

Review Article

El Niño-related Factors Contributing to Forest Degradation and Determinants of Amazonian Lands Recovery

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Abstract

Amazon forests intrinsic defenses against fire outbreaks and spread have been challenged in the past decades by extreme weather conditions, such as drought, global warming and land use practices. These alterations are particularly relevant to vegetation and soil resistance to burn, potentially impairing Amazon enhanced properties as a carbon sink. The aim of this narrative review is to outline the factors that made Amazon lands prone to El Niño (EN) environmental threats, its consequences and the conditions that favor forest regrowth. EN drought was one of the most impactful events for these forests, in which an unexpected decrease in precipitation and elevated temperature gave rise to devastating wildfires predominant in the Northern and Central Amazon. Before EN-years, rainfall periods declined causing observable, although less pronounced alterations in soil moisture and accumulated water aboveground, along with gradual scarcity of water resources in vegetation. Short- and long-term impairment of carbon stocks will have an impact on Amazon forest biomes considering foreseen climatic adversities and related fire episodes. Until the end of the XXI century, in the worst CO₂ emissions conditions, Amazonian forest degradation might reach a proportion of 40%. Forest resilience to precipitation changes can be reflected in structural adaptative modifications in vegetation and cover lands as dry to wet seasonal transitions take place. Fire-effects on Amazon forests impel selective recruitment of tree species, in terms of survival and carbon accumulation abilities, in burnt lands sensitive to the number of fire incidences. Soil composition also presents distinctive components, as a result of fires when compared to undisturbed areas, suggesting vegetation and underground forest alterations in burnt sites. Predicted climate changes allowed the projection of forest responses under diversified conditions, in which the severity of drier periods and fires could be both overcome by certain vegetation species regrowth or a restrictive factor for forest survival, in the most harmful carbon emissions scenario expected in the last four decades of the century. Environmental regulations are needed to control deforestation minimizing its deleterious impact on forest biomass, carbon emissions and regeneration of the Amazonian biosphere. Governmental positions on previous mandates that overlooked the application of forest protection laws from environmental hazards have been related to toxic levels of carbon emissions, comparable to the damage that occurred during EN events. Social influence on this matter was also demonstrated by social media political comments that were associated with the incidence of fire episodes in the Amazon within a time-frame of up to one week.

Keywords

Amazon, El Niño, Tropical Forest, Forest Degradation, Forest Regrowth

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1. Introduction

The most extensive rain forests in tropical regions worldwide can be found in the Amazon [1], where a major amount of aboveground and soil carbon is stored [2]. Biomass carbon in the Amazon basin was previously calculated in a total of 86 Pg [3]. Geographic frontiers of Amazon forests encompass the legal Amazon located entirely in Brazil, which is subdivided in the states of Mato Grosso, Tocantins, Maranhão, Pará, Amapá, Roraima, Amazon, Rondônia, and Acre, along with eight neighboring countries partially occupying French Guiana, Suriname, Guiana, Venezuela, Colombia, Ecuador, Peru, and Bolivia.

Since 2020, literature concerning the 'Amazon wildfires' and the impact in the sustainability of its land and ecosystems has grown considerably, as it is shown by research papers published in PubMed databases. The following year, the number of studies incremented by half, with the period between 2023-2024 also accounting for 22 registries, contrasting with a total of 15 publications from 2008 until 2019 [4]. Not surprisingly, the year 2020 was historic for Pantanal, which comprises the greatest territory of tropical wetlands. Pantanal 2020's disaster was characterized by an intense drought with a mean yearly rainfall 26% below the average of the previous four decades threatening the life of countless species [5-7]. As a result, these conditions favored the occurrence of wildfires [8], registering an increment of 123% in the same year when compared to the annual mean in nearly a 18-years range prior to the event [5]. The vast majority (95%) of the territory burnt took place in lands of natural vegetation. Of these, more than a quarter affected wetlands that have been dried by severe weather conditions [5].

Considering a timeline of several centuries, Amazonian forests have been protected from wildfires devastation, either natural or human-ignited, since wetlands acted as a buffer to neutralize sources of fire and its spread [9]. Other resilient features of these forests are related to lands where flora has enhanced fire-resistant anatomic characteristics and the increased forestation of flammable C4 grasses to protect the most vulnerable areas of biosphere diversity [9]. More recently, however, climate change has affected the Amazon, in addition to deforestation rates that have been constant accounting for over 70.000 km² in a 10-year period, contributing to fragmented forests more prone to be damaged by wildfires [10, 11]. During 2015-2016, El Niño (EN) disaster has burnt central Amazonian humid lands, which were exposed to unforeseen high temperatures and drought [9, 12-15].

In a selected area of 6.5 million hectares (Mha) damaged by this event, the extension of primary and secondary burnt forests were 1 Mha and 20.000 ha, respectively, in the mentioned period of time [16]. The CO₂ emissions to the atmosphere derived from these wildfires reached 30 Tg, a proportion several times higher than that verified in worldwide fire occurrences. Prior to the EN event, forest patterns tended to accumulate two times more carbon necromass in primary forests

with no past disturbances than in secondary forests (30.2 ± 2.1 Mg ha⁻¹ versus 15.6 ± 3.0 Mg ha⁻¹). Interestingly, the findings of this research also revealed that the decrease in carbon necromass reserves was not mediated by previous disturbance or closeness to areas with more severe wildfires [16].

In tropical forests, carbon reserves in African and Asian lands are projected to surpass the American forests (22.1 as opposed to 18.8 Kg C m⁻²). In low emissions indexes, forest biomes will progressively increase over time. Nonetheless, for the worst emissions scenario, there will be an abrupt decline of 40% when compared to 2020's levels, from 2060 until the end of the century [17]. Current meteorological changes affecting particularly Amazonian territories are characterized by intensified and prolonged warm seasons, along with the delay of wet periods - a trend that has been recently described as the 'hot season gets hotter' [18]. During spring, temperatures could rise by approximately 1 K in the Amazon compared to the yearly average, whereas an increase of 30% is plausible in the most harmful emissions predictions for the culmination of the XXI century. Simultaneously, forest pre-conditions, such as heating ability and soil moisture favor the late onset of tropical rainfalls [18].

The way climate change impacts Amazonian biodiversity worsening one of the richest forest carbon stocks and wetlands in tropical regions is a core area of research with a plethora of pathways yet to be fully elucidated. The current review aims to highlight Amazonian forests vulnerabilities that preceded EN drought and wildfires, as well as the corresponding repercussions for Amazonian lands, identifying survival skills and regeneration patterns during forest regrowth. Socio-political influence on regulations concerning forest management will also be addressed contextualized in a chronological perspective whenever relevant.

2. Amazonian Climate and Forest Conditions Associated to the El Niño Event

The climate change adversities faced in the Amazon and Brazil causing periods of intensive droughts in 2005, 2010 and 2015, aggravated fire incidences and CO emissions. These occurrences were mainly related to increased temperature levels in the tropical areas of the Pacific and North Atlantic (TNA) in 2005 events, and to the EN years in the subsequent droughts [13, 19]. Available data revealed that the most recent disasters had the highest impact in the proportion of damaged land, at a faster pace, whereas lasting for longer periods when compared to the previous years' episodes [13-15]. Although during dry seasons the number of fires registered in 2015 was almost half the amount verified in prior droughts, in dry-to-wet transition periods, biomass burning events exceed by 192% and 332% the values estimated for 2005 and 2010 droughts, respectively [13].

Geographic locations affected the southern and south-western Amazonian forests in 2005, the Cerrado Brazilian territory in 2010, and were dominant in the central and northern Amazon in the later event. There was an increment in CO levels that reached 30% during dry seasons, in 2005 and 2010, and in dry-to-wet transitions between 2015-2016 [13]. Within diverse forest biomes, a decrease in carbon stocks was predicted as a result of climate changes that would aggravate the odds of wildfires events, accounting for an increase of 30 days or more of fire occurrences alarm, by 2100, in the most nefarious carbon emissions projections [20].

Using vapor pressure deficit as a predictor of fire risk, atmospheric water needs were found to pose a threat to ecosystems due to the current trends of excessive demand [20]. In a retrospective assessment, changes before the EN episode in the Amazon wetlands although subtle were detected in soil composition and precipitation patterns analyses between 2004 and 2016. Surface and more profound soil moisture suffered a steady decline in humidity over the years assessed, as well as it occurred in groundwater stocks, the latter being assumed as a core driver of hydrological drought. The most affected territories were located in the northeast Amazon forests [15]. Soil moisture reduction between 2010-2020 was found to be influenced by decreased precipitation, while water levels in vegetation were affected by deforestation and reduced biomass [10].

In Roraima, meteorological conditions that favored EN fires included alterations in rainfall patterns of ≤ -1 SD in 59% of the studied land for the initial period and 48% at the end of the event, encompassing an area of 132.900 km² and 106.200 km² respectively. In the same way, fire-related modifications characterized by ≥ 1 SD were registered within a spatial distribution of 86.200 km² [12]. Considering that the climate change impact relies on the interplay of meteorological and forest characteristics, predictive systems have been enhanced to enable estimations that combine the repercussions of fires, water resources and vegetation survival, as the example of the Earth System Model (ESM) [17].

Based on this technology, the foreseen trend of 40% forest loss derived from wildfires before the transition to the XXII century is linked to the EN drought and the above-mentioned changes in the Atlantic Ocean, which would intensify rainfall decrease [17]. Both past evidence and future predictions highlighted several alterations in the Amazon structure, along with contributing factors that shape patterns of forest preservation and evolutive skills.

3. Threats to Amazonian Biodiversity and Forest Resilience in the Face of Environmental Adversities

Amazonian forests recovery, as shown by tree regeneration and growth, as well as by carbon accumulation has been confirmed in relation to drought, delay and decrease of rainfall periods that paved seasonal alterations during the previous

decades [21]. Considering the epicenter of EN in the Amazon, long-term tree survival was impacted to a greater extent than in non-EN years for regions devastated by drought and by fires within a timeframe of 36 and 30 months following the event, respectively [22]. Climate variability over time and cyclic trends determine vegetation regeneration and adaptive modifications, including processes of secundarization of primary forests and community turnover [17, 23-25].

3.1. Impact of Rainfall Trends and Patterns of Post-fires Recovery in the Amazonian Forests

Cano and colleagues have detailed processes of structural alterations in Amazonian plants and landcovers according to precipitation levels predictions [17]. Grasslands are typical in drought scenarios where repeated fires are easily ignited by the increased fuel compromising seeding survival. In drought seasons, the dominant leaves and trees prone to flammability make this land susceptible to wildfires. As precipitation rises, these tropical forests may be transformed in savanna in a proportion of 40% within few decades. More extensive fires originate altered patches with scarce trees. Shorter canopy and reduced landcover impel the competition with the remaining species, as it is the case of highly flammable C3 and C4 grasslands limiting water availability due to decreased moisture in patches damaged by recent fires, favoring drier and fuel-laden lands. This event is known as 'arrested recovery' preventing tree growth, while fires tend to occur repeatedly with the dominance of grasslands and short tree forests that usually compose a savanna [17].

In farmer lands of Rondônia, analyses have found significant negative correlations between fire occurrences and rainfall with a monthly decline of -0.0542mm and positive with temperature levels showing an increase of 0.006 °C per month [26]. Fire and humidity are determinants of forest resilience in each season and could occur simultaneously in moderate precipitation scenarios being influenced by previous climate conditions. With higher precipitation, forest lands could develop abundant tall trees areas, in which canopy may reduce grassland covers. The loss of forest ability to retain water within the canopy relies on evapotranspiration, contributing to soil moisture decrease [17]. As the rainfall seasons pass by, grasslands might eventually grow in tree forests containing closed canopy. In the transition to drier lands, these species regain enhanced skills to maintain humidity ensuring its survival. If fires are activated, the cycle would resume as in states of low precipitation levels [17].

In what concerns tree mortality caused by fires, in Brazilian central areas of the Amazon at 1, 3, and 9 years of followup, in undisturbed primary forests, the amount of trees remained unchanged throughout the years. For forests affected by fires in one occurrence, the number of trees of both reduced (10-20cm) and large (>50cm) diameter at breast height (DBH) decreased after one to three years. Nevertheless, it was ob-

served a considerable recruitment of 10-20cm DBH trees, three and nine years following fire activity, to an amount comparable to that verified in primary forests, which was not registered for larger species (>20cm DBH) [23].

At the same time-point assessments, for twice-burnt areas, recruitment was also high for trees with 10-20cm of DBH, even though the regeneration of 20-30cm DBH species was limited and minimal for the remaining sizes. The more the fire occurrences (up to three events), the greater the odds of tree mortality, particularly threatening for species with 10-30cm and above or equal to 50cm of DBH. Simultaneously, community turnover was identified as a process similar to secondaryization in primary forests, comprising gradual alterations in stem composition as fires reoccur, mostly in small trees of 10-20cm DBH [23]. Prevalent species found in undisturbed primary forests (*Protium* and *Tetragastris* spp.) tend to decrease in number once the land is burnt for the first time, eventually reaching scarcity after the second event, and absence in thrice-burnt areas. The same trend was seen post-first fire regarding the dominant tree species (*Cecropia* spp. and *Jacaranda copaia*) that were not observed in unburnt primary forests, which reduced considerably in number for twice-burnt lands and were extinguished after the third consecutive fire occurrence [23].

Twice-burnt forests composed largely by *Pseudobombax* sp. showed a marked decline in the amount of species registered in areas after the third fire episode, while in unburnt primary forests and in lands affected by a single fire event, these trees were absent. In thrice-burnt forests, *Cordia* sp. was the most abundant species, although these trees were not seen or were identified in negligible numbers in twice- and once-burnt areas, as well as in unburnt primary forests [23]. For shrubs and saplings trees consisting of 1m height and a DBH of less than 10cm, it was verified that the number of the dominant species in each once-, twice- and thrice-burnt lands was scarce to none in the remaining burn classifications showing that tree reproductive development was achieved in the understorey [23].

In relation to the EN drought and fires, a followup of two years and a half demonstrated that the difference regarding the impact on stem carbon stocks in burnt areas and non-disturbed forests was not statistically significant. Furthermore, trees that endure these events managed to maintain carbon retention rates [21], even though these results may not account for carbon levels decline and the compromise of species survival in these nefarious climate conditions [21]. As such, tree growth and carbon accumulation resilience may not suffice to counterbalance post-fire flora mortality that has been reported in previous research [17, 22].

In secondary forests, it was observed a significantly more pronounced radial development of trees than in areas that were solely exposed to drought. The single predictor of tree growth was wood density, in which species of lighter wood density were significantly more abundant in areas burnt during EN [21]. This advantage compared to high-wood density trees is, possibly, due to the abundance of nutrients derived

from burnt organic matter favoring a faster growth [21]. In both periods pre- and post-EN times, grasslands covers were a predictor of wildfires. Less affected forests were those that had not been burnt previously with dense landcover, as opposed to barren and light-density covers [14].

In later research, trees of lighter density, exposed to aggravated fires, displaying thicker barks and accumulating higher nitrogen levels in its leaves had less chances of persevering in EN adverse conditions. The evidence demonstrated that these years have contributed to the loss of nearly 2.5 ± 0.3 billion stems and accounted for 495 ± 94 Tg emissions of CO₂. Three years after EN, forests flora restoration had only allowed to mitigate these repercussions in 37% of emissions [22].

The speed of tree development was also significantly faster in secondary forests than in primary forests during a long-term followup period [21]. These findings seem to be related to a higher number of trees of low-wood density in secondary forests. As argued by the authors, considering the example of *Jacaranda copaia* within the mentioned species showing a 2cm growth, the subsequent increase on carbon reserves would be of 0.66 Kg of C. Comparatively, in primary forests, an equivalent stem in size (e.g. *Eschweilera coriacea*) that underwent a similar growth would absorb 1.57 Kg of C [27]. In order to reach equivalent levels of carbon, the first stem would have to outgrow the later 1.6 times, thus explaining the similarity in carbon retention among the diverse forest varieties, in spite of the difference verified in tree growth in each setting [21].

3.2. Soil Alterations in Burnt Forests

Soil organic matter (SOM) compounds are altered by wildfires events influencing the odds of forest regeneration. Comparing undisturbed areas of Amazon forests, lands deteriorated by fires and Brachiaria pasture (as designated by the authors), in terms of soil composition, it was possible to identify chemical elements variations across forest sites and soil layers (0-5cm; 5-10cm; and 40-50cm depth). Lipids, unspecified aromatic compounds (UACs), polycyclic aromatic hydrocarbons (PAHs), and peptides were more abundant in burnt forests than in native lands or Brachiaria pasture, mainly in the most superficial layer (0-5cm), which also contained the lowest levels of polysaccharide-derived substances. These alterations could be attributed to the impact of pyrogenic effects on soil composition and the consequent vegetation degradation and mortality [28].

At 5-10cm depth, lipids and peptides were dominant in burnt areas (versus native forests and Brachiaria pasture). Particularly, the increase of lipids could be a result of deposited biomass on soil due to fires that cause a shift in temperature gradient, an argument that is further sustained by the long n-alkane chains observed in more profound layers (5-10cm depth). Long-term (20 months) deleterious effects of fires on SOM confirmed limited forest regeneration capabilities

ties with extreme temperatures superior to 350 °C above-ground, alongside the presence of harmful chemicals (e.g., PAHs) in burnt sites undermining the survival of microorganisms and regrowth of underground biomass [28].

Changes in native lands that were not detected in the remaining studied areas (burnt lands and *Brachiaria* pasture) revealed the impact of fires on SOM composition compromising forest resilience after burn. At the same time, these undisturbed lands seem to be also vulnerable to fire-effects from adjacent burnt areas, in which pyrogenic elements could have been transported by air [28]. In native forests, lipids have a different composition than that verified in burnt forests and *Brachiaria* pasture, as elements essential to canopy regeneration can be found (e.g., isodolene, calamenene, and corocalene)

in SOM. By contrast, the scarcity of these chemicals due to fire degradation in burnt lands prevents vital modifications in SOM composition that would enable forests regrowth, even if matched conditions on litter C: N ratio are maintained (22:1 in burnt sites and 23:1 in native lands). In superficial layers, n-alkanes chains (C25-C31) relativized to the organic carbon content reflect alterations in soil composition from vegetation maturation dominant in undisturbed forests, as opposed to burnt areas and *Brachiaria* pasture where these elements were lacking [28]. In Figure 1, resilient skills of the Amazon in adverse climate conditions are summarized, analyzing the features that make these forests more exposed to droughts and fires, as well as several ways to enhance forests resistance to environmental damage.

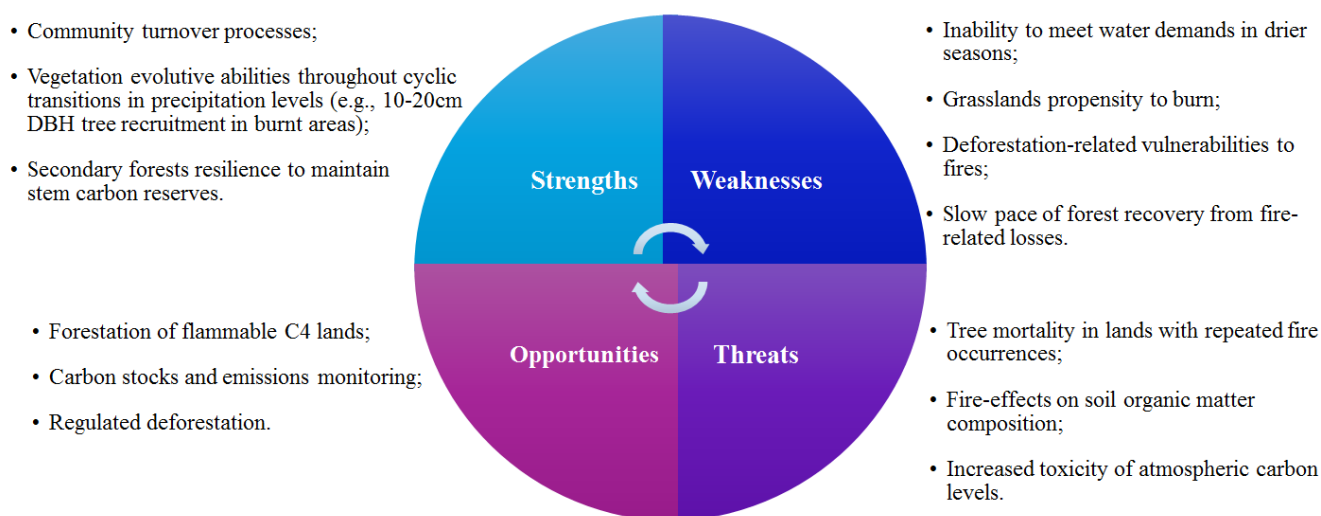


Figure 1. SWOT analysis of Amazonian forests resilience to extreme droughts and fires.

4. Scopes of Intervention for Socio-political Influence on Amazon Forest Preservation

Deforestation has been determined by environmental policies, which concomitantly regulated biomass burning and contributed to protect forest vegetation and ecosystems [29]. This research analyzed carbon emissions in Amazonian forests in relation to the application of protective laws in two different chronological periods of time that have been marked by diverse political governance - from 2010 until 2018 and during the 2019-2020's years. In the later period of time, there was an increment in CO₂ emissions (0.44-0.52 ± 0.10 versus 0.24 ± 0.08 annual Pg C) reaching equivalent proportions to those verified in the EN years. Similar trends were found in deforestation practices assessed with high accuracy level revealing an increase of 77% and 82%, in 2019 and 2020, respectively. There were 14-42% more lands devastated by

wildfires in the same time range. Infractions referring to deforestation reduced in 30% to 54%, as well as applied fines with a decline of 74% (2019) and 89% (2020) [29].

The differences observed were considered to be associated with law enforcement practices, in each period of time, with a nefarious impact on forest patterns being related to more relaxed environmental policies [29]. In the Brazilian Amazon, carbon emissions estimated in deforestation-related fires were calculated in 216.696 Kg of CO₂ and 18.979 Kg of CO per hectare with a mean equivalent of yearly CO₂ emissions of 301 ± 53 Mt year⁻¹ that has aggravated over time since 2013 [30]. Within the Acre state, 2019 registered the most extensive burnt lands in deforested areas, in a four-years period since the EN episode, in 2016, with twice the impact verified in the previous two years and affecting a slightly larger area than that destroyed during the EN years [31]. Strong correlations between fire occurrences and deforestation were observed in the Amazon [31, 32], the percentage of deforested Acre lands reaching 19%, in 2019, with an equivalence of 2.259.990 ha [31] and 17% in the central legal Amazon [33].

Even when deforestation takes place in areas controlled by

governmental policies, the application of environmental regulations might be ineffective requiring an enhancement of forest management interventions [31]. In this context, controlled deforestation was considered to be a key strategy to reduce 38-56% of CO₂ emissions and to prevent disturbances in protected lands. Moreover, if fire reoccurrences are avoided, it is expected that carbon reserves could be reestablished in a short-term period [34].

Political authorities appear to have a wider spectrum of influence in the occurrence of Amazonian wildfires [35, 36], which might be partially mediated by the impact of social media interactions content [36]. In both research, the timeframe for the onset of wildfires ranged from 10 hours to 7 days, with a cross-correlation of 56% between fire occurrences dates and matching google searching content [35], whereas predictive computations estimated a six-day lag between Twitter posts and fire outbreaks observed in satellite data in the Brazilian Amazon [36]. Diverse carbon emissions estimations will determine Amazon resilience to climate change, in which it is expected the display of alternative behaviors, also affected by land use activities and the application of forest regulations to control carbon atmospheric levels and deforestation [24, 31].

5. Discussion and Predictions on Forest Resilience Under Different Climate Scenarios

Dynamic patterns of the Amazonian forests have revealed past and future adaptations to challenges largely imposed by weather conditions. EN events could have been a marking point in the Amazon long protected forests from fire occurrences due to its extensive wetlands, motivating the investment in prospective and retrospective research studies. Post-fire land devastation has led to irreparable losses in certain species, the development of evolutive features in others, whereas the potential of optimal forest regrowth might only be achieved within a time-range of several years [17, 22, 23].

Structural alterations observed in Amazonian forests in response to climate change create favorable conditions in soil temperature and composition to the incidence of drought and fires, as rainfall seasons become less intense and delayed [10, 15]. Similarly, in the most harmful CO₂ emissions levels predictions, the main factors contributing to the occurrence of wildfires non-induced by human beings refer to soil moisture and moderate humidity reflecting the maintenance of reduced precipitation periods. Projections suggest that even though, in a short-term, the risk of wildfires events is decreased by humidity, as drier seasons become more severe over time due to the decline in soil moisture and water conservation, forest resilience to wildfires could be compromised, particularly from 2060 onwards [17].

Using GFDL-ESM4.1 predictive model, wildfires repercussions on greenhouse gas emissions are determined ac-

cording to vegetation characteristics, depending on its degrees of complexity [17]. Regarding forests with rudimentary plants dynamics, a similar pattern of recovery among species was observed with a progressive increase in biomass each year (-0.05%). However, there were different trends in forests of more sophisticated vegetation dynamics, in which large land areas were destroyed by wildfires and a rapid recovery of vegetation was noted within a certain time-frame [17].

Fire-related biomass decrease was equivalent in both landscapes (23.4% and 22.5%) occurring at the same pace. Divergent trends were evident in what concerns to the rate of biomass modification. With EC-Earth3-Veg predictions, whose parameters include patch and vegetation dimensions differences, when there was an increment in biomass, the rate detected was twice the value found using GFDL-ESM4.1 for reduced biomass concentrations, which were accelerated compared to cmIP6 ESMs projections [17].

In terms of net alterations in biomass between 2015-2100, two distinctive trends were also recognized. Recurrent fires lead to forest biomass loss, at a regional level, in GFDL-ESM4.1 estimations, at the same time that for EC-Earth-3-Veg forecast, accelerated rates of biomass expansion were noted reflecting a concomitant rise in net biomass [17]. Another variable relates water resources demands to post-fire forest resilience revealing biomass incremented rates in EC-Earth-3-Veg superior to those registered using GFDL-ESM4.1 when exposed to the same climate conditions. To further analyze the differences found, potential confounding variables affecting precipitation levels were controlled for, including the influence of El Niño-Southern Oscillation and Atlantic Multi-decadal Oscillation phenomena. A sudden decline in vegetation was confirmed, highlighting distinctive forest behaviors, in each model of intense emissions conditions affected by the kind of vegetation processes and hydrological variants [17]. Prior research found that although tree competition has allowed forest regrowth in burnt areas, recurrent fire episodes reduce the odds of vegetation survival, while a retarded pattern of recovery may avert the restoration of its previous natural defenses against climate adversities [21-23].

Amazon resilience and species survival is further threatened by fire repercussions on soil organic matter components and decreased carbon reserves [20, 28]. When compared to undisturbed lands, it was estimated a mean of 40% loss in aboveground carbon reserves in tropical forests altered by human activities, especially in burned areas and those simultaneously changed by logging, revealing modifications in its structure [24]. In this context, a similarity with secondary forests was noted that could revert tropical forests from containing significant amounts of carbon stocks to areas with limited carbon reserves. Notwithstanding the damage induced in primary forests, carbon stored seems to be more resilient accumulating stocks higher than in secondary forests. In disturbed areas, edge factor was a main determinant of carbon stored aboveground, which was considered to be related to an increasing susceptibility to adverse effects from human and

climate disturbances [24].

Advances in predictive models have identified several conditions that might push forests balance beyond its ability to preserve water needs, vegetation regrowth and overall recovery from deforestation and climate adversities [25]. Evidence has demonstrated that for global warming, levels should not surpass 1.5 °C, while rainfall levels above 1.800 mm per year with a maximum cumulative water deficit of -350mm for rainfall seasonality intensity would be ideal. Dry seasons might not last for more than five months, at the same time that the total deforestation superior to 10% of the forest cover could endanger vegetation survival and contribute to the decline of wet seasons [25]. These thresholds might be crucial when defining sustainable strategies for forest management.

6. Conclusion

Amazonian past resistance to forest degradation has been compromised by the latest variations in seasonal trends, including the rise of temperature in the surface of the North Atlantic Ocean and EN droughts. Vegetation struggles to persevere in vast areas of grasslands prone to successive fires that delay tree regeneration reducing above and underground water resources. Forest resilience relies more and more on trees competition and precipitation cycles, prompting the development of plants' adaptative features to endure such weather conditions. Carbon emissions repercussions are still a major concern entailing the greatest chances of being mitigated by environmental regulations that optimize forest regrowth, while also leading to the worst impact on forest degradation if harmful levels are not timely subverted.

Abbreviations

C	Carbon
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DBH	Diameter at Breast Height
EN	El Niño
ESM	Earth System Model
Mg ha	Megagrams per Hectare
Mha	Million Hectares
Mt	Megaton
PAHs	polycyclic Aromatic Hydrocarbons
Pg	Petagram
SOM	Soil Organic Matter
Tg	Teragrams
TNA	Tropical Areas of the Pacific and North Atlantic
UACs	Unspecified Aromatic Compounds

Author Contributions

Ana Rodriguez is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

- [1] Du, Y., Gao, G., Ma, X., Xu, S., Fu, B. Amazon Basin Shows Reduced Forest Loss but Increased Forest Spatial Fragmentation in 1992-2020. *The Science of the Total Environment*. 2025, 18(990), 179917. <https://doi.org/10.1016/j.scitotenv.2025.179917>
- [2] Betts, R. A., Malhi, Y., Roberts, J. T. The Future of the Amazon: New Perspectives From Climate, Ecosystem and Social Sciences. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. 2008, 363(1498), 1729-35. <https://doi.org/10.1098/rstb.2008.0011>
- [3] Saatchi, S. S., Houghton, R. A., Alvalá R. C. Dos S., Soares, J. V., Yu, Y. Distribution of Aboveground Live Biomass in the Amazon Basin. *Global Change Biology*. 2007, 13(4), 816-37. <https://doi.org/10.1111/j.1365-2486.2007.01323.x>
- [4] National Library of Medicine. PubMed. Available from: <https://pubmed.ncbi.nlm.nih.gov/> (accessed 29 May 2025).
- [5] Mataveli, G. A. V., Pereira, G., De Oliveira, G., Seixas, H. T., Cardozo, F. D. S., Shimabukuro, Y. E., Kawakubo, F. S., Brunsell, N. A. 2020 Pantanal's Widespread Fire: Short- and Long-term Implications for Biodiversity and Conservation. *Biodiversity and Conservation*. 2021, 30(11), 3299-3303. <https://doi.org/10.1007/s10531-021-02243-2>
- [6] Pelissari, T. D., Teodoro, P. E., Teodoro, L. P. R., Lima, M., Santana, D. C., Rossi, F. S., Dos Santos, D. H., Silva, R. A., Lourençoni, T., Junior, C. A. S. Dynamics of Major Environmental Disasters Involving Fire in the Brazilian Pantanal. *Scientific Reports*. 2023, 13(1), 21669. <https://doi.org/10.1038/s41598-023-49154-6>
- [7] Tomas, W. M., Berlinck, C. N., Chiaravallotti, R. M., Faggioni, G. P., Strüßmann, C., Libonati, R., Abrahão, C. R., Alvarenga, G. V., Bacellar, A. E. F., Batista, F. R. Q., Bornato, T. S., Camilo, A. R., Castedo, J., Fernando, A. M. E., Freitas, G. O., Garcia, C. M., Gonçalves, H. S., Guilherme, M. B. F., Layme, V. M. G., ... Morato, R. Distance Sampling Surveys Reveal 17 Million Vertebrates Directly Killed by the 2020's Wildfires in the Pantanal, Brazil. *Scientific Reports*. 2021, 11(1), 23547. <https://doi.org/10.1038/s41598-021-02844-5>
- [8] Marques, J. F., Alves, M. B., Silveira, C. F., Silva, A. A., Silva, T. A., Dos Santos, V. J., Calijuri, M. L. Fires Dynamics in the Pantanal: Impacts of Anthropogenic Activities and Climate Change. *Journal of Environmental Management*. 2021, 299, 113586. <https://doi.org/10.1016/j.jenvman.2021.113586>
- [9] Feldpausch, T. R., Carvalho, L., Macario, K. D., Ascough, P. L., Flores, C. F., Coronado, E. N. H., Kalamandeen, M., Phillips, O. L., Staff, R. A. Forest Fire History in Amazonia Inferred from Intensive Soil Charcoal Sampling and Radiocarbon Dating. *Frontiers in Forests and Global Change*. 2022, 5, 815438. <https://doi.org/10.3389/ffgc.2022.815438>

- [10] Bueso, D., Piles, M., Ciais, P., Wigneron, J.-P., Moreno-Martínez, Á., Camps-Valls, G. Soil and Vegetation Water Content Identify the Main Terrestrial Ecosystem Changes. *National Science Review*. 2023, 10(5), nwad026. <https://doi.org/10.1093/nsr/nwad026>
- [11] Noble, C. D., Gilroy, J. J., Peres, C. A. Small Forest Patches and Landscape-Scale Fragmentation Exacerbate Forest Fire Prevalence in Amazonia. *Journal of Environmental Management*. 2025, 375, 124312. <https://doi.org/10.1016/j.jenvman.2025.124312>
- [12] Fonseca, M. G., Anderson, L. O., Arai, E., Shimabukuro, Y. E., Xaud, H. A. M., Xaud, M. R., Madani, N., Wagner, F. H., Aragão, L. E. O. C. Climatic and Anthropogenic Drivers of Northern Amazon Fires During the 2015-2016 El Niño Event. *Ecological Applications: A Publication of the Ecological Society of America*. 2017, 27(8), 2514-27. <https://doi.org/10.1002/eap.1628>
- [13] Ribeiro, I. O., Andreoli, R. V., Kayano, M. T., Sousa, T. R., Medeiros, A. S., Godoi, R. H. M., Godoi, A. F. L., Duvoisin, S., Martin, S. T., Souza, R. a. F. Biomass Burning and Carbon Monoxide Patterns in Brazil During the Extreme Drought Years of 2005, 2010, and 2015. *Environmental Pollution*. 2018, 243(Pt B), 1008-14. <https://doi.org/10.1016/j.envpol.2018.09.022>
- [14] Singh, M., Zhu, X. Analysis of How the Spatial and Temporal Patterns of Fire and their Bioclimatic and Anthropogenic Drivers Vary Across the Amazon Rainforest in El Niño And Non-El Niño Years. *PeerJ*. 2021, 9, e12029. <https://doi.org/10.7717/peerj.12029>
- [15] Toledo, N., Moulatlet, G., Gaona, G., Valencia, B., Hirata, R., Conicelli, B. Dynamics of Meteorological and Hydrological Drought: The Impact of Groundwater and El Niño Events on Forest Fires in the Amazon. *The Science of the Total Environment*. 2024, 954, 176612. <https://doi.org/10.1016/j.scitotenv.2024.176612>
- [16] Withey, K., Berenguer, E., Palmeira, A. F., Espírito-Santo, F. D. B., Lennox, G. D., Silva, C. V. J., Aragão, L. E. O. C., Ferreira, J., França, F., Malhi, Y., Rossi, L. C., Barlow, J. Quantifying Immediate Carbon Emissions from El Niño-Mediated Wildfires in Humid Tropical Forests. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. 2018, 373(1760), 20170312. <https://doi.org/10.1098/rstb.2017.0312>
- [17] Cano, I. M., Shevliakova, E., Malyshev, S., John, J. G., Yu, Y., Smith, B., Pacala, S. W. Abrupt Loss and Uncertain Recovery from Fires of Amazon Forests Under Low Climate Mitigation Scenarios. *Proceedings of the National Academy of Sciences USA*. 2022, 119(52), e2203200119. <https://doi.org/10.1073/pnas.2203200119>
- [18] Song, F., Dong, H., Wu, L., Leung, L. R., Lu, J., Dong, L., Wu, P., Zhou, T. Hot Season Gets Hotter Due to Rainfall Delay Over Tropical Land in a Warming Climate. *Nature Communications*. 2025, 16(1), 2188. <https://doi.org/10.1038/s41467-025-57501-6>
- [19] Justino, F., Bromwich, D. H., Wang, S. H., Althoff, D., Schumacher, V., Silva, A. Influence of Local Scale and Oceanic Teleconnections on Regional Fire Danger and Wildfire Trends. *The Science of the Total Environment*. 2023, 883, 163397. <https://doi.org/10.1016/j.scitotenv.2023.163397>
- [20] Clarke, H., Nolan, R. H., Dios, V. R., Bradstock, R., Griebel, A., Khanal, S., Boer, M. M. Forest Fire Threatens Global Carbon Sinks and Population Centres Under Rising Atmospheric Water Demand. *Nature Communications*. 2022, 13(1), 7161. <https://doi.org/10.1038/s41467-022-34966-3>
- [21] Berenguer, E., Malhi, Y., Brando, P., Cordeiro, A. C. N., Ferreira, J., França, F., Rossi, L. C., Seixas, M. M. M., Barlow, J. Tree Growth and Stem Carbon Accumulation in Human-modified Amazonian Forests Following Drought and Fire. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. 2018, 373(1760), 20170308. <https://doi.org/10.1098/rstb.2017.0308>
- [22] Berenguer, E., Lennox, G. D., Ferreira, J., Malhi, Y., Aragão, L. E. O. C., Barreto, J. R., Espírito-Santo, F. B., Figueiredo, A. E. S., França, F., Gardner, T. A., Joly, C. A., Palmeira, A. F., Quesada, C. A., Rossi, L. C., Seixas, M. M. M., Smith, C. C., Withey, K., Barlow, J. Tracking the Impacts of El Niño Drought and Fire in Human-modified Amazonian Forests. *Proceedings of the National Academy of Sciences of the United States of America*. 2021, 118(30), e2019377118. <https://doi.org/10.1073/pnas.2019377118>
- [23] Barlow, J., Peres, C. A. Fire-mediated Dieback and Compositional Cascade in an Amazonian Forest. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. 2008, 363(1498), 1787-1794. <https://doi.org/10.1098/rstb.2007.0013>
- [24] Berenguer, E., Ferreira, J., Gardner, T. A., Aragão, L. E. O. C., Camargo, P. B., Cerri, C. E., Durigan, M., Junior, R. C. O., Vieira, I. C. G., Barlow, J. A Large-scale Field Assessment of Carbon Stocks in Human-modified Tropical Forests. *Global Change Biology*. 2014, 20(12), 3713-26. <https://doi.org/10.1111/gcb.12627>
- [25] Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., Levis, C., Lapola, D. M., Esquivel-Muelbert, A., Jakovac, C., Nobre, C. A., Oliveira, R. S., Borma, L. S., Nian, D., Boers, N., Hecht, S. B., Ter Steege, H., Arieira, J., Lucas, I. L., ... Hirota, M. Critical Transitions in the Amazon Forest System. *Nature*. 2024, 626(7999), 555-564. <https://doi.org/10.1038/s41586-023-06970-0>
- [26] Moreira, R. M., Martins, R. A. Influence of Precipitation and Temperature on Burned Areas in the Agricultural and Cattle Ranching Frontier of the Brazilian Amazon. *Environmental Monitoring and Assessment*. 2024, 196(10), 986. <https://doi.org/10.1007/s10661-024-13080-5>
- [27] Ter Steege, H., Pitman, N. C. A., Sabatier, D., Baraloto, C., Salomão, R. P., Guevara, J. E., Phillips, O. L., Castilho, C. V., Magnusson, W. E., Molino, J.-F., Monteagudo, A., Núñez Vargas, P., Montero, J. C., Feldpausch, T. R., Coronado, E. N. H., Killeen, T. J., Mostacedo, B., Vasquez, R., Assis, R. L., ... Silman, M. R. Hyperdominance in the Amazonian Tree Flora. *Science*. 2013, 342(6156), 1243092. <https://doi.org/10.1126/science.1243092>

- [28] Leal, O. D. A., Jiménez-Morillo, N. T., González-Pérez, J. A., Knicker, H., Costa, F. S., Jiménez-Morillo, P. N., Júnior, J. A. C., Santos, J. C., Dick, D. P. Soil Organic Matter Molecular Composition Shifts Driven by Forest Regrowth or Pasture After Slash-and-Burn of Amazon Forest. *International Journal of Environmental Research and Public Health*. 2023, 20(4), 3485. <https://doi.org/10.3390/ijerph20043485>
- [29] Gatti, L. V., Cunha, C. L., Marani, L., Cassol, H. L. G., Messias, C. G., Arai, E., Denning, A. S., Soler, L. S., Almeida, C., Setzer, A., Domingues, L. G., Basso, L. S., Miller, J. B., Gloor, M., Correia, C. S. C., Tejada, G., Neves, R. A. L., Rajao, R., Nunes, F., ... Machado, G. B. M. Increased Amazon Carbon Emissions Mainly From Decline in Law Enforcement. *Nature*. 2023, 621(7978), 318-323. <https://doi.org/10.1038/s41586-023-06390-0>
- [30] Amaral, S. S., Costa, M. A. M., Neto, T. G. S., Costa, M. P., Dias, F. F., Anselmo, E., Santos, J. C. D., Carvalho, J. A. D. CO₂, CO, Hydrocarbon Gases and PM_{2.5} Emissions on Dry Season by Deforestation Fires in the Brazilian Amazonia. *Environmental Pollution*. 2019, 249, 311-320. <https://doi.org/10.1016/j.envpol.2019.03.023>
- [31] Silva, S. S. D., Oliveira, I., Morello, T. F., Anderson, L. O., Karlokoski, A., Brando, P. M., Melo, A. W. F. D., Costa, J. G. D., Souza, F. S. C. D., Silva, I. S. D., Nascimento, E. D. S., Pereira, M. P., Almeida, M. R. N. D., Alencar, A., Aragão, L. E. O. E. C. D., Brown, I. F., Graça, P. M. L. D. A., Fearnside, P. M. Burning in Southwestern Brazilian Amazonia, 2016-2019. *Journal of Environmental Management*. 2021, 286, 112189. <https://doi.org/10.1016/j.jenvman.2021.112189>
- [32] Lima, C. F., Torres, F. T. P., Minette, L. J., Lima, F. A., Lima, R. C. A., Sato, M. K., Silva, A. A., Schettini, B. L. S., Ferreira, F. A. C., Machado, M. X. L. Is There a Relationship Between Forest Fires and Deforestation in the Brazilian Amazon? *PLoS One*. 2024, 19(6), e0306238. <https://doi.org/10.1371/journal.pone.0306238>
- [33] Reis, M., Graça, P. M. L. D. A., Yanai, A. M., Ramos, C. J. P., Fearnside, P. M. Forest Fires and Deforestation in the Central Amazon: Effects of Landscape and Climate on Spatial and Temporal Dynamics. *Journal of Environmental Management*. 2021, 288, 112310. <https://doi.org/10.1016/j.jenvman.2021.112310>
- [34] Brando, P. M., Soares-Filho, B., Rodrigues, L., Assunção, A., Morton, D., Tuchsneider, D., Fernandes, E. C. M., Macedo, M. N., Oliveira, U., Coe, M. T. The Gathering Firestorm in Southern Amazonia. *Science Advances*. 2020, 6(2), eaay1632. <https://doi.org/10.1126/sciadv.aay1632>
- [35] Caetano, M. A. L. Political Activity in Social Media Induces Forest Fires in the Brazilian Amazon. *Technological Forecasting and Social Change*. 2021, 167, 120676. <https://doi.org/10.1016/j.techfore.2021.120676>
- [36] Rodrigues, V. P., Caetano, M. A. L. The Impacts of Political Activity on Fires and Deforestation in the Brazilian Amazon Rainforest: An Analysis of Social Media and Satellite Data. *Heliyon*. 2023, 9(12), e22670. <https://doi.org/10.1016/j.heliyon.2023.e22670>