Model-based estimation of Amazonian forests recovery time after drought and fire events

Bruno De Faria[1,2,*], Gina Marano[3], Camille Piponiot[4], Ludmila Rattis[5,6], Andre Rech[1] and Alessio Collalti[7,8]

[1] Department of Forestry, Federal University of Vales do Jequitinhonha e Mucuri Campus JK, 39100-000, Diamantina, MG, Brazil
[2] Federal Institute of Technology North of Minas Gerais (IFNMG), 39100-000, Diamantina, MG, Brazil
[3] Department of Agriculture, University of Napoli Federico II, 80055 Portici (Naples), Italy
[4] Smithsonian Tropical Research Institute, Panamá, República de Panamá.
[5] Woods Hole Research Center, Falmouth, Massachusetts 02540, USA.
[6] Instituto de Pesquisa Ambiental da Amazônia, 78640-000, Canarana, MT, Brazil.
[7] Institute for Agriculture and Forestry Systems in the Mediterranean, National Research Council of Italy, 06128 Perugia, Italy
[8] Department of Innovation in Biological, Agro-food and Forest Systems, University of Tuscia, 01100 Viterbo, Italy

*Correspondence: blfaria@gmail.com;

Abstract: In the last decades droughts, deforestation and wildfires have become recurring phenomena that have affected both human activities and natural ecosystems in Amazonia. The time an ecosystem requires to recover from carbon losses is a crucial metric to evaluate disturbance impacts on forests. However, the factors influencing and controlling the recovery time and its spatiotemporal patterns at the regional scale are still poorly understood. In this study, we combined forest growth model, remote sensing and field plots, to map Amazonia-wide (300-ha resolution) impact and recovery time of aboveground biomass (AGB) after drought, fire and a combination of logging and fire. Our simulated results indicate that AGB decreases by 4%, 19% and 46% in forests disturbed by drought, fire and logging + fire, respectively, with an average AGB recovery time of 27 years for drought, 44 years for burned and 63 years for logged + burned areas and with maximum values reaching 184 years in areas of high fire intensity. Our findings provide two major insights in the spatial and temporal patterns of drought and wildfire in the Amazon: 1) the recovery time of the forests takes longer in the southeastern part of the basin, and, 2) as droughts and wildfires become more frequent – since the intervals between the disturbances is getting shorter than forest regeneration – potentially causing a long-lasting damage in these fragile ecosystems and a permanent degradation.

Keywords: Amazon; recovery time; aboveground biomass; climate change; 3-PG;

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1. Introduction

Natural disturbances affect forests since millennia and they a key role in forest ecosystem dynamics [1]. Nevertheless, global changes in climate and land-uses can ramp up disturbances rates in several biomes. Events like droughts and wildfires are becoming widespread phenomena that affect many natural areas on the globe and the ecosystem services they provide [2], even humid biomes with high precipitation trends such as Amazonia [3–5]. Amazonian forests account for considerable carbon storage in living biomass and soils estimated around 150-200 Pg [6,7] and they house more than the half of the world's remaining rainforest areas representing one of the most important biodiversity hotspots on the planet [8]. But the high environmental value of the Amazon forests is considerably under pressure due to the increased frequency and intensity of disturbances in the tropical regions [9]. Forest fires and large-scale drought events directly dependent on climate [1] and the significant impacts they have on Amazonian forests are often related to a combination of climate change effects, i.e. mostly warming and reduction in precipitation, and human activities such as selective logging and land-use changes. As consequence, forest degradation in the Amazon caused by repeated fires, drought events and selective loggings [10,11] results in long-term reduction of carbon stocks [12].

The Amazon Basin's historical baseline of disturbances has heavily been altered in the last 20 years by increasing rates of deforestation, drought and wildfire impacts. In the early 2000's logging activities affected circa 10,000–20,000 km^2 $year^{-1}$ of tropical forests in the Brazilian Amazon and it is estimated that understory fires destroyed ca. 85,000 km^2 of standing forests in the period 1999-2010 [13,14]. Recent studies have proven that forests are becoming more exposed to droughts [15,16]. Indeed, severe climatic events, such as the three devastating droughts of 2005, 2010 and 2016, were classified at the time of their occurrence as "one-in-a century" in this region [17,18], yet their time of return has proven to be much shorter. Altogether, droughts, wildfires and logging activities increase the susceptibility of forests to successive burning events through fragmentation, edge effects, and ignition [19]. Therefore, the increasing risk of wildfires is an additional driver of change in the Amazon region [20]. More frequent and intense disturbances could potentially release part of the C stored in Amazonian forests.

The degree of degradation of the forest C stocks depends on three major factors: (1) the type of disturbance (e.g. logging, droughts and wildfires); (2) intensity (i.e. percentage of C loss); and, (3) the time return interval (i.e. years from one event to the next one) of the abovementioned disturbances [11,21,22]. An additional hurdle to our common understanding of forest recovery processes lies in the substantial lack of field data from relatively long-term studies (e.g. > 20 years) of disturbed forests. Existing studies that focused on relatively short-term responses (usually < 20 years) of vegetation are either limited in scale [11,23,24] or evaluated the effects of single types of disturbances often in relatively small areas [25–27]. As a result, we still have a limited understanding of the combined effects of these disturbances on aboveground biomass (AGB) recovery time (i.e. how much time does it take for the forest to return to its pre-disturbance status), especially at the regional scale.

The integration of geospatial techniques with remote sensing and process-based forest growth models offers powerful tools for assessing, monitoring and modelling forest ecosystems [28] under different climatic, management and disturbance scenarios. Models can provide further insights on the mechanisms and processes involved at the chosen scale of investigation, considering both spatial and temporal climate (or human)-induced variations (i.e. scenarios). Through remote sensing techniques, in combination with GIS technology, it is possible to assess forest AGB at broader scales [29].

At regional scale, net primary production (NPP) is often used as an indicator of plant growth capacity [30], while AGB and forests well-being and are known to be strongly associated with climate because physiological processes, such as photosynthesis, are influenced by temperature, precipitation, dry season length and soil fertility [31,32]. Process-based forest growth models can help assessing the recovery time of vegetation through spatial variability using envelopes of climatic variables to predict

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recovery of above-ground carbon. Ultimately, the return interval of forest AGB can be used as a proxy for ecosystem functioning after disturbance events [33].
In this study, we assessed the recovery time (i.e. the time necessary for a forest to recover at its pre-disturbance biomass) of Amazonian forests AGB from drought, fire and a combination of logging and fire disturbances, using a dynamic forest carbon model that simulates vegetation recovery time as a function of climate scenarios.
Specifically, with the present study we aim to investigate the recovery time of AGB in the Amazon forests when subjected to a disturbance caused by: (1) an extreme drought; (2) observed fire regimes, and; (3) a combination of logging and fire disturbances by integrating the existing knowledge [10,34–36] with our modelling framework.

2. Materials and Methods

We used a spatially implicit forest productivity model based on the net primary productivity of the 3-PG model (Figure 1) (see 2.1 *Model section*) to estimate the recovery time, here defined as the time necessary for a forest to recover at its pre-disturbance AGB levels. Analysis of AGB recovery was carried out for the entire Amazonian rainforest biome, which encompasses about 5.5 million km^2 located between 15°S-5°N and 40°W-80°W. For logged areas and future droughts, we limited our analysis to the Brazilian Amazon (Figure 2).

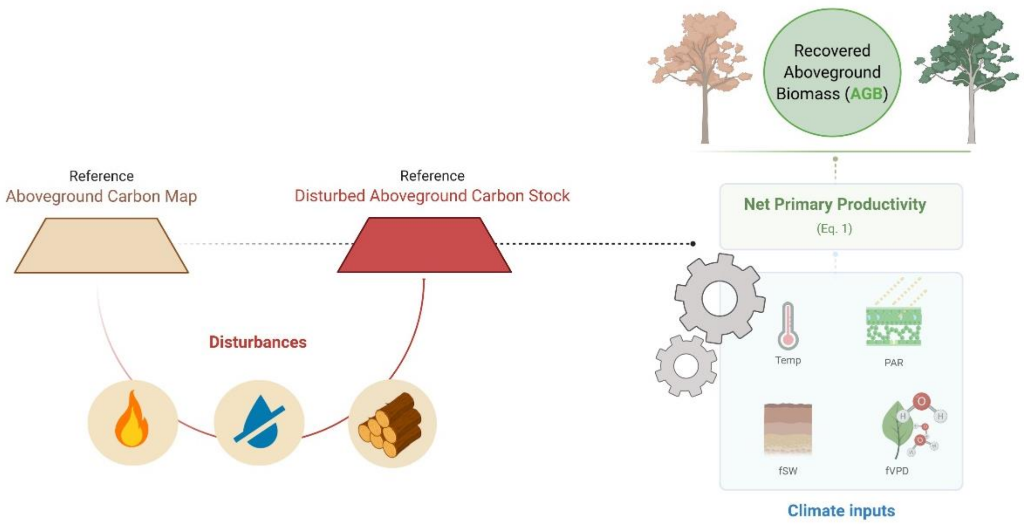

Figure 1. The processes focused in this study that simulates vegetation recovery time as a function of climate variables (soil-plant available water [fSW], photosynthetically active radiation [PAR], vapour pressure deficit [fVPD], and air temperature [Temp]). Drought stress affects aboveground biomass (AGB) as a function of (MCWD) and fire-induced biomass losses, resulting from changes in fire intensity.

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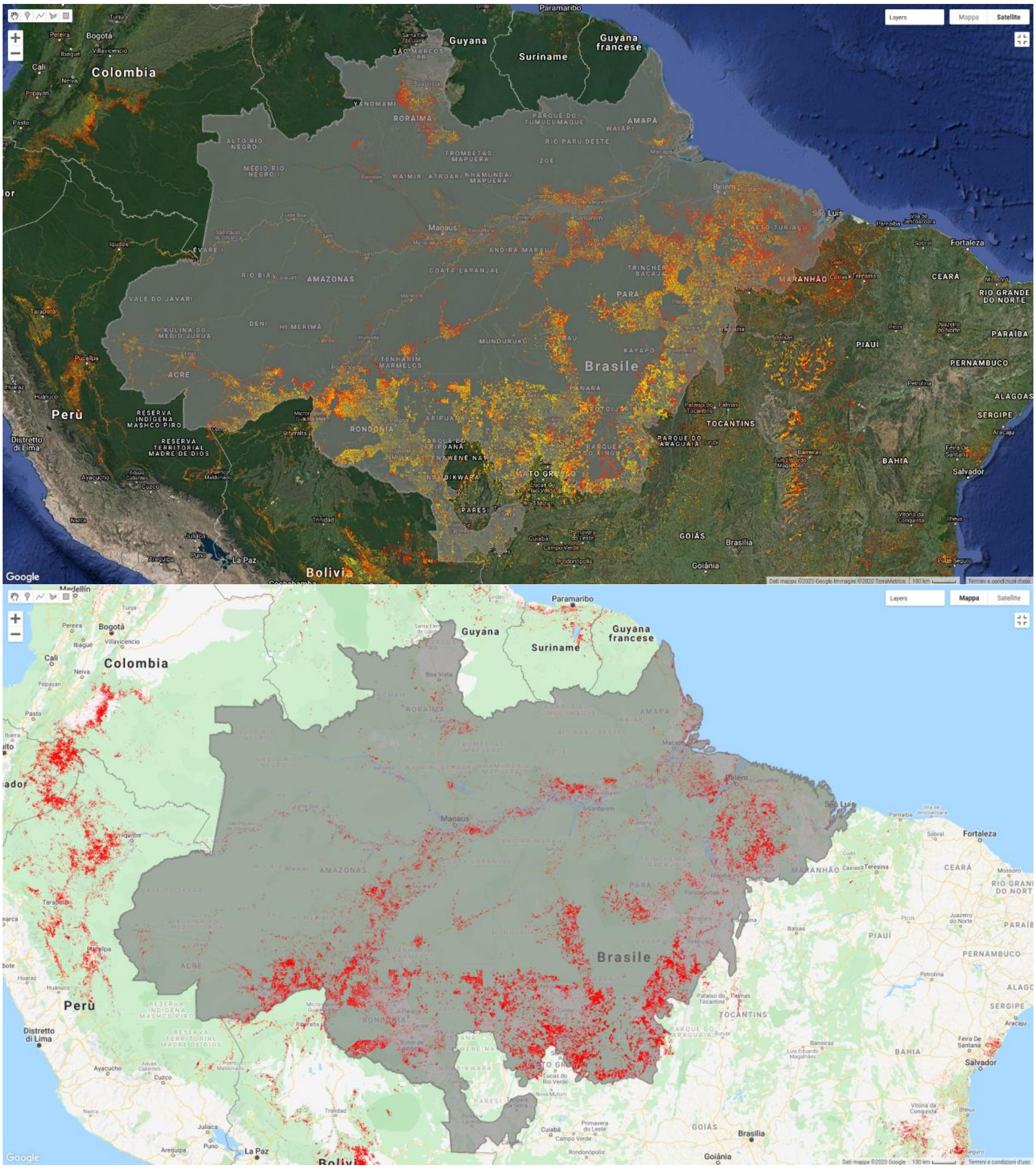

Figure 2. study area: Amazonian forest in Brazil. Amazon biome extent (gray area) has been retrieved from Global Forest Watch (https://data.globalforestwatch.org/datasets/), while forest loss map (yellow-red) has been displayed according to [37,38] (Global Forest Change dataset in Google Earth Engine). Red pixels identify areas of where tree cover loss has been detected (FORMA alerting system).

2.1 The model

In this study, recovery times are estimated using the 3-PG model (Physiological Principles in Predicting Growth; [39]) driven by four monthly climatic variables: photosynthetically active radiation (PAR, mol PAR m^{-2} $month^{-1}$), vapour pressure deficit (VPD, KPa), precipitation (mm $month^{-1}$) and air temperature (°C), respectively, to estimate gross and net primary productivity (GPP and NPP, both in gC m^{-2} $month^{-1}$) and the relative changes in C-biomass stocks as follows:

$$NPP = GPP * Y \qquad \text{(Eq. 1)}$$

Where Y is the carbon use efficiency (i.e. the fraction of GPP not used to support autotrophic respiration; [40,41]. GPP is computed as:

$$GPP = \alpha_x * modifiers * PAR * (1 - e^{k * LAI}) \qquad \text{(Eq. 2)}$$

where α_x is the maximum quantum canopy efficiency (i.e. the maximum capacity in converting light into photosynthates without environmental or other functional limitations, mol C mol PAR^{-1} m^{-2} month^{-1}), *modifiers* comprise environmental limitations to photosynthesis (temperature *fTEMP*, soil water *fSW* or vapor-pressure deficit *fVPD*), with values ranging from zero (complete limitation) to one (no limitation). For an in-depth description of modifiers algorithms see also [30,42]. The last two terms in Eq. 2 reflect the incident PAR effectively absorbed by the canopies based on their leaf area index (LAI, m^2 m^{-2}) and the leaf light extinction coefficient (k, unitless) as in the Beer's Law.

Each month, the model assumes that leaf, wood, and root carbon pools increase by an overall amount equal to the NPP, which are respectively allocated proportionally in their three pools as in the standard 3-PG carbon partitioning–allocation scheme. The assimilation of NPP is the outcome of the climate interacting with vegetation through a series of differential equations that describe the flow of C within the forest compartments [30]. Therefore, the model predicts the distribution of forest biomass from carbon stocks, but in order to obtain biomass we converted C to biomass assuming that one ton of biomass contains 0.485 tons of C [43]. The re-equilibration of forest carbon fluxes after disturbances (i.e steady state undisturbed conditions) is when the AGB growth and the decay rates stabilize.

We used the pantropical map as generated by [44] as reference biomass (pre-impact) levels to initialize the model and combining it with two comprehensive recent estimates of carbon density (i.e. estimations of [45,46] and covering a wide 250-500 Mg ha^{-1} range (Figure S1).

2.2 Estimating drought, fire and logging impacts on AGB stocks

The loss of above-ground biomass due to drought events was modeled as a function of the MCWD, a common index used to measure the cumulative water stress in Amazonia (e.g [34,47,48]). The MCWD reflects the intensity and length of dry season, when evapotranspiration exceeds precipitation (i.e. negative balance). A measure of water deficit related to tree mortality in Amazonian forests that is denoted as:

$$\Delta AGB = 0.378 - 0.052 * \Delta MCWD \qquad \text{(Eq. 3; [34])}$$

MCWD anomalies (ΔMCWD) have been shown to be a strong predictor of drought-associated tree mortality in the Amazon [47]. The Maximum Cumulative Water Deficit index represents the maximum climatological water deficit reached in the year. Specifically, a monthly water deficit was calculated as the difference between precipitation and evapotranspiration (with ground measurements estimated at 100 mm per month [48,49], thus, evapotranspiration is fixed at 100 mm month^{-1}). As a result, it is estimated that the forest is in water deficit when monthly precipitation falls below 100 mm. Therefore, the MCWD is calculated as the sum of sequential monthly water deficits, where negative MCWD values indicate higher drought stress. We quantified the MCWD for the year of 2010 using the product 3B43 of TRMM (Tropical Rainfall Measuring Mission at 0.25° grid-resolution), and, then, the average of carbon losses for each pixel using Eq. 3.

Effects of wildfire were estimated by using the CARLUC-Fire model [36]. This model specifically accounts for the effects of fire by estimating forest carbon losses after a fire event as a function of fire intensity (FI), defined as the energy released per unit length of fire-line (kWm^{-2}), which is a key factor in estimating how vegetation responds to fire events. The relationship between fire intensity and fire-induced biomass losses was derived from a large-scale fire experiment in southeast Amazonia [10,36] (Eq. 4). Based on this experiment, AGB losses were calculated as a function of FI as follows:

$$Percent\ loss\ of\ ABG\ carbon\ = \frac{1}{(1 + e^{(2.45 - 0.002373 * FI)})} \quad \text{(Eq. 4)}$$

As an important proportion of fires occurred in areas that were previously logged, we accounted for this effect in the estimation of the initial AGB by incorporating an additional loss in fire effects of 40% in burned areas that were also cleared. We assumed this based on findings of [35] that an average of forest under selective logging stores about 40% less carbon. Logged areas were defined using data from the annual Landsat-based Project for Monitoring Amazonian Deforestation. Because (PRODES, http://www.obt.inpe.br/prodes) edge effects from logging have been shown to affect forests up to 2-3 km from the border [50], we include forests located within 3 km from a deforested pixel, as a selective logging influence zone.

2.3 Experimental runs

We ran the 3-PG model at 3 km x 3 km spatial resolution under mean monthly climate conditions for the 1980-2009 period, to estimate the forest recovery time for both drought, fire and logging + fire impacts. Climate input variables used to calculate the climatic means consisted of monthly series of temperature and mean vapor pressure deficit from the Climate Research Unit (CRU TS; [51]), while PAR were obtained from the GOES–9 satellite product [52]. In each pixel, AGB recovery was assessed by simulating AGB dynamics with the model after an AGB loss corresponding to disturbance impact.

2.4 Disturbance return interval

In order to inquire whether climate change could determine an increase in future drought frequency in the area of study, we analyze future precipitation scenarios under three future climate scenarios based on Representative Concentration Pathways (i.e. RCP 2.6, 4.5 and 8.5) representing low emission, medium emission and the (extreme) unmitigated climate change scenarios, respectively. We built three scenarios using precipitation (related with water stress, MCWD) from the ensemble of 35 climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5, [53]). In details, we derived the forcing from the mean monthly simulated precipitation anomalies first averaged for all 35 models and then bias corrections with Tropical Rainfall Measuring Mission (TRMM - data product 3B43 - [54]).

To investigate frequency of future Amazonian droughts we assumed severe drought condition when MCWD anomalies (subtraction between future projections and the historical average) is <40mm (threshold derived by Phillips et al. 2009), below this threshold water stress is assumed to induce losses in AGB.

Fire return interval was calculated using The Global Fire Atlas dataset [55], during 2003–2016 summarized in a yearly 0.25° gridded based on average values of individual fires ignitions

3. Results

Disturbances have substantially affected biomass in Amazonia. In the locations affected by drought, fire and logging + fire, AGB decreased by 4%, 19% and 46%, respectively (Figure 3). Our results suggest that during the 2010 drought about 1.5 million km^2 of the Amazon lost a considerable amount of AGB (we considered losses ≥ 10% of the initial AGB). Fire could induce substantial losses in above-ground carbon affecting 550,000 km^2 especially in southern Amazon. Moreover, approximately 150,000 km^2 of the burned forest patches were located within 3 km from a logged forest

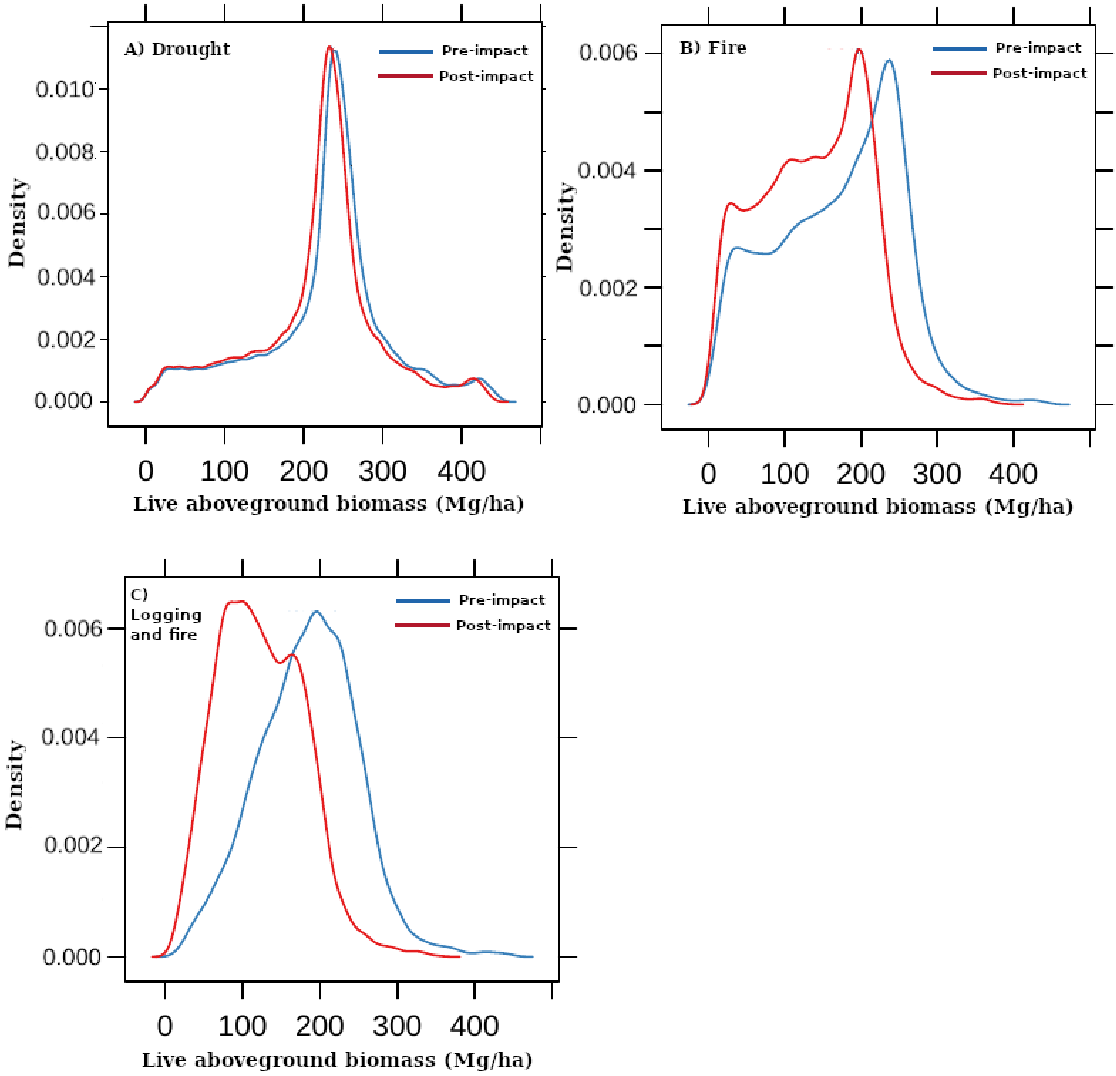

Figure 3. Biomass disturbances after drought, fire and logging + fire impacts. AGB pre- and post-impact to A) drought, B) fire, limiting our analysis to areas that burned between 2003 and 2016 and C). Logging + fire, limiting our analysis to areas up to 3 km to logging areas that also burned.

Average AGB recovery time was 27 years for dried, 44 years for burned, and 63 years for logged + burned areas. Recovery time from drought revealed a northwest-to-southeast gradient in the study area (Figure 4A). Roughly 20% of these drought-affected areas, corresponding to *ca*. 364,000 km^{2,} will recover in the first 10 years, with maximum values reaching 90 years in parts of southeastern Amazonia (Fig. 4A). Forest fires were widespread across the "arc of deforestation" (the region in southern and eastern Amazonia where the rates of deforestation were found higher) during 2003-2016 (Fig. 4B). The longest recovery times during this period were concentrated along the eastern and southwestern extent of Amazon forests in Brazil, where the maximum was about 150 years after fire disturbance. Subsequent wildfires events accounted for 10% of all forest fires during 2003-2016 delaying forest recovery time within these areas (Figures 4B). The longest recovery times were found in logged-and-burned forests with maximum values reaching 184 years (Figure 4C, 4F).

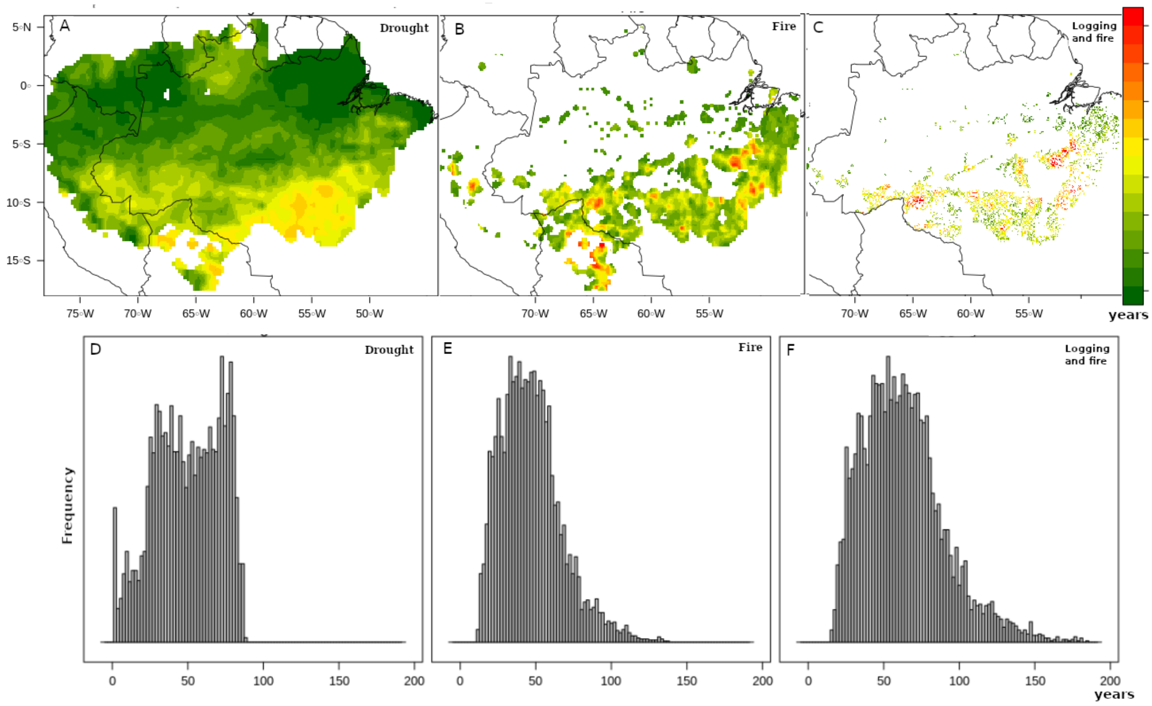

Figure 4. Aboveground recovery time (in years) for 2010-drought (A) Fire - areas that burned between 2003 and 2016 (B) and in areas that both were burned and logged (C). Histogram plots summarize AGB recovery pixels distributions (in years), for drought (D), fire (E) and logging + fire (F).

Shorter drought and fire return intervals suggest that these disturbances in future could undermine the full forest recovery. Our analyses suggest that in a scenario similar to the business-as-usual pathway of greenhouse gas emissions as the RCP 8.5, drought events will significantly impact Amazonia, especially after 2060 with mean projected drought return interval of 4 years. However, with low emission (RCP 2.6) and medium emission (RCP 4.5) climate change scenario this interval can increase to 10 and 16 years respectively (Figure 5)

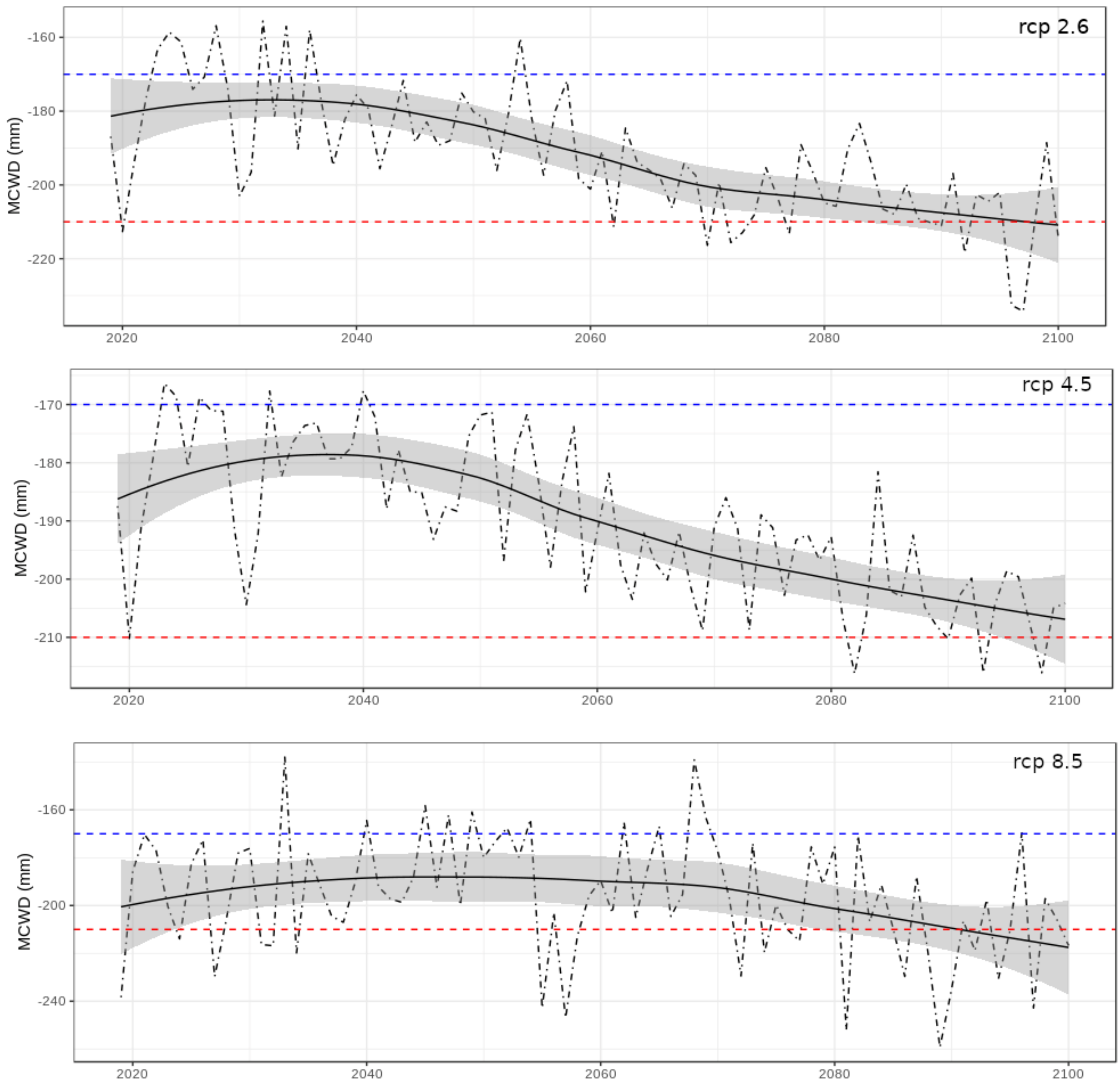

Figure 5. Future drought frequency: Projections in maximum cumulative water deficit (MCWD) across the Brazilian Amazon based on the multi-model ensemble for climate change scenarios. Black dotted lines: Mean annual MCWD across Brazilian Amazon. Blue dotted lines: Historical mean of non-drought years. Red dotted lines: severe drought condition (i.e drought induces losses in aboveground biomass). Mean change and 95% confidence intervals (black solid and shaded area).

Fire frequency in Amazonia is currently high in regions with human activities. Assuming the mean Fire return interval (FRI) as observed during 2003-2016, recurrent fires burning most of the areas in the “arc of deforestation”, ranging between 2-13 years with a median of 5.44 years (Figure 6).

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Figure 6- Fire intervals during 2003–2016 at 0.25° gridded.

4. Discussion

With the present study, we explored the AGB changes and the recovery time after drought, fire and a combination of logging and fire disturbances of the Amazon forest, using a modeling-based post-drought and post-fire carbon recovery assessment. Specifically, we investigated the recovery time in which the ecosystem response to droughts and/or fire reflects the response of forest carbon stocks to climatic conditions and their changes. For droughts events, our findings reveal that Amazonian forests persist in a reduced biomass state for more than 27 years after a drought-induced disturbance. Regarding the burned areas, recovery rates are much slower, with a resulting (on average) reduced biomass state for more than 40 years since the last fire. Moreover, combined disturbances such as logging and high intense fires can slow post-disturbance recovery time of forest up to 184 years. The intensity of the event is strongly related to both the amount of AGB lost and the recovery time of the forest. Our biomass recovery rates are consistent with [56] that showed AGB of Neotropical second growth forest took a median time of 66 years to recover to 90% of previous growth values. On the other hand, recent evidence [57] suggest that recovery time might take at least 150 years until secondary forests regain carbon levels similar to primary forests, thus indicating that these biomes have recovery capacity rates that are much lower than previously published.
Our results also suggest that by the end of the century, especially after 2060, the Brazilian Amazon will be affected by more frequent droughts with the southern area being more vulnerable since it will need longer to recover after droughts. The interplay between longer forest recovery times and more frequent droughts is an evidence in the Amazonia, where longer recovery times are already documented, see for example [58]. Moreover, if on the one hand the extreme droughts of 2005, 2010 and 2016 have prevented the full recovery of the forests, on the other, drought effects on forest canopy carbon fixation capacity could persist for several years during recovery processes [58], leading to forest degradation and changes in forest species composition [59,60].
Our findings also confirm that the land carbon sink in the Brazilian Amazon will be strongly impacted by a regime of chronic state of incomplete recovery [58], with adverse consequences also on the GPP due to shifts in precipitation patterns caused by anthropogenic emissions [61–63]. Indeed, across Amazon forests, GPP is modelled to decrease linearly with increasing seasonal water deficit [62]. Longer and more intense dry seasons have been forecasted, together with an increased frequency and severity of drought events [64–66] and future Amazon droughts are expected to

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become even more frequent [67,68]. Our projections suggest about one extreme drought per decade (drought return interval ranging from 4 to 16 years depending on the scenario of climate change). If drought frequency increases, Amazon forest, both as species composition and regional carbon sequestration, will be affected, which will thereby have an impact on global carbon cycling and contribute further to climate change [47,60,69,70]. Previous studies have already documented increased fire occurrence and tree mortality during and after Amazon droughts [4,69,71–73]. If these events continue to increase in frequency, large parts of the Amazon could potentially shift from rainforest vegetation to a fire-maintained degraded forest [74,75]. This change in forest type, structure and ecology would most likely reduce both the forest sink capacity and even its biodiversity [74]. The net increase of areas that are more susceptible to wildfires, induced by either drought events increase, or potentially intensified by climate change, could lead to significant biomass losses [7,76]. However, human pressures play a crucial role in fire ignitions, wildfires could break out also in non-dry years as in 2019, when more than 9,000 km^2 burnt despite the absence of anomalous drought. As droughts and wildfires are expected to become more frequent, the time of occurrence between these disturbances may even get shorter than forest recovery time, determining permanently damaged ecosystems and widespread degradation [75].

Although forest growth models are powerful tools that can be applied in simulating the C dynamics in forests [77,78], our results are subject to a uncertainty and a number of caveats [79,80]. Recovery time depends on climate, soils types, management history, and the presence of forest fragments nearby [56,81–83]. In this study, we modeled vegetation recovery time as a function of climate. This approach does not account for regional variation in growth rates depending on soils types (due to their inner physico-chemical properties such as water retention) or local-scale variation based on prior land use or distance from seed sources. In addition to the mechanisms mentioned above, CO_2 fertilization of Amazonian vegetation and Nitrogen deposition could play an important, but yet often neglected, role in forest regeneration [84]. It has also been proved that atmospheric CO_2 generally stimulates plant growth with increased rates in photosynthetic activity and indirectly through increased water-use efficiency [85], but not in any cases [86]. As CO_2 accumulates in the atmosphere, Amazonian trees may also accumulate more biomass resulting with denser canopies and faster growth [87]. But an increased atmospheric CO_2 concentration necessarily implies an increase in air temperatures which are all in turn speculated to increase plants' respiration which should results in a levelled-off forests' carbon use efficiency [63]. Recent studies indicate that the ability of intact tropical forests to remove carbon from the atmosphere is already saturating [7,88] calling for more studies on the possible consequences of climate change and CO_2 atmospheric concentration on forest dynamics.

5. Conclusions

This study is an example of how forest growth models are useful tools for complementing field-based studies on recovery time and represents a unique opportunity to investigate the spatial and temporal variation of forest recovery. Our biomass recovery map illustrates both spatial and climatic variability in carbon sequestration potential due to forest re-growth. By mapping potential for biomass recovery across Amazonia, policy makers could for example focus their efforts on specific areas to be protected and preserved, besides, the recovery map could also be used to identify areas with higher carbon sequestration potential that will support policies to mitigate forest degradation in areas where biomass resilience is under increasing stress (such as southeastern Amazonia). The capacity and time for forest recovery after drought, fire and logging is an important topic for research and conservation in Amazonia. Future changes in fire regimes could push some Amazonian regions into a permanently drier climate regime and greatly weaken the resilience of the entire region to possible large-scale drought-fire interactions driven by climate change. We are far from an integrated view of forest recovery processes, yet some generalizations presented in this study may provide some new insights about forest recovery time after disturbances. The consequences that an extreme climatic event, such as a drought, may cause in the forest can last for many decades. Amazonian forests resilience may thus be jeopardized by projected increases in fire and drought frequency and intensity in the region.

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Supplementary Material

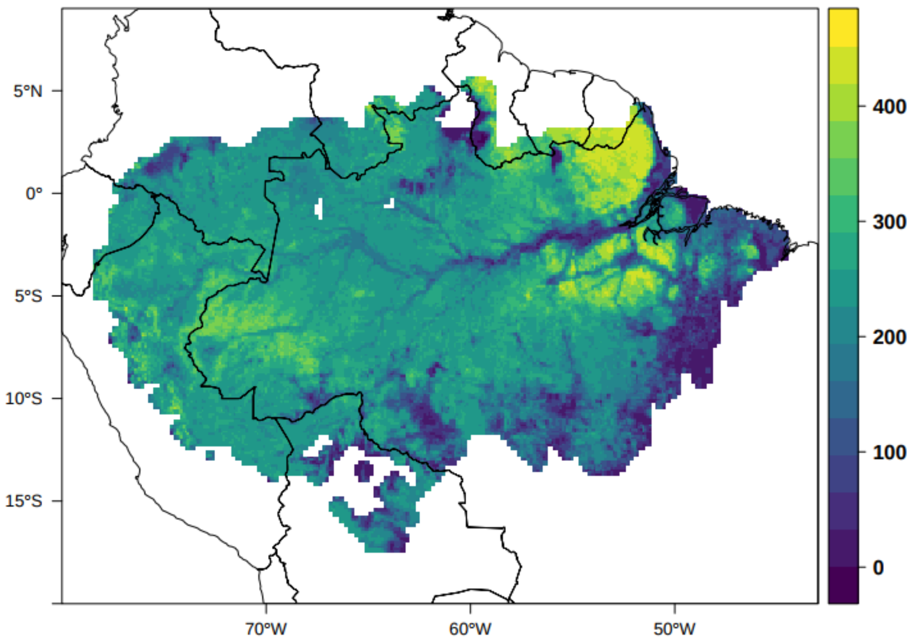

Figure S1. Pre-disturbance reference biomass map [44]