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Prioritizing Amazon Forest conservation: Assessing potential biomass under climate change

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ABSTRACT

This study aims to identify the capacity of intact forests to maintain Above Ground Biomass (AGB) under new climate conditions. Using a predictive approach under different climate scenarios (SSP1–2.6 and SSP5–8.5), and considering the mean of General Circulation Models (GCMs) for the period (2021–2040), it was revealed that the regions with the greatest capacity for AGB in the optimistic scenario are concentrated in the northwest and southeast regions, covering the basins of the Negro, Xingu and Tapajós rivers. In the SSP5–8.5 scenario, although potential AGB gains are concentrated in the same regions, the spatial distribution is more restricted and dispersed. Indigenous Landsemerge as areas with the greatest potential AGB gains in both climate scenarios. However, these predictions do not include the impact of extreme climate events, such as storms, severe droughts, and wildfires, which could lead to an underestimation of actual biomass variations.

1. Introduction

Climate change is intensifying disturbances and altering the dynamics of terrestrial biomes (Higgins et al., 2023). The Amazon Forest biome, Earth's largest tropical forest region, is now accumulating less carbon than previously (Brienen et al., 2015), with some parts of the Basin already acting as net sources of carbono (Gatti et al., 2021). Both current and future Amazon forest carbon balance have been shown to be very sensitive to temperature (Galbraith et al., 2010, Sullivan et al., 2020). This has important consequences for conservation and resilience of Amazon forests, including those in indigenous land that stores large amounts of biomass (Ibáñez et al., 2019).

Factors such as soil nutrient availability, light competition, species diversity, and microclimatic conditions influence the growth of trees and underpin the spatial variation observed in Amazon forest dynamics (Esquivel-Muelbert et al., 2018; Uribe et al., 2023;

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Tavares et al., 2023). However, precipitation and temperature, as highlighted by Uribe et al. (2023), are underlying variables that directly and indirectly influence the amount of carbon assimilation and storage in the forest, and have the potential to accelerate aboveground biomass loss (Galbraith et al., 2013).

Under severe changes in climate, there are concerns that Amazon forests may transition into an alternative non-forest stable state, resulting in significant losses of aboveground biomass (AGB) (Flores et al., 2017; Ibáñez et al., 2019; Pinho et al., 2020). Understanding these effects is crucial, as the abundance of AGB stored in these forests, estimated at around 60–140 PgC (petagrams of carbon) over an area of 6 million km^2 (Galbraith et al., 2010), plays a key role in climate stabilization, helping to reduce Greenhouse gases (GHG) and promote the resilience of natural ecosystems to climate change (Walker et al., 2020; Tavares et al., 2023).

Conservation and restoration of vegetated areas in the Amazon are crucial for global climate balance (Pan et al., 2013). However, the remaining forests in protected areas, such as Conservation Units (UC's), Indigenous Lands (TI's) and Non-Destined Public Forests (FPND) are facing degradation because of agricultural expansion and uncontrolled fires, threatening biodiversity, and the guarantee of service provision ecosystems. The effectiveness of these areas in conserving native vegetation is compromised by a range of environmental stressors, including climate change (Walker et al., 2020). Therefore, understanding how Amazon forests will be impacted by changes in climate is necessary to strengthen the management of these areas and protect biodiversity. This study contributes to conservation efforts in the Amazon by analyzing the capacity of intact primary forests in the Brazilian Amazon to increase AGB under projected climate change patterns. Specifically, we aimed to prioritize the identification of areas with high potential for AGB gain in the biome, not only for the purpose of conserving biodiversity but also to strengthen the Amazonian ecosystem's resilience to climate change. This approach guides forest management and conservation practices to ensure environmental sustainability and the well-being of local communities, emphasizing the importance of prioritizing areas with biomass gain potential for conservation.

2. Methods

2.1. Study area

The study focuses on the Amazon Forest biome, located in the northern region of Brazil, delineated by the Brazilian Institute of Geography and Statistics (IBGE), full covering six states and partially four others (Fig. 1). The region, characterized by forests, spans

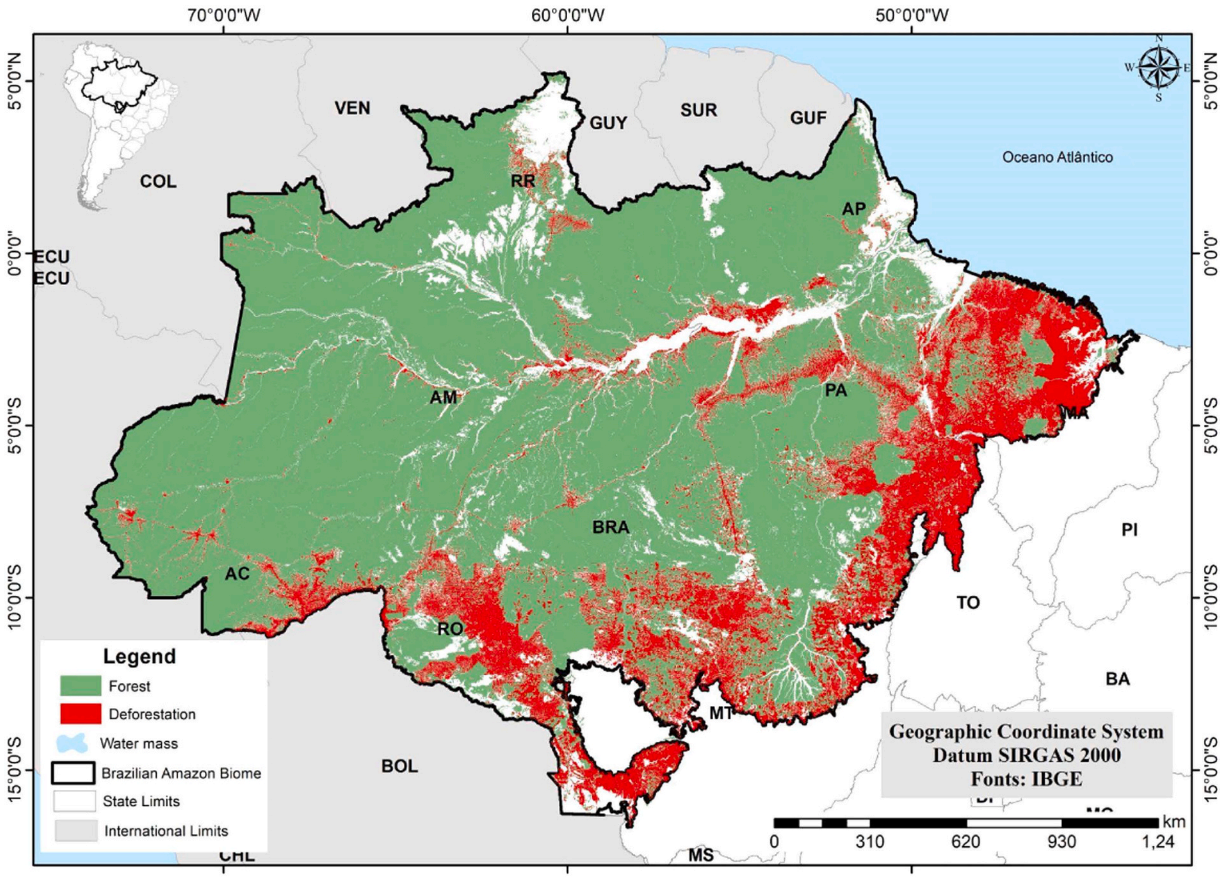

Fig. 1. - Location of the study area in the Brazilian Amazon Forest biome.

approximately 4 million km^2 (INPE - National Institute for Space Research, 2023), of which about 20 % has already been deforested, underscoring the urgency of scientific research to understand and mitigate the human impacts and climate change in this important global biome. It is important to emphasize that deforestation, fires, and logging are not included in the predictions.

2.2. Estimation of forest biomass

To estimate forest biomass, the AGB database from the *Global Ecosystem Dynamics Investigation* (GEDI) Level 4 A *Footprint level above ground biomass* (L4A), version 2.1, was adopted as a data source (Dubayah et al., 2022). GEDI, a *Light Detection and Ranging* (LiDAR) laser instrument, stands out for - ability to penetrate dense forest canopies, providing comprehensive and detailed sampling, which is essential for obtaining AGB estimates in Mg.ha^{-1} (Sun et al., 2022). This feature is relevant for the analysis of tropical forests, where canopy density can significantly obstruct data collection from other types of remote sensors. The level 4 products include interpolated data to estimate the average biomass in 1 km cells.

The selection of structurally intact Amazon forest areas was guided by the application of rigorous filters, aiming to mitigate the impact of human influence. The Global Consensus Land Cover (GLCC, v2) was used, which offers detailed information on land cover, including data on cultivated and managed vegetation, as well as urban/built areas, to assist in the exclusion of regions affected by anthropization (Tuanmu and Jetz, 2014). The resolution is 1 km and the time period is 2000–2006, providing the percent cover of each land cover type within the 1 km cells. This approach is more precise than other land cover products that are categorical, where each cell is attributed to the land cover type that exceeds 50 % of the cell's area. The Intact Forest Landscapes (IFL) product was used to identifying areas of forest that remain structurally intact and conserved, without significant signs of human activity, ensuring that the selected sample adequately represented forests in a natural state (Potapov et al., 2017).

After applying these filters, an exclusion criterion was adopted for AGB points lower than 50 Mg.ha^{-1}, to eliminate herbaceous and shrubby vegetation, thus focusing on forest areas with significant aerial biomass. This selection and filtering process is essential to ensure the accuracy of AGB estimates, reducing the risk of including non-forest or degraded areas that could distort the results.

Subsequently, the GEDI 1 km cell of interpolated biomass were validated from the forest inventory plots for an analysis of the model's accuracy, using metrics such as Mean Absolute Error (MAE) (see Fig. S1.-Supporting Information Appendix), Root Mean Square Error (RMSE) (see Fig. S1- Supporting Information Appendix) and Willmott indices (Willmott et al., 2011). The results provide a measure of the precision and reliability of AGB estimates by presenting a moderate positive correlation between the observed (RAINFOR) (Mitchard et al., 2014; Lopez-Gonzalez et al., 2014) and predicted (current AGB) variables (Fig. 2), with a 95 % confidence interval between 0.38 and 0.67. Furthermore, the model's RMSE varies between 92.80 Mg.ha^{-1} and 120.79 Mg.ha^{-1} (see Fig. S1-Supporting Information Appendix), and the model's MAE varies between 72.28 Mg.ha^{-1} and 95.99 Mg.ha^{-1}. These metrics show that the model provides estimates without a systematic tendency to overestimate or underestimate observed values, suggesting a consistent relationship between model predictions and actual observed values (see Table S2 -Supporting Information Appendix). In short, the results of the model accuracy analysis are effective.

The variability in RAINFOR data, due to the small size of plots (1 ha), may challenge the accurate correlation with GEDI predictions. However, the use of RAINFOR data highlights a fundamental consistency in the methodology, ensuring a robust analysis of forest biomass.

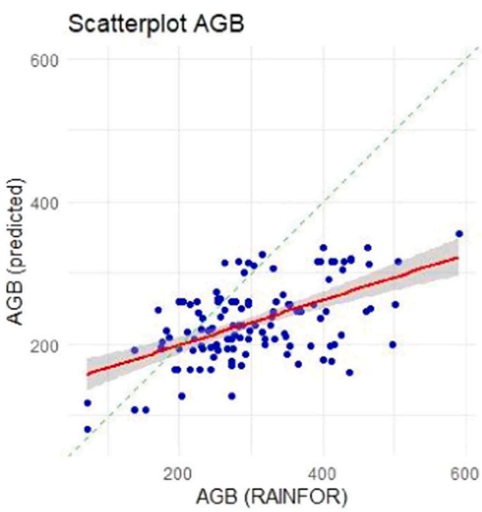

Fig. 2. Scatterplot of AGB (RAINFOR) versus AGB (predicted).

2.3. Data on protected areas

The data were obtained from governmental sources. The Chico Mendes Institute for Biodiversity Conservation (ICMBIO) provided information on UC's, the National Indian Foundation (FUNAI) on TI's, and the Brazilian Forest Service (SFB), under the Ministry of Environment and Climate Change (MMA), on FPND (ICMBio - Chico Mendes Institute for Biodiversity Conservation, 2023; FUNAI – National Indian Foundation, 2020; SBF - Brazilian Forest Service SFB, 2024). In total, 365 protected areas were analyzed: 159 UC's covering 684,020 km^2, 206 TI's covering 1,034,332 km^2, and FPND areas covering 325,241 km^2.

2.4. Construction of the climate database

The climate data was obtained from WORLDCLIM, an internationally recognized platform for providing both contemporary climate data and future projections at various scales. The spatial resolution of the data is 10 minutes, covering approximately 340 km^2 per data point in the study area.

The current climate datasets were extracted from annual averages, derived from monthly records spanning from 1970 to 2000. Four bioclimatic variables were prioritized due to their relevance for understanding ecological processes in the Amazon and facilitating the analysis of the Amazon forest's resilience capacity in the face of environmental changes. These variables include: Average Annual Temperature (°C) (BIO1); Annual Temperature Range (°C) (BIO7); Accumulated Precipitation ($mm.year^{-1}$) (BIO12); and Precipitation Seasonality (%) (BIO 15). These variables were chosen because they are essential for modeling the resilience of the Amazon ecosystem (Anjos and Toledo, 2018).

For short-term climate projections, covering the period from 2021 to 2040, bioclimatic data were used from scenarios developed within the scope of the *World Climate Research Program Coupled Model Intercomparison Project Phase 6* (CMIP6). In this context, five General Circulation Models (GCMs) were selected based on rigorous reliability criteria, which include Equilibrium Climate Sensibility (ECS) and Transient Climate Response (TCR). The models chosen were: BCC-CSM2-MR, MIROC-ES2L, CNRM-CM6–1, CNRM-ESM2–1and MIROC6, which are detailed in Wu et al. (2019), Hajima et al. (2020), Voldoire et al. (2019), Séférian et al. (2019) and Tatebe et al. (2019), respectively (see Table S1 - Supporting Information Appendix). After the selection, an "ensemble" was performed to highlight the most consensual predictions among the different modeling methods, aiming to mitigate the effects of uncertainties in the forecasts (Franklin and Miller, 2010; Diniz-Filho et al., 2009). For each of the four climatic attributes, the five models were chosen based on low correlations and low collinearity, according to Anjos and Toledo (2018). These more sensitive models use ECR and TSR as references, following the IPCC guidelines.

CMIP6 data were analyzed considering four different climate scenarios. However, this study focused especially on the most optimistic scenario, characterized by low GHG emissions (SSP1–2.6), and the most pessimistic scenario, associated with high GHG emissions (SSP5–8.5). These scenarios are outlined by the IPCC and represent divergent trajectories of emissions and climate policies until the year 2100, incorporating variables of social, economic and technological development, population growth, environmental concerns and regional differences (Silva-Bezerra et al., 2022). The SSP1–2.6 scenario suggests a trajectory of reduced emissions, with strong climate change mitigation, while the SSP5–8.5 scenario predicts high emissions, leading to a significant increase in global temperature and more severe impacts on the climate and the environment.

2.5. AGB underfuture climatic conditions

We used the present-day relationship between GEDI-derived AGB and four climate attributes from WorldClim (BIO1, BIO7, BIO12 and BIO15), to develop a multiple linear regression model (LM) that predicts AGB response to these same climate attributes in the near future (2021–2040) (see Fig. S2.-Supporting Information Appendix).

However, in the analysis of the LM residues it was found that there was spatial dependence. For this reason, and also to understand the distribution patterns of AGB in the current scenario, the Geographically Weighted Regression (GWR) method was used (Brunsdon et al., 1996). This approach allowed a detailed exploration of the spatial variations of the AGB, resulting in a global coefficient of determination (GlobalR^2) of 0.42. This result shows that the GWR model explained a considerable fraction of the spatial variation observed in AGB. The success of this modeling is due, in part, to the careful change of the bandwidth parameter, set at 0.07 for the spatial coordinates of the data, which optimized the interpretation of the spatial influence between observations, reflected in a residual standard error of 58.35 $Mg.ha^{-1}$.

The forest cover percentage, which is the proportion of a cell's area covered by forest relative to the total area of the cell, was used in the study to calculate the average value of AGB for each 1 km×1 km pixel. This value was adjusted proportionally based on the present forest cover, assuming that the maximum AGB value represents the maximum potential biomass that a forest could achieve in that specific location. This approach allows for obtaining more precise estimates of AGB, taking into account the variation in vegetation density within a cell.

Using the AGB model fitted under for current conditions, it was possible to predict the future of AGB under different climate scenarios. This was done using bioclimatic variables to estimate AGB across four distinct scenarios in a short-term horizon. The results were compared with contemporary data to assess the impact of climate change on AGB distribution and potential, informing forest conservation and management strategies.

3. Results

3.1. General trend of potential AGB change under short-term future climate scenarios

Fig. 3 illustrates the potential change in AGB in two contrasting scenarios, defined as the optimistic scenario (SSP1–2.6) and the pessimistic scenario (SSP5–8.5), for the short-term time interval between 2021 and 2040 in the Amazon Forest biome. Data analysis shows that a significant proportion of the biome is predisposed to experience reductions in potential AGB, with projections estimating losses across approximately 74 % and 79 % of the biome in the optimistic and pessimistic scenarios, respectively. These results suggest a correlation between projected climate changes and the decrease in AGB in a large part of the biome, regardless of the future scenario considered.

Intact forests having limited adaptive capacity occupy approximately 1.5 million km^2 under the SSP1–2.6 scenario, while for the SSP5–8.5 scenario, the estimated area is around 1.6 million km^2. AGB potential losses are predominantly in the north and southwest regions under the SSP1–2.6 scenario. In the SSP5–8.5 scenario, besides these areas, significant reductions in AGB are also observed in the northeast and south regions.

Green tones in the two rightmost panels of Fig. 3 indicate areas with potential for biomass gain for the optimistic climate scenario, the spatial mean of the new equilibrium forest biomass across all cells predicted to increase AGB, is 177 $Mg.ha^{-1}$. For the pessimistic scenario, the new equilibrium AGB is 160 $Mg.ha^{-1}$. Thus, in the optimistic scenario, the average AGB is approximately 10.5 % higher than that projected in the pessimistic scenario.

The mapping performed under the SSP1–2.6 scenario shows that the areas with potential for AGB recovery are in the northwest and southeast regions of the biome, covering the basins of the Negro, Xingu and Tapajós rivers. In this scenario, AGB equilibrium gains are distributed across several fragments throughout the biome. In contrast, in the SSP5–8.5 scenario, although AGB equilibrium gains are concentrated in the same regions, they have a more restricted and dispersed spatial distribution across the landscape (Fig. 3). The results highlight consistent patterns in the Amazon, emphasizing the need for proactive strategies to address climate change.

3.2. Analysis of AGB potential gain and loss in the Amazon States

The results in Fig. 4 present two scenarios of GHG emissions (SSP1–2.6 and SSP5–8.5) for the area and AGB in Brazilian Amazon states. The analysis covers gains and losses in area (in 1000 km^2) and the average AGB (in $Mg.ha^{-1}$).

The variations in AGB gain and loss among the Amazonian states are significant in both scenarios. In the SSP1–2.6 scenario, Amazonas lost about 1000 km^2 of area and 80 $Mg.ha^{-1}$ of AGB, while Roraima had a small gain of 50 km^2 and 5 $Mg.ha^{-1}$ of AGB. In the SSP5–8.5 scenario, Amazonas continued to lose 1000 km^2 and 90 $Mg.ha^{-1}$ of AGB. Pará also faced moderate losses of 200 km^2 and 50 $Mg.ha^{-1}$ in the SSP1–2.6 scenario, increasing to 500 km^2 and 60 $Mg.ha^{-1}$ in the SSP5–8.5 scenario (Fig. 4). The charts show the variation in Y1 area (in thousand km^2) and Y2 average AGB (in $Mg.ha^{-1}$) under two climate change scenarios: SSP1–2.6 (upper chart) and SSP5–8.5 (lower chart). Red bars indicate loss of area and triangles AGB average reduction, while green bars indicate gain of area and dots AGB average increase.

In the SSP1–2.6 scenario, the states of Amapá, Maranhão, and Roraima stood out with the highest average AGB gains, recording 65 $Mg.ha^{-1}$, 64 $Mg.ha^{-1}$, and 45 $Mg.ha^{-1}$, respectively. However, the same scenario showed significant losses, with Amapá, Rondônia, and Amazonas presenting average losses of −106 $Mg.ha^{-1}$, −48 $Mg.ha^{-1}$, and −47 $Mg.ha^{-1}$, respectively (Fig. 4).

In the SSP5–8.5 scenario, the average AGB gains were considerably lower compared to SSP1–2.6, with Maranhão and Roraima leading with gains of 60 $Mg.ha^{-1}$ and 43 $Mg.ha^{-1}$, respectively. On the other hand, AGB losses were more pronounced in this scenario, with Amapá, Pará, and Mato Grosso suffering average losses of −146 $Mg.ha^{-1}$, −74 $Mg.ha^{-1}$, and −72 $Mg.ha^{-1}$, respectively (Fig. 4).

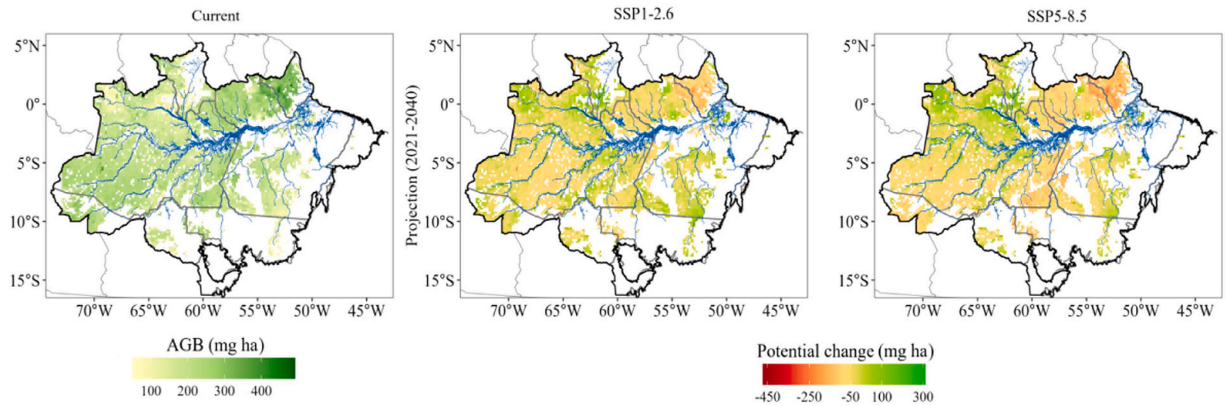

Fig. 3. Potential Change in Above Ground Biomass (AGB) under contrasting climate scenarios, based on optimistic (SSP1–2.6) and pessimistic (SSP5–8.5) climate prediction models for the short-term period (2021–2040) in the biome Amazon. The effects of deforestation and fire are not included in the two future scenarios analyzed.

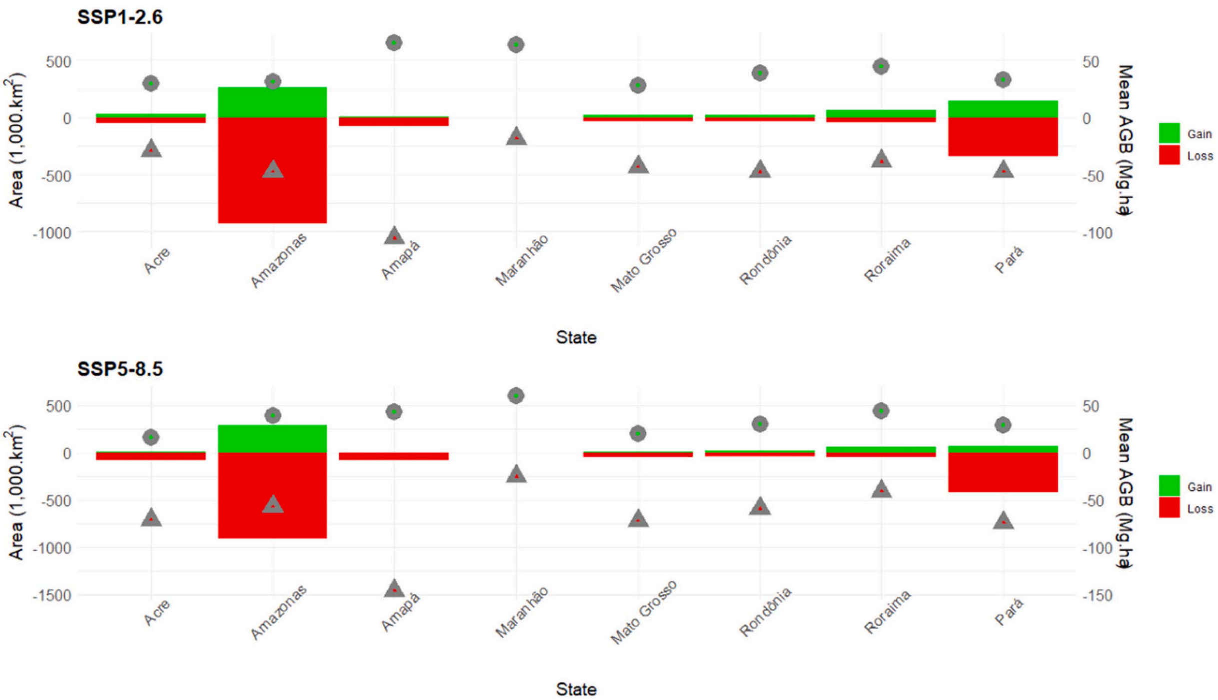

Fig. 4. Comparative Analysis of AGB Gain and Loss in SSP1–2.6 and SSP5–8.5 Scenarios for Different Amazonian States.

Fig. 4 in terms of AGB area gain (in km^2), Amazonas was the positive highlight in both scenarios analyzed. In the SSP1–2.6 scenario, it led with the largest gain of 262 km^2, followed by Pará with 143 km^2 and Roraima with 61 km^2. In the SSP5–8.5 scenario, Amazonas maintained its leadership with 284 km^2, followed by Pará with approximately 70 km^2 and Roraima with 54 km^2. Thus, while Amazonas had a small increase of 22 km^2 in AGB area in the pessimistic scenario, Pará and Roraima experienced losses of 73 km^2 and 7 km^2, respectively, compared to the SSP1–2.6 scenario.

In the SSP1–2.6 scenario, Amazonas and Pará were the states that lost the most AGB area (in km^2), with significant losses of 933 km^2 and 345 km^2, respectively. In the SSP5–8.5 scenario, Amazonas also stood out with a loss of AGB area of 910 km^2 (Fig. 4).

The Table S3 (Supporting Information Appendix) shows the projected changes of AGB, along with the total area of intact forest, across the Amazonian states under two climate scenarios (SSP1–2.6 and SSP5–8.5) for the period 2021–2040. It highlights significant variations among states: while some, like Amazonas and Pará, exhibit substantial AGB gains despite losses, others experience more pronounced losses compared to gains. The data underscore the complex interaction between climate scenarios and regional forest dynamics, providing crucial insights for sustainable management and conservation strategies in the Amazon region.

3.3. Analysis of AGB potential gain in protected areas

This section examines Amazon protected areas and their potential for AGB gains over a short-term time horizon (2021–2040), under two distinct climate scenarios: the most optimistic, SSP1–2.6, and the most pessimistic, SSP5–8.5. The protected areas under analysis include UC's, TI's and FPND.

Twenty percent of UC's show an increase potential AGB under the SSP1–2.6 scenario. In the SSP5–8.5 scenario, which assumes higher carbon emissions and lower mitigation efforts, the fraction of UC's with AGB potential gains decreases to 19 %. For TI's, 19 % of them had a potential gain in AGB in the SSP1–2.6 scenario, which reduces to 14 % under SSP5–8.5. Regarding FPND awaiting designation for conservation or sustainable use, approximately 22 % of them exhibit AGB potential gains in the SSP1–2.6 scenario, increasing slightly to 23 % in the SSP5–8.5 scenario.

Fig. 5 illustrates the climate scenarios for potential AGB gain in scenarios SSP1–2.6 and SSP5–8.5 for the short-term period (2021–2040) in the Amazon Forest biome, highlighting information from protected areas.

The results indicate that protected areas, covering about 98 % of the examined forest regions, play a crucial role in conserving and increasing AGB, especially under the SSP1–2.6 scenario, where potential gains are about 23 % greater than in the SSP1–2.6 scenario. SSP5–8.5. In the short term, AGB potential gains in the SSP1–2.6 scenario are estimated at 539,929.12 km^2, distributed across 135,084.79 km^2 in UC's, 198,755.65 km^2 in TI's and 72,165.27 km^2 in FPND. For SSP5–8.5, the AGB potential gain is estimated at 439,476.66 km^2, with a distribution of 131,594.45 km^2 in UC's, 145,001.78 km^2 in TI's and 74,982.56 km^2 in FPND (Fig. 5).

In scenarios SSP1–2.6 and SSP5–8.5, TI's emerges as areas with the highest proportion of AGB equilibrium gains, with approximately 37 % and 33 %, respectively. Then, the UC's follow with 25 % in SSP1–2.6 % and 30 % (SSP5–8.5). Finally, FPND register lower proportions, 13 % (SSP1–2.6) and 17 % (SSP5–8.5). These results emphasize the significant role of TI's in the conservation and

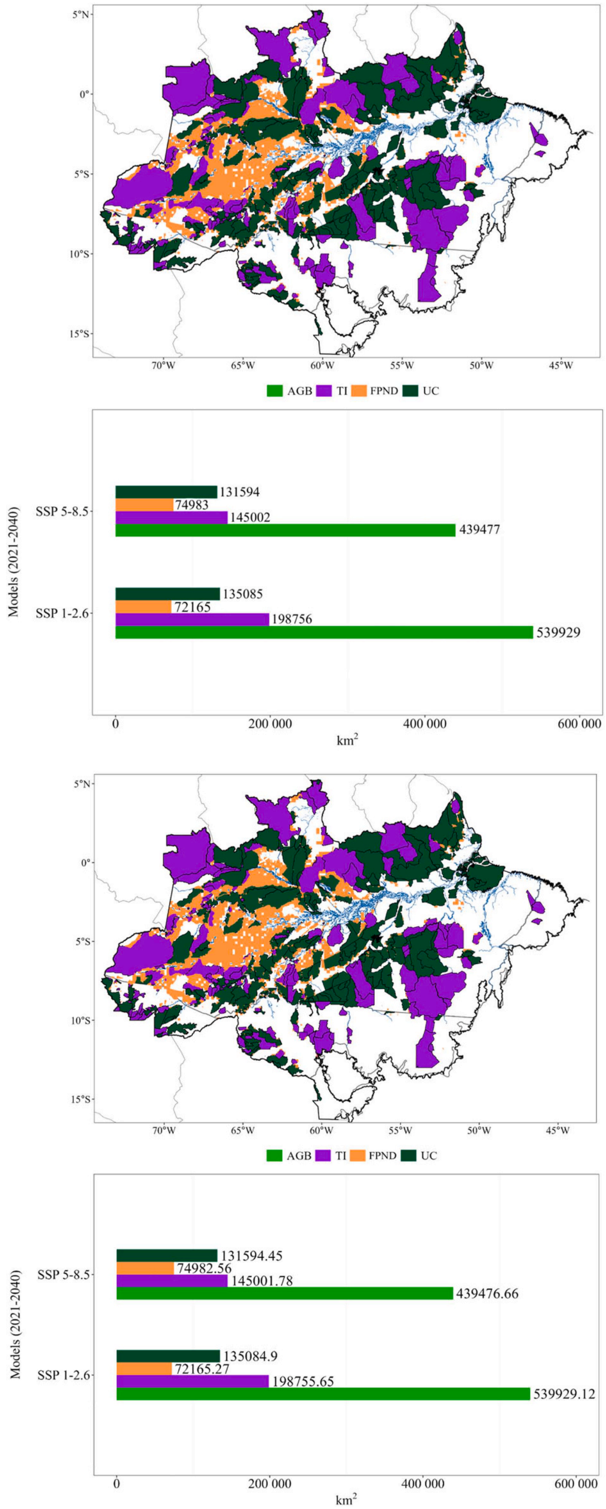

Fig. 5. Map shows areas of the Brazilian Amazon Forest Biome occupied by Indigenous Lands (TI), Non-destined Public Lands (FPND), and Conservation Areas (UC). Graph shows area (km^2) of Intact Amazon Forest Biome that the two models predict to have potential biomass gain (AGB), with further breakdown by TI, FPND and UC Amazon Forest biome.

increase of AGB, followed by UC's, regardless of the scenario considered (Fig. 5).

3.4. Adaptive performance of protected areas under different climate scenarios

The study investigates how protected areas in the Amazon adapt to different climate scenarios. The analysis in Fig. 6 compares the adaptive performance of UC's and TI's in terms of AGB potential gain under optimistic (SSP1–2.6) and pessimistic (SSP5–8.5) climate change scenarios.

The spatial distribution of protected areas, as illustrated in Fig. 6, shows a notable difference between the two scenarios. In the optimistic scenario SSP1–2.6, protected areas, especially TI's, are well distributed, with a significant presence near the agricultural frontier along the entire edge of the Amazon. In contrast, in the pessimistic scenario SSP5–8.5, protected areas tend to concentrate more in the western extreme of the Amazon, particularly in the states of Acre and Amazonas, indicating a preference for regions less affected by human intervention.

When analyzing the sizes and AGB potential gains of the 15 UC's and TI's under the SSP1–2.6 and SSP5–8.5 climate scenarios, we noticed that the dimensions of these protected areas are quite similar between the two categories. However, when we focus on AGB potential gain results, a notable distinction emerges. Specifically in the TI's, two of them achieved an impressive feat, reaching 100 % AGB potential gain, a mark not observed in any of the UC's. This data suggests greater effectiveness of TI's in conserving their primary forests.

Among the UC's, two stand out notably: the Itatupã-Baquiá Sustainable Development Reserve (RDS) and the Terra Grande- Pracuuba Extractive Reserve (Resex), both located in the state of Pará. These UC's reached the top positions in the ranking in both

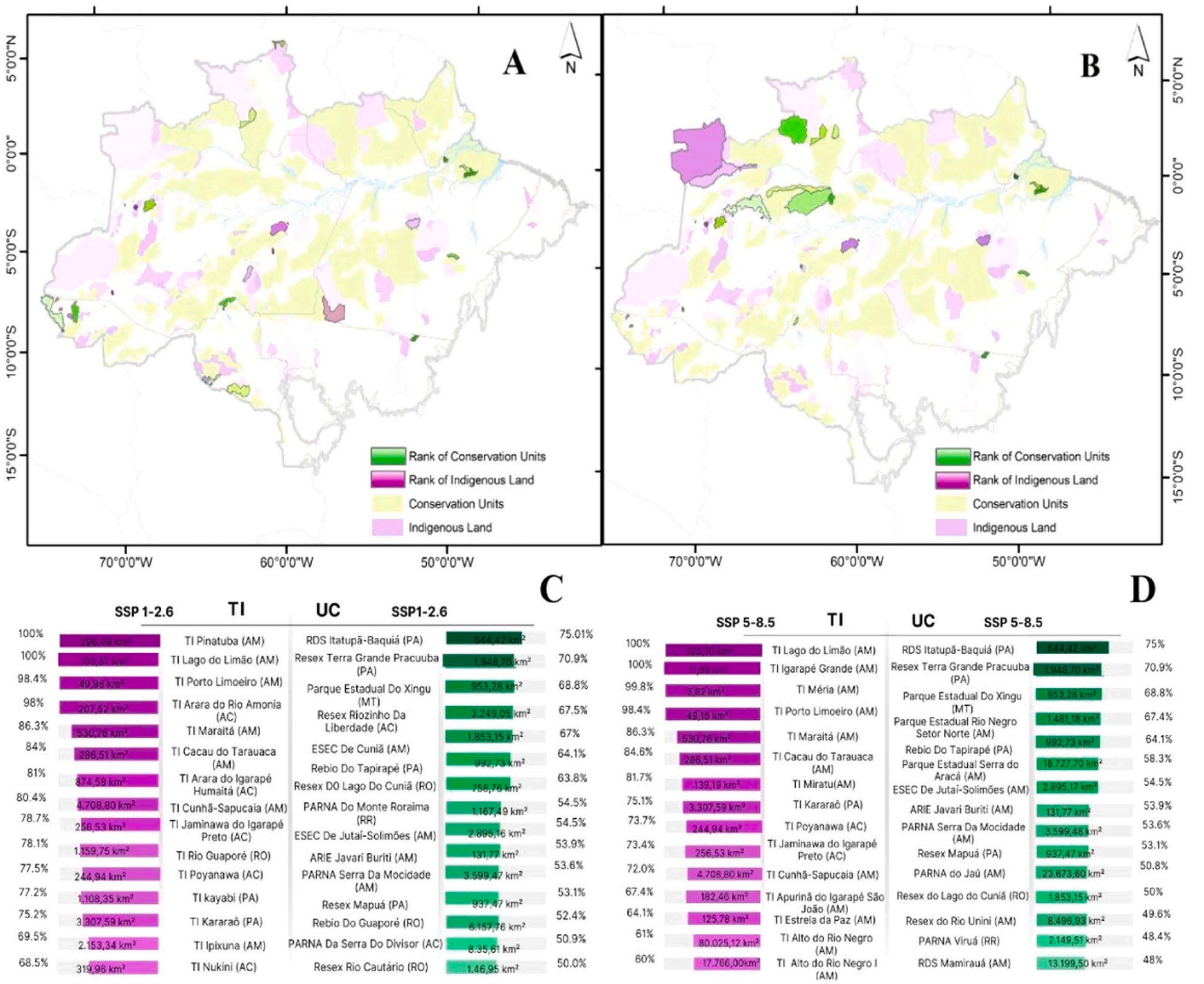

Fig. 6. Distribution of the delimitation of Protected Areas in the SSP1–2.6 (A) and SSP5–8.5 (B) scenario, for the short-term period (2021–2040), in the Amazon. Presentation of the Ranking of the 15 UC's and TI's with the greatest adaptive capacity to potential gain AGB in their respective areas for SSP1–2.6 (C) and SSP5–8.5 (D) scenarios.

scenarios, SSP1–2.6 and SSP5–8.5, with potential gains of 75 % and 70.9 %, respectively, in terms of AGB.

When comparing the aggregate performance of the 15 TI's and UC's in the SSP1–2.6 scenario, it is observed that the TI's achieved a total potential gain of 78 % in AGB, while the UC's achieved 56 %. In the SSP5–8.5 scenario, the difference between the two categories of protected areas narrows to 9 percentage points, with UC's registering a potential gain of 53 % and TI's, 62 %. These results indicate that, over time, TI's demonstrated a superior ability to increase AGB, as illustrated in Fig. 6 C and D.

4. Discussion

Our analysis of the impact of climate change on near-future AGB of Amazon forests reveals a worrying scenario for the future of the largest tropical forest in the world. This study, aligned with the projections of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (GCM of CMP5), suggests significant losses of AGB, with direct implications for GHG mitigation efforts and biome conservation.

The relationship between AGB and climatic attributes reflects a rapid forest response to new climatic conditions. However, these predictions do not account for extreme weather events such as storms and severe droughts or for the occurrence of forest fires, which can markedly alter forest structure. For instance, Restrepo-Coupe et al. (2023) found that a forest near Santarém took at least a year to recover after the 2015 drought. Therefore, the forecasts may underestimate actual variations in biomass.

The prediction that the southern and eastern regions of the Amazon will suffer the greatest equilibrium losses, potentially leading to the replacement of the tropical forest with vegetation with drier characteristics, highlights the urgency of actions aimed at conservation and sustainable management in these regions (Arruda et al., 2024). The decrease in carbon storage in the AGB, highlighted by Bunker et al. (2005), and the projection that potential losses will almost double in relation to gains (Walker et al., 2020), highlight the magnitude of the challenge we face.

Gomes et al. (2019) indicate that nearly half of the tree species in the Amazon will be at risk of extinction by 2050 due to global warming, especially in the eastern, southern, and a large portion of the southwestern parts. This biodiversity threat may impact AGB in the region, reducing plant diversity, altering nutrient cycles, modifying growth patterns, and increasing vulnerability to natural disturbances (Esquivel-Muelbert et al., 2018; Uribe et al., 2023; Tavares et al., 2023).

In scenario SSP1–2.6, AGB potential losses are mainly concentrated in the headwaters of the Amazon basin, especially to the north in the states of Pará and Amapá, and in the western portion along the Solimões River basin in the state of Amazonas. In scenario SSP5–8.5, significant AGB potential losses are evident along the Madeira and Tapajós rivers, located southwest of the basin, affecting the integrity of both the biome and the hydrographic unit. Pontes et al. (2019) indicated that changes in vegetation affect water quality and significantly reduce water transfer to the atmosphere through evapotranspiration.

Highlighting the importance of scale and regional context in assessing AGB growth, the analyzed scenarios reveal a significant difference between average AGB gain per hectare and area gain (km^2) in Amazonian states. In the SSP1–2.6 scenario, Amapá, Maranhão, and Roraima had high average AGB gains per hectare, but these did not translate into large absolute area gains. Conversely, Amazonas led in area gain, showing significant territorial expansion, but did not achieve the highest AGB gains among the analyzed scenarios. In the SSP5–8.5 scenario, although area gains were smaller, Amazonas also stood out. This indicates that the relationship between AGB gain and area gain varies depending on the scenario analyzed.

The analysis of the distribution of AGB gain in area by state in the Amazon region, along with the evaluation of the absolute AGB values in the increment areas (Fig. 4), highlights variations in the different responses of each state's forests to future climate change projections, with some states exhibiting more significant AGB gains compared to others. For instance, despite having extensive areas of intact forest, Amazonas may show a lower proportion of AGB gains. In the pessimistic scenario, Roraima shows AGB area gains that are considerably lower than those of Amazonas, highlighting a difference of approximately five times in favor of the latter. This reveals crucial information for forest conservation and management and provides essential data to enhance strategies aimed at preserving this ecosystem.

The results obtained in the different scenarios (Fig. 3 and Fig. 4) may provide valuable input for the development of policies and strategies aimed at conservation and the implementation of forest restoration projects.

Identifying and prioritizing areas with the potential for gains in AGB are key strategies for addressing global challenges, especially in the Amazon. This guides conservation policies, providing data on resilience and regeneration, as well as the role of tropical forests in mitigating climate change (Arruda et al., 2024).

The spatial distribution of AGB equilibrium gains, especially under the SSP1–2.6 and SSP5–8.5 scenarios, reveals the importance of protected areas, such as TI's and UC's, in biodiversity conservation and carbon storage. However, the effectiveness of these areas is threatened by both severe climate change and anthropogenic pressures, including weakened forest protection policies and predatory economic interests (Moraes et al., 2021; Qin et al., 2023).

The vulnerability of protected areas, exacerbated by droughts and droughts, highlights the need for adaptive management that considers climate variability and the intensification of land use. The conservation of these areas is not only a matter of environmental preservation, but also an imperative for the maintenance of ecosystem services, including water regulation in the Amazon basin (Lapola et al., 2023; Fassoni -Andrade et al., 2021).

Given the projection that 37 % of protected areas in Brazil will be affected, with more significant damage to TI's (Arruda et al., 2024), the need to rethink and strengthen conservation strategies becomes evident. The proportionally greater effectiveness of TI's in increasing AGB highlights the vital role of indigenous communities in preserving biodiversity and adapting to climate change (Ferrante; Fearnside, 2020; Qin et al., 2023), revealing not only the importance of protected areas in biodiversity conservation and combating climate change, but also highlights the crucial role of TI's in the effective preservation of primary forests. The superiority of

TI's in terms of AGB potential gains reinforces the need for conservation policies that recognize and value their unique contributions to the ecological health of the planet.

Therefore, the revision of environmental policies is necessary in the face of increasing deforestation and pressure to relax legal protections. The conservation of the Amazon must be seen as a global priority. The synergy between protected areas, conservation policies, and climate actions is essential to ensure its resilience and contribute to global climate stability.

The results of the study highlight the importance of protected areas in mitigating the effects of climate change, acting not only as reservoirs of biodiversity and carbon, but also as hydrological regulators, and must be conserved, as changes in protected areas can cause a decrease in the transfer of water to the atmosphere through evapotranspiration (PONTES et al., 2019). Their strategic distribution along watercourses plays a vital role in preserving aquatic recharge regions and supplying water during periods of drought, in addition to serving as natural flooding areas during floods (Souza et al., 2019; Pontes et al., 2019; Toreti, et al., 2023).

The analysis emphasizes the need for adaptive management and conservation strategies for protected areas in light of projected climate scenarios. Such strategies are essential to ensure their resilience, maximizing their contribution to biodiversity conservation and mitigation of climate impacts in the Amazon.

The methodology employed in this study demonstrates the potential for application in other tropical forest regions, providing a framework for estimating changes in forest biomass under various climate change scenarios, and supporting conservation and mitigation strategies globally.

5. Conclusion

This study assessed projected potential losses of AGB under different scenarios by examining the impact of climate change in the Amazon, identifying areas with potential gains as strategies to guide conservation policies. The results reveal a concerning scenario in the southern and eastern regions, with possible substitutions of tropical forest by drier vegetation. This would compromise biodiversity and reduce carbon storage, exacerbating global climate change challenges.

The spatial analysis of AGB potential gains and losses under the SSP1–2.6 and SSP5–8.5 scenarios highlighted the critical importance of protected areas, such as TI's and UC's, in combating biodiversity loss and mitigating climate change. However, the vulnerability of these areas to severe climate change and anthropogenic pressures highlights the urgent need to strengthen forest conservation and protection policies, in addition to adopting adaptive management that considers climate variability and human impacts.

The results of this study highlight the proportionally greater effectiveness of TI's in increasing AGB, highlighting the fundamental role of indigenous communities in conserving biodiversity and adapting to climate change. The projection that 37 % of protected areas in Brazil will be affected, with more significant damage to TI's, reinforces the need to rethink and strengthen conservation strategies, ensuring not only environmental preservation, but also the maintenance of vital ecosystem services.

It is concluded that the conservation of the Amazon is a global priority due to its importance for biodiversity, climate, and indigenous peoples. An integrated approach that combines protected areas, conservation policies, and actions against climate change is essential to ensure its resilience and preserve its natural and cultural wealth for future generations.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e03106.

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