during the first monitoring interval. When combined with natural mortality, this extraction resulted in post-harvest biomass losses of approximately 25 t ha⁻¹, representing a reduction of 7.74% of the biomass stock in living trees. Comparable magnitudes have been reported in other managed Amazonian forests. In the Jamari National Forest, Rondônia, LiDAR-based models estimated biomass losses of 8.9% following selective logging with an average extraction intensity of 14.8 m³ ha⁻¹ (Gomes et al., 2020).

Condé et al. (2022) observed that, under moderate logging intensity in the northern Brazilian Amazon, timber volumes and forest carbon stocks remained essentially constant. The authors also emphasized the need for long-term monitoring using permanent plots. These findings indicate that carbon-stock



stability in managed Amazonian forests depends on logging intensity, post-harvest recovery, and continued monitoring.

West et al. (2014) provided long-term experimental evidence that the method of timber extraction strongly influences post-logging biomass trajectories. In Paragominas, Pará, the authors monitored a control plot and plots subjected to conventional logging and reduced-impact logging for 16 years. Although the commercial timber volumes felled under reduced-impact logging and conventional logging were similar (38.9 and 37.4 m³ ha⁻¹, respectively), the immediate losses of aboveground biomass differed considerably, reaching 17% under reduced-impact logging and 26% under conventional logging. The subsequent recovery trajectories were also contrasting. Mean annual aboveground biomass increment reached 2.8 t ha⁻¹ yr⁻¹ in response to reduced-impact logging and only 0.5 t ha⁻¹ yr⁻¹ under conventional logging. After 16 years, aboveground biomass returned to its initial level in response to reduced-impact logging but reached only 77% under conventional logging.

The APU 4 results show that harvested volume alone does not explain the response of the residual forest. Selective harvesting removed 17.20 m³ ha⁻¹, equivalent to 21.40 t ha⁻¹ of total biomass and 10.06 t C ha⁻¹. Over the complete monitoring period, mortality accounted for a larger reduction, removing 88.67 t ha⁻¹ of biomass and 41.68 t C ha⁻¹, whereas growth and recruitment added 108.72 t ha⁻¹ of biomass and 51.10 t C ha⁻¹. These flows resulted in a net biomass change of only -1.35 t ha⁻¹ after 13.1 years. A comparison with West et al. (2014) demonstrates that post-harvest recovery is determined by the interaction among logging practices, residual-tree damage, delayed mortality, growth, and recruitment.

The comparison also illustrates what biomass recovery represents. In the experiment reported by West et al. (2014), recovery was evaluated against the initial aboveground biomass of each treatment. In APU 4, the final total biomass approached the initial stock, but the commercial component remained below its original level, while non-commercial trees accumulated 12.61 t ha⁻¹ of biomass and 5.93 t C ha⁻¹.

Thus, approximate recovery of total biomass resulted from structural compensation among forest components and did not represent complete restoration of the pre-harvest commercial structure.

To contextualize the APU 4 results with evidence from managed tropical forests, Table 5 compares published findings with the quantitative patterns recorded in this study. The comparison does not assume strict equivalence among studies with different inventory thresholds, spatial scales, logging intensities, and monitoring periods. Rather, it identifies the ecological mechanisms that support, qualify, or limit the interpretation of the observed biomass and carbon balance.

5. CONCLUSION

The integration of IPCC methodological guidance with the SEEA Central Framework provided a consistent structure for organizing live-tree volume, biomass, and carbon stocks and flows. Within the monitored tree component (DBH ≥ 20 cm), gains from growth and recruitment nearly balanced mortality and harvesting over the 13.1-year period.

Multivariate analyses identified a transition from the first post-harvest condition toward later stock accumulation. Growth in the non-commercial component compensated for much of the decline in commercial trees. Thus, approximate stability of total carbon reflected structural compensation and did not indicate unchanged species composition, diameter structure, or timber availability.

Sequential stock-flow accounting allowed explicit quantification of additions and reductions associated with growth, mortality, and harvesting. This organization can support management planning, certification, carbon monitoring, and public reporting by linking field measurements to transparent physical accounts.

The estimates should be interpreted in light of several important limitations. Mean wood density, biomass expansion factors, and root-to-shoot ratios simplify variation among Amazonian species and compartments. The exclusion of trees below 20 cm DBH likely underestimated stand-level stocks and delayed representation of regeneration. Necromass, litter, or soil organic carbon

measurements were not included in the study either, so the results do not represent the complete ecosystem carbon balance.

Future assessments should combine repeated inventories with species-specific wood density, regional allometric equations, formal uncertainty propagation, measurements of smaller diameter classes, and direct monitoring of dead organic matter and soil carbon. These improvements will enable a more comprehensive evaluation of recovery, carbon permanence, and the environmental performance of managed Amazonian forests.

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AUTHOR CONTRIBUTIONS

Batista, F. R. O.: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review and editing, and Visualization; Melo, L. de O.: Methodology, Data curation, and Writing – original draft; Dias, C. T. dos S.: Formal analysis and Writing – review and editing; Martorano, L. G.: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review and editing, Visualization, Supervision, and Project administration.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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