Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests

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Summary

Wildfires produce substantial CO_2 emissions in the humid tropics during El Niño-mediated extreme droughts, and these emissions are expected to increase in coming decades. Immediate carbon emissions from uncontrolled wildfires in human-modified tropical forests can be considerable due to high necromass fuel loads. Yet, data on necromass combustion during wildfires is severely lacking. Here, we evaluated necromass carbon stocks before and after the 2015-16 El Niño in Amazonian forests along a gradient of prior human disturbance. We then used Landsat-derived burn scars to extrapolate regional immediate wildfire CO_2 emissions during the 2015-16 El Niño. Before the El Niño, necromass stocks varied significantly with respect to prior disturbance and were largest in undisturbed primary forests (30.2 ± 2.1 Mg ha^{-1}, mean ± se) and smallest in secondary forests (15.6 ± 3.0 Mg ha^{-1}). However, neither prior disturbance nor our proxy of fire intensity (median char height) explained necromass losses due to wildfires. In our 6.5 million ha study region, almost 1 million ha of primary (disturbed and undisturbed) and 20,000 ha of secondary forest burned during the 2015-16 El Niño. Covering <0.2% of Brazilian Amazonia, these wildfires resulted in expected immediate CO_2 emissions of

approximately 30 Tg, 3-4 times greater than comparable estimates from global fire emissions databases. Uncontrolled understorey wildfires in humid tropical forests during extreme droughts are a large and poorly quantified source of CO_2 emissions.

1. Introduction

Increased concentrations of atmospheric CO_2 during El Niño Southern Oscillation events [1,2] have largely been attributed to emissions from the tropics [3,4], with wildfires playing an important role [4,5]. In recent decades, despite a global reduction in burned vegetation area [6,7], relatively low-intensity understorey wildfires that spread from agricultural lands have increased in the fire-sensitive Amazon rainforest [8–11]. CO_2 emissions from such wildfires are expected to grow further [10] as fire-conducive weather patterns increase across the humid tropics, particularly in South America [12].

Large-scale understorey wildfires in Amazonia are unprecedented in recent millennia. During pre-Columbian times, fires were limited to those occurring naturally from lightning strikes and prescribed burns by indigenous peoples [13]. These fires were localised and prescribed burns were planned in accordance with environmental and ecological conditions [13]. However, pervasive human modification of tropical forest landscapes, through, for example, road building, cattle ranching, and timber exploitation, combined with unprecedented drought events and the widespread use of fire as a land management tool, has fundamentally altered Amazonian fire regimes. Today, uncontrolled large-scale understorey wildfires are being witnessed in the Amazon with sub-decadal frequency [14]. Such wildfires result in high rates of tree mortality [15,16], shifts in forest structure [17,18], and drier microclimatic conditions [19], ultimately leading to increased susceptibility to future wildfires [19–21].

Carbon emissions from understorey wildfires can be split into committed and immediate emissions. Committed emissions result from the complex interplay between delayed tree mortality and decomposition, and are dependent on future climatic conditions and human influences. Research indicates that long-term storage of carbon in wildfire-affected Amazonian forests can be compromised for at least several decades: even 31 years after a fire event, burned forests store ~25% less carbon than unburned control sites due to high levels of tree mortality that are not compensated by regrowth [22]. Immediate understorey emissions are those that occur during wildfires and, in contrast to committed emissions, are relatively simple to estimate. Biome- and continent-wide analyses that rely on satellite observations (known as top-down studies) suggest that these immediate emissions from tropical forests can be substantial [23,24] and, for example, can transform the Amazon basin from a carbon sink to a large carbon source during drought years [25].

One potentially important source of immediate carbon emissions during wildfires is dead organic matter found on forest floors. This necromass, which includes leaf litter and woody debris, is a fundamental component of forest structure and dynamics and can account for up to 40% of the carbon stored in humid tropical forests [26–28]. During long periods of drought, this large carbon pool can become highly flammable [29]. However, studies quantifying necromass stocks have overwhelmingly focused on undisturbed primary forests [27]; studies that estimate necromass in human-modified tropical forests – forests that have been structurally altered by anthropogenic disturbance, such as selective logging and fires, and those regenerating following deforestation (commonly called *secondary forests*; table 1) – are rare (c.f. [30,31]). This represents a key gap in our understanding because human-modified tropical forests are increasingly prevalent [32] and increasingly vulnerable to wildfires [33-35]. While many local-scale, bottom-up studies have quantified combustion characteristics and carbon emissions following fires related to deforestation and slash-and-burn practices (see Leeuwen et al. [36] for a recent review), we know of no study that quantifies necromass before and after uncontrolled understorey wildfires in human-modified Amazonian forests. These knowledge gaps and data shortfalls limit our understanding of immediate carbon emissions from understorey wildfires. Improving such estimates is essential for refining Earth Systems models and both national and global estimates of greenhouse gas emissions.

Here, we address these knowledge gaps using a hybrid bottom-up/top-down approach to study a human-modified region of central-eastern Amazonia which experienced almost 1 million ha of understorey wildfires during the 2015-16 El Niño (figure 1). We combined data from a previously published large-scale field assessment of carbon stocks [37] with on-the-ground measures of woody debris before and after the 2015-16 El Niño, proxies of fire intensity and coverage within study plots, and remotely sensed analyses of fire extent across the region. Specifically, we (a) quantify carbon stocks vulnerable to combustion across human-modified tropical forests in central-eastern Amazonia; (b) use post-burn measures to investigate the factors influencing the loss of necromass during wildfires; (c) estimate region-wide immediate carbon emissions from wildfires; and (d) compare these region-wide emission estimates to those derived from widely used global fire emissions databases.

2. Methods

(a) Quantification of necromass stocks in human-modified Amazonian forests

We established 107 plots (0.25 ha) in human-modified forests in central-eastern Amazonia in 2010 (figure 1). Plots were located in the municipalities of Santarém, Belterra, and Mojuí dos Campos in the state of Pará, Brazil, and form part of the Sustainable Amazon Network (RAS – *Rede Amazônia Sustentável* in Portuguese [38]). Study plots covered a range of prior human impacts (table 1) and included undisturbed primary forests (n = 17), primary forests selectively logged prior to 2010 (n = 26), primary forests burned prior to 2010 (n = 7), primary forests logged and burned prior to 2010 (n = 24), and secondary forests recovering after complete removal of vegetation (n = 33; see table 1).

Summary carbon estimates for these 107 plots can be found in Berenguer et al. [37]. Here, we focused on carbon stored in their necromass pools. We estimated necromass stocks in dead-standing tree and palm stems, coarse woody debris (CWD; ≥ 10 cm diameter at one extremity), fine woody debris (FWD; 2-10 cm diameter at both extremities), and leaf litter (including twigs < 2 cm diameter at both extremities, leaves, and fruits and seeds). Full carbon estimation methods can be found in Berenguer et al. [37]. In brief, in each plot we measured the diameter and height of all large (≥10cm DBH) dead tree and palm stems. We measured the diameter and height of all small dead tree and palm stems (≥2-10 DBH) in five subplots (5 x 20 m) in each plot. We used the allometric equations of Hughes et al. [39] and Cummings et al. [40] to estimate, respectively, carbon stocks for dead-standing trees and palms. Subplots were also used to estimate the diameters and lengths of all pieces of fallen CWD (≥ 10 cm). We estimated the volume of each piece of CWD using Smalian's formula [27] after accounting for the extent of damage (i.e. void space). We multiplied the volume of each CWD piece by its decomposition class to calculate CWD mass [41]. In all study plots, we established five smaller subplots (2 x 5 m) to assess fine woody debris (FWD). These were sampled and weighed in the field. A sub-sample (≤ 1 kg) was collected in each subplot and oven-dried to a constant weight. The wet-to-dry ratios of the FWD samples were used to estimate the total FWD stocks per plot. To estimate the biomass of leaf litter, ten 0.5 x 0.5 m quadrats were established in each plot. We oven-dried leaf litter samples to a constant weight to get an estimate of the leaf litter stocks in each plot. Biomass estimates for each necromass component were then standardised to per ha values, and the carbon content was assumed to be 50% of biomass dry weight [42]. See Supplementary Materials (Section 1) for all equations we used to estimate necromass biomass.

(b) Longitudinal monitoring of coarse woody debris

To estimate necromass change through time, we continued to monitor 18 of the 107 RAS plots (figure 1). These 18 plots were chosen because they are spatially distributed across the region and we were able to secure long-term authorization to monitor them. They included undisturbed primary forests (n = 5), primary forests logged prior to 2010 (n = 5), primary forest logged and burned prior to 2010 (n = 4), and secondary forests (n = 4; table 1). We conducted surveys of the 18 plots between November 2014 and September 2015, using a slightly altered sampling design to align with the Global Ecosystem Monitoring (GEM) protocol (see [43] for details). We established five 1 x 20 m subplots in each of the 18 plots, measured all pieces of CWD, and estimated their biomass and carbon content following the methods outlined above (see Methods (a)).

(c) Impacts of El Niño mediated wildfires on necromass stocks

Extensive understorey wildfires burned seven of our 18 study plots during the 2015-16 El Niño, including two previously undisturbed primary forests, four primary forests logged prior to 2010, and one primary forest that was logged and burned prior to 2010. To investigate necromass carbon stock losses due to these wildfires, we resurveyed all 18 plots in June 2017. We re-measured each individual piece of CWD and estimated biomass using the methods described above (Methods (a)). By comparing CWD stocks before and after the El Niño in the 11 plots that did not experience wildfires, we were able to estimate CWD background decomposition rates. By comparing CWD stocks before and after the El Niño in the seven plots that did suffer wildfires, we were able to measure CWD combustion completeness.

We used values from the 2010 surveys to provide estimates of the pre-El Niño carbon stocks in leaf litter and FWD. Based on visual inspection of the sites (figure S2), we assumed 100% combustion completeness of these necromass components in the fire-affected proportion of burned plots. Recognising that this is a strong assumption, we consider the validity of it in our Discussion. We did not consider wildfire-mediated changes in necromass carbon stocks in dead standing trees and palms, due to a lack of data on combustion compleness.

In the seven plots that burned, we calculated average char height for each stem, defined as the sum of maximum and minimum char heights divided by two. We then used these average stem char heights to calculate the plot-level median char height, which we used as our proxy for fire intensity. In addition, we used the proportion of sampled stems with burn scars as an estimate of the area of each plot that burned (Supplementary Materials). To increase our sample of fire-affected plots (to 16), we also measured the area burned in an additional 9 of the original RAS plots that were sampled during the 2010 censuses and burned during 2015-16 (table 1). Prior to the wildfires, these additional plots included undisturbed primary forests (n = 3), primary forests logged prior to 2010 (n = 1), primary forests logged and burned prior to 2010 (n = 4), and secondary forests (n = 1).

We used these data to estimate the per ha necromass loss (NL) attributable to wildfires using the following equation:

$$NL = FL_{CWD} \times \left(CC_{CWD} - D_{CWD}\right) + FL_{LLFWD} \times BA \quad (1)$$

where, FL_{CWD} is the per ha fuel load of CWD estimated from the 107 RAS plots surveyed in 2010; CC_{CWD} is the combustion completeness of CWD estimated from seven of the 18 CWD monitoring plots that burned during the 2015-16 El Niño; D_{CWD} is the background CWD decomposition rate estimated from the 11 CWD monitoring plots that did not burn during the 2015-16 El Niño; FL_{LLFWD} is the per ha fuel load of leaf litter and FWD estimated from the 107 plots surveyed in 2010; and BA the proportion of the plot that burned estimated from the 16 RAS plots that burned during the 2015-16 El Niño (table 1).

(d) Data analysis

We used the Kruskal-Wallis test to investigate variation across forest classes of prior human disturbance (table 1) and used the Conover-Iman test with Bonferroni adjustments to perform multiple pairwise comparisons of forest class medians. We assessed differences across forest classes in: carbon stocks stored in each necromass component (i.e., dead-standing stems, CWD, FWD, and leaf litter) from the 2010 survey; total and percentage necromass carbon stock losses in the 18 plots surveyed between 2014 and 2017; and the proportion / area of plots burned during the 2015-16 El Niño. We used linear regression to investigate the relationship between: necromass carbon stocks before and after the 2015-16 El Niño; fire intensity and stock losses; and the burned area in each plot and stock losses.

(e) Quantification of burned area and estimation of region-wide emissions from forest fires

To estimate wildfire-mediated carbon emissions from necromass across our study region, we first calculated the cumulative area of primary and secondary forest that experienced understorey wildfires during 2015-16 in the central-eastern region of the Amazon, an area of ~6.5 million ha (figure 1). We built a time-series of Landsat (5, 7 and 8) imagery from 2010 to 2017 for the RAS study region and the surrounding area from the EROS Science Processing Architecture (ESPA) / U.S. Geological Survey (USGS) website (https://espa.cr.usgs.gov). We performed an unsupervised classification of raw imagery, followed by manual correction of classification errors, to identify several land-uses throughout the time-series (see table S2 for all land-use classes and the Supplementary Materials Section 2 for a detailed description of burned areas detection). We then used the burned area of primary and secondary forests and estimates of per ha necromass stock losses from wildfires (Eq. 1) to determine region-wide necromass carbon emissions, using a conversion factor of 3.286 kg of CO_2 per kg of C [44]. This conversion factor does not include other forms of emitted C (such as CO), in keeping with global fire emissions databases.

We took two approaches to account for uncertainty in expected regional necromass emissions. First, we considered four land-use scenarios using two sets of primary and secondary forests (table S1). To account for potential variation in fire susceptibility across primary forest disturbance classes, we estimated the five variables in Eq. 1 using all undisturbed and disturbed primary forest classes (prim1) and then only disturbed primary forests (prim2). For secondary forests, we used CC_{CWD} and FL_{LLFWD} from all secondary forests, used D_{CWD} and BA from all forest classes combined, and used CC_{CWD} from all primary forest classes because none of the secondary forests plots we were monitoring for changes in CWD burned during 2015-16 (sec1). Our other scenario for secondary forests (sec2) was more restrictive: we used the fuel load (FL_{CWD}, FL_{LLFWD}), decomposition (D_{CWD}), and BA values from secondary forests only and combined these with all CC_{CWD} values we had from disturbed and undisturbed primary forests.

Second, to account for uncertainty in the distribution of the variables in Eq. 1, we ran 1000 bootstrap with replacement simulations to determine each variable's mean value and standard error. We calculated the standard error of Eq. 1 using the variable standard errors, accounting for error propagation, and we constructed 95% confidence intervals for Eq. 1 as its mean value ± 1.96 times the standard error of the mean.

(f) Quantitative comparisons with GFED and GFAS

We compared our region-wide CO_2 emission estimates to two fire emissions databases frequently used in Earth Systems models and carbon budgets: the Global Fire Emissions Database (GFED) version 4.1s [45] and the Global Fire Assimilation System (GFAS) version 1.1 [46]. For both datasets, we obtained data for our study period (August 2015 – July 2016) and cropped them to our ~6.5 million ha study region, shown in figure 1.

We first calculated cumulative emissions from GFED and GFAS (Supplementary Materials) and compared these to our emissions estimates. Second, to investigate potential sources of discrepancy between estimates, we spatially mapped GFED, GFAS, and our CO_2 emissions estimates. At both GFED and GFAS resolutions (0.25 and 0.1 degrees, respectively), we mapped our mean (across land-use scenarios; table S1) expected emissions assuming that emissions were constant in burned area (i.e. if a cell contained *x*% of the burned area, we assumed it accounted *x*% of the total emissions). Finally, because GFED also provides estimates of the area burned at 0.25 degrees, we used our land-use map to estimate burned area at that resolution.

3. Results

(a) Vulnerable necromass carbon stocks across human-modified Amazonian forests

Total necromass and its components varied significantly with respect to forest class ($p < 0.05$ in all cases; figure 2*).* Primary forests contained significantly higher total necromass than secondary forests ($p < 0.01$ for all pairwise comparisons), with the highest total found in undisturbed primary forests (30.2 ± 2.1 Mg ha^{-1}, mean ± se). By contrast, secondary forests contained only half as much necromass as undisturbed primary forests (15.6 ± 3.0 Mg ha^{-1}). Variation in total necromass was driven in large part by variation in CWD, which accounted for 61.3 ± 2.7% of the total necromass stocks across forest classes. Leaf litter was the next most important component of total necromass, with 19.8 ± 2.7% residing in this component. Dead standing stems accounted for 14.4 ± 1.8% of total necromass. Finally, FWD was by far the smallest necromass component, harbouring just 4.6 ± 0.2% of the total.

(b) Impacts of El Niño mediated wildfires on necromass stocks

On average, 87.1 ± 2.7% of the ground area of our fire-affected study plots burned, and there was no significant difference in the total unburned area of fire-affected plots across forest classes (χ^2_3 = 2.1; p = 0.56). For CWD, all but two pieces had burned from a total of 34, and CWD carbon stocks losses from combustion varied from 38% to 94% (mean = 65.4%, SE = 7.1%).

Necromass carbon stock losses in the seven burned plots were unrelated to median char height (R^2 = 0.09; p = 0.51; figure 3a) and area of plot burned (R^2 = 0.10; p = 0.49; figure 3b). Forest class did not predict necromass carbon stock losses in burned sites when expressed as either percentage (χ^2_2 = 2.25; p = 0.32) or total (χ^2_2 = 1.12; p = 0.57) loss. Similarly, forest class did not predict necromass losses in unburned sites when expressed as either percentage (χ^2_3 = 1.58; p = 0.66) or total (χ^2_3 = 2.18; p = 0.54) loss.

On average, burned sites lost 73.0 ± 4.9% of their pre-El Niño necromass stocks (figure 4), compared to a 26.1 ± 4.8% reduction in unburned sites (from decomposition). As expected, pre-El Niño necromass stocks strongly predicted post-El Niño necromass in our unburned sites (R^2 = 0.95; p < 0.001; figure 4a). This relationship disappeared in fire-affected plots (R^2 = 0.08; p = 0.54; figure 4b), indicating that combustion completeness was insensitive to initial necromass stocks. Despite our small sample size, visual inspection suggests that these findings were unaffected by forest class.

(c) Region-wide burned area and estimates of carbon stock losses

During the 2015-16 El Niño, 982,276 ha (15.2%) of forest in our study region experienced understorey wildfires. These wildfires were overwhelmingly concentrated in primary forests: <2% of the burned area was in secondary forests, despite these accounting for 9% of the forest cover in our study region. When considering all primary forest and secondary forest plots (prim1 + sec1), resultant necromass carbon stock losses amounted to 10.06 Tg (95% confidence interval, 5.85-14.27 Tg). Converting to CO_2, this is equivalent to expected emissions of 33.05 Tg

(95% confidence interval, 19.22-46.87 Tg; figure 5). Our mean carbon-dioxide emission estimates were relatively insensitive to the land-use scenarios (figure 5). However, the 95% confidence interval was substantially wider with land-use scenario prim2 (scenarios b & d; figure 5) due to greater uncertainty in decomposition rates when restricted to disturbed primary forest only compared to all primary forests – undisturbed and undisturbed – combined.

(d) CO_2 emissions comparison with GFED and GFAS

GFED and GFAS both vastly underestimated expected wildfire CO_2 emissions for our study region and period. Respectively, these databases suggest cumulative emissions that are 77% and 68% lower than the expected value we found with land-use scenario a (figure 5). These discrepancies can be explained by the underdetection of understorey wildfires by both GFED and GFAS algorithms. This can be seen across our whole study region, but is particularly evident in areas free from historic deforestation (figure 6). GFED and GFAS appear to be more successful at detecting fires in agricultural areas with lower levels of forest cover (figure 6). Highlighting the insensitivity of GFED to understory wildfires, this database suggests that, at most, 6% of any given 0.25-degree cell across our study region, and approximately 90,000 ha in total, burned during the 2015-16 El-Niño (figure 6e). By contrast, we show that as much as 74% of a cell (figure 6f) and almost 1 million ha of forest was affected by understory wildfires.

4. Discussion

(a) Region-wide carbon emissions from El Niño-mediated wildfires

We investigated necromass carbon stocks in human-modified forests before and after large-scale understorey wildfires in central-eastern Amazonia that occurred during the 2015-16 El Niño. Our novel assessment revealed that expected immediate necromass CO_2 emissions from these wildfires are around 30 Tg (figure 5). This is equivalent to total CO_2 emissions from fossil fuel combustion and the production of cement in Denmark, or 6% of such emissions from Brazil, in 2014 [47]. Consequently, wildfire-mediated immediate carbon emissions, which are not currently considered under national greenhouse gas inventories [48], represent a large source of CO_2 emissions. Moreover, these immediate emissions will be greatly exacerbated by further committed emissions resulting from tree mortality, which can be as high as 50% [16] and may not be balanced by post-fire regrowth on decadal time scales [22].

Our results add to the work on prescribed burns associated with deforestation [36], contributing important information about the role of El Niño-mediated wildfires. The scale of the immediate emissions we estimated, coupled with future committed emissions, make wildfires particularly relevant for climate change mitigation programmes such as REDD+ [9,49]. For REDD+ to succeed in Amazonia, we demonstrate that forests must be protected from wildfires, as even the immediate emissions from large-scale wildfires can equal those from whole countries. Future climate change will make this only more imperative, with extreme droughts, higher temperatures, and reduced rainfall all predicted for the Amazon Basin in the near future [50–52]. Wildfires may also undermine the important role that protected areas have historically served as carbon stores [53], as illustrated by the large areas burned in the Tapajós National Forest and the Tapajós-Arapiuns Extractive Reserve (figure 1).

(b) Fuel loads in humid tropical forests

Total necromass carbon stocks in the 107 RAS plots surveyed in 2010 did not vary significantly between disturbed and undisturbed primary forests (figure 2e). The mean value we found for total necromass carbon stocks in undisturbed forests was 30.2 ± 2.1 Mg ha^{-1}. This value is broadly consistent with previous estimates for the eastern Amazon. For example, Keller et al. [41] and Palace et al. [54] found necromass carbon stocks of, respectively, 25.4 and 29.2 Mg ha^{-1} in undisturbed primary forests in the Tapajós region of Pará. In primary forests disturbed by reduced-impact logging, these studies found, respectively, 36.4 and 42.75 Mg ha^{-1} of necromass carbon. However, our estimates for necromass stocks in disturbed primary forests are markedly lower (figure 2e). This discrepancy is likely a function of time since disturbance. Keller et al. [41] and Palace et al. [54] assessed necromass carbon stocks soon after disturbance, when necromass stocks are likely to be higher. In contrast, disturbance of RAS sites occurred between 1.5 and 25 years before the 2010 surveys. Necromass stocks can be highly dynamic, with residence times for most coarse woody debris estimated at less than a decade [28], especially in the case of small diameter and low wood density tree species [55]. Thus, necromass stocks in many of our disturbed primary forest sites may have had time to decrease to an equilibrium level, similar to that of undisturbed forests, where input and decomposition are largely balanced.

We did, however, find significantly larger necromass stocks in primary forests compared to secondary forests. This may be explained by a) pre-abandonment land-uses removing all fallen biomass in intensive clearance or maintenance fires; b) the smaller necromass input pool in secondary forests due to lower levels of aboveground live biomass [37]; and c) the lower wood density of stems in secondary forests [56], resulting in more rapid coarse woody debris decomposition.

(c) Impacts of El Niño mediated wildfires on necromass stocks

On average, wildfires burned 87.1 ± 2.7% of our fire-affected necromass monitoring plots (figure 3b). This figure is substantially higher than the 62-75% burn coverage measured during experimental fires in previously undisturbed transitional Amazonian forests [18]. The areal extent of these wildfires reduced necromass (in CWD, FWD, and leaf litter) carbon stocks by 46.9 ± 6.9%, when gross necromass loss (73.0 ± 4.9%) was corrected for decomposition (26.1 ± 4.8%). The understorey wildfires that affected our burned plots were relatively low intensity, with maximum median char height of 20.5 cm. Nonetheless, our findings demonstrate that these low-intensity wildfires can dramatically diminish necromass stocks in human-modified tropical forests.

Further, both area of plot burned and necromass carbon stock losses showed little variation across disturbance classes. This may indicate that the 2015-16 El Niño, which was one of the strongest in recorded history, produced drought conditions so severe that necromass moisture content was reduced across all forest classes to a level which permitted combustion and sustained fires, overriding any pre-existing microclimatic differences that may have existed due to the initial disturbance. This is further corroborated by the fact that wildfires did not distinguish between largely undisturbed forests (mostly inside protected areas) and those that have been modified by humans (mostly outside protected areas), burning vast areas of both types of forest (figure 1).

(d) Caveats

Though our dataset is the first that allows for quantification of necromass carbon stocks pre- and post-uncontrolled understorey wildfires in human-modified Amazonian forests, our sample size was limited, with just 18 necromass monitoring plots, of which seven burned during the 2015-16 El Niño. Consequently, results which follow from these samples should be treated with a degree of caution. In particular, we found that necromass stock losses were not significantly related to our plot-level estimate of burned area and that fire susceptibility did not appear to vary across disturbance classes. In both cases, the lack of significance may reflect the small sample sizes rather than a genuine lack of relationship.

Moreover, due to the limitations of our data, we assumed 100% combustion of leaf litter and FWD in the fraction of plots that burned when calculating necromass carbon losses (Eq. 1). In a recent review, Leeuwen et al. [36] found that mean combustion completeness of leaves, litter, and smaller classes of woody debris was 73-94%. However, as they acknowledge, combustion completeness can be significantly higher during El Niño years. Thus, given the strength of the 2015-16 El Niño, and our personal observations (figure S2), our combustion completeness assumption is likely to be reasonable.

Because of our small sample size, the 95% confidence intervals for our region-wide CO_2 immediate emissions are wide, ranging from around 8 Tg to almost 48 Tg. Future research efforts should prioritise necromass monitoring in a larger number of sites, across a range of tropical forests, to better constrain these values; as we show, such emissions have the potential to significantly exacerbate global climate change.

Despite the above limitations, there are reasons to suspect that our necromass stock loss and carbon emission estimates are highly conservative. First, we did not measure wildfire-induced carbon changes in the soil organic layer, yet research from the same region suggests that wildfires significantly reduce soil carbon pools [57]; nor could we estimate combustion of dead-standing stems, which account for ~15% of total necromass (figure 2). Second, none of the disturbed primary forest plots in which we monitored necromass changes were recently disturbed prior to the 2015-16 wildfires, allowing time for decomposition to reduce high levels of post-disturbance necromass. Had our sample included recently disturbed sites, necromass losses would have been greater. Third, detection of low intensity understorey wildfires continues to present a remote sensing challenge. Although manual correction of our unsupervised land-use classifications revealed only a small number of misclassifications, it is possible that some wildfire-affected sites were missed, leading to an underestimation of regional emissions.

In addition to showing that wildfire carbon emissions can be substantial, we also showed that such emissions remain poorly quantified. GFED and GFAS, CO_2 emission databases that are widely used in Earth Systems models and carbon budgets, returned considerably lower emission estimates for our study region and period than our expected values (figure 5). Nevertheless, the scale of this discrepancy is underestimated for several reasons. First, we focused solely on necromass carbon losses from understory wildfires whereas GFED and GFAS include emissions from all land use classes combined. Both databases therefore account for grassland and agricultural fires, which can affect large areas of human-modified tropical landscapes. Second, GFED includes both committed and immediate CO_2 emissions. Third, and again with respect to GFED, fuel loads are much high than those present in our post-disturbance plots, because they are primarily derived from slash-and-burn and deforestation studies.

(e) Conclusions

We demonstrate that there was a substantial loss of necromass following El Niño-mediated wildfires in the central-eastern Amazon. We conservatively estimate that wildfires in this region burned 982,276 ha (15.2% of our study region) of primary and secondary forest, resulting in expected immediate CO_2 emissions of approximately 30 Tg. Better understanding this large and poorly quantified source of atmospheric carbon is crucial for climate change mitigation efforts.

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Author contributions

JB, FE-S and EB designed the study. EB and JF were responsible for plot selection and subsequent authorizations from landowners. EB, JB, JF, LEOCA and YM designed the field protocols. EB, AP, FF, LCR, and KW performed data collection. KW, GDL, AP, EB and CVJS performed data analyses. KW, GDL, EB, and JB wrote the paper with input from all co-authors.

Data accessibility

The field data and code used in this paper have been deposited at https://doi.org/10.6084/m9.figshare.7059494. The satellite imagery is available from USGS (see https://landsat.usgs.gov/landsat-data-access). The GFED and GFAS dataset are available from https://www.globalfiredata.org/data.html and http://apps.ecmwf.int/datasets/data/cams-gfas/, respectively.

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Figure legends

Figure 1. (a) The 2017 land-use map across the ~6.5 million ha study region. (b) The land-use map within the RAS study area (shown by the white border in (a)). Also shown in this panel are the locations of the 107 study plots (black circles). The 18 of these that were used for necromass monitoring are shown as orange circles. The inset shows the Santarém study region (red circle) within South America, the Brazilian Amazon (green), and Pará (white border).

Figure 2. Necromass carbon stocks in leaf litter (a), fine woody debris (FWD; b), coarse woody debris (CWD; c), dead standing stems (d), and the total across all components (e) in human-modified Amazonian forests. Boxplots show the interquartile range. Letters above the boxplots show the results from multiple pairwise comparisons of forest class medians. Classes that do not share a letter have significantly different medians ($p < 0.05$).

Figure 3. The relationship between percentage reduction in necromass carbon stocks and fire intensity (a), as measured by median char height, and plot-level estimates of burned area (b) in human-modified Amazonian forests.

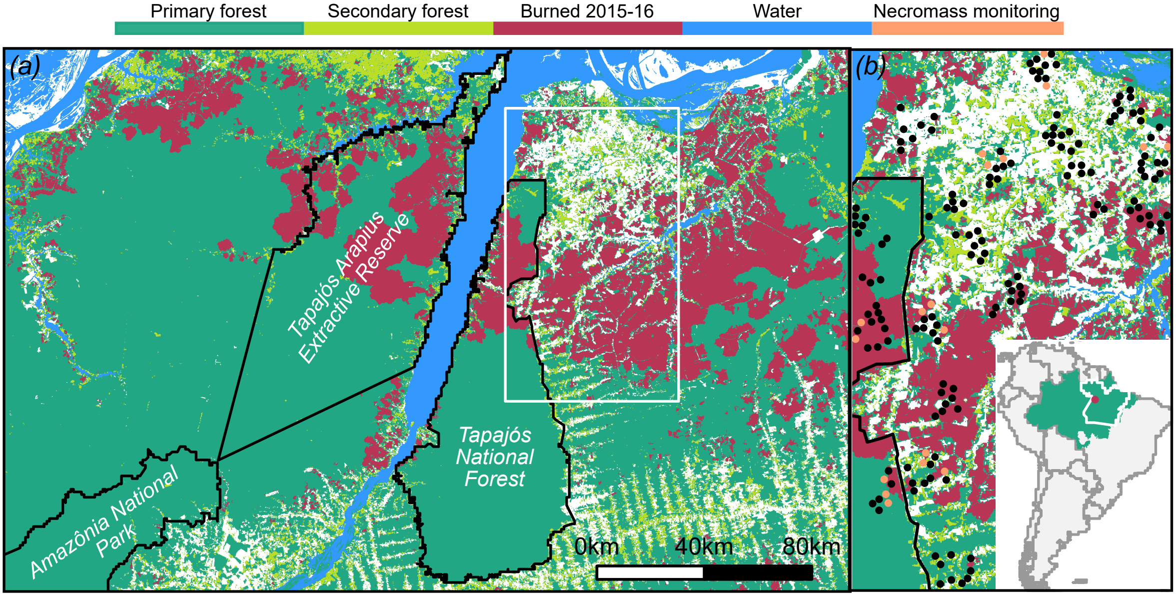
Figure 4. Pre- vs post-El Niño necromass carbon stocks in unburned control sites (a) and sites burned in 2015-16 (b), and pre-El Niño necromass carbon stocks vs post-El Niño necromass losses in unburned control sites (c) and sites burned in 2015-16 (d) in human-modified Amazonian forests. In panel (a) the black line shows the significant ($p < 0.001$) relationship between pre- and post-El Niño necromass carbon stocks in unburned sites. The equation for this relationship is shown in the panel. The grey band represents 1 s.e.m. Note that, due to data limitations, pre- and post-El Niño necromass totals are based on coarse and fine woody debris and leaf litter only (i.e. dead standing stems are not included).

Figure 5. CO_2 emissions for wildfires in central-eastern Amazonian human-modified tropical forests. Points show expected emissions for four land-use scenarios (see Section 2e and table S1): a, prim1 + sec1; b, prim2 + sec1; c, prim1 + sec2; d, prim2 + sec2. Error bars show CO_2 emission 95% confidence intervals. Also shown are cumulative CO_2 emissions for our study region and period from the Global Fire Emissions Database (dotted line) and the Global Fire Assimilation System (dashed line).

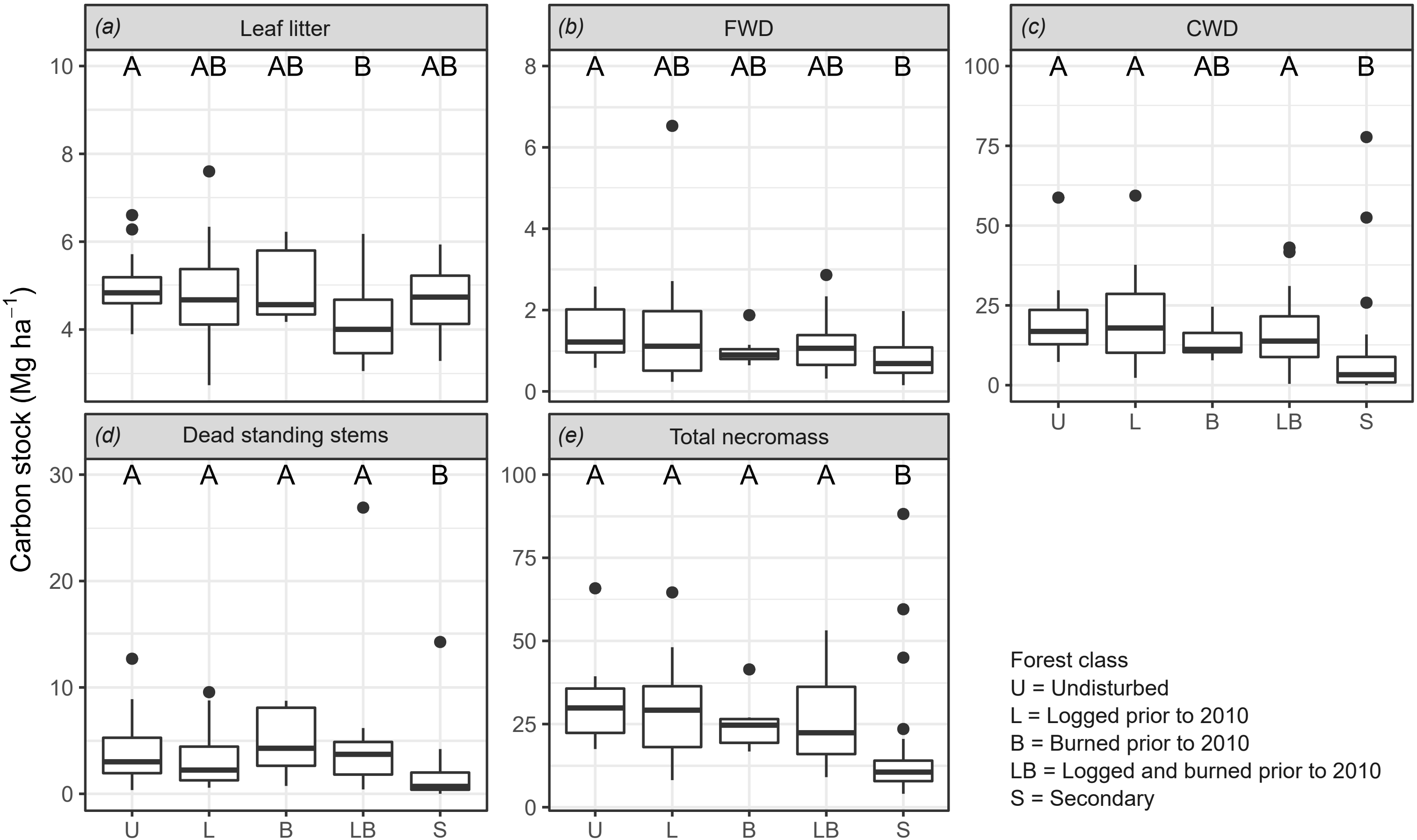
Figure 6: Comparing our findings to those from the Global Fire Assimilation System (GFAS) and the Global Fire Emissions Database (GFED). CO_2 emissions for our study region and period from GFAS (a) and our emissions shown at the same scale (0.1 degrees; (b)). CO_2 emissions from GFED (c) and our emissions shown at the same scale (0.25 degrees; (d)). The proportion of land burned for our study region and period from GFED (e) and our estimate of burned area shown at the same scale (0.25 degrees; (f)). In all panels, our Landsat-derived fire map is shown in dark green, deforestation in light grey, and water in blue.

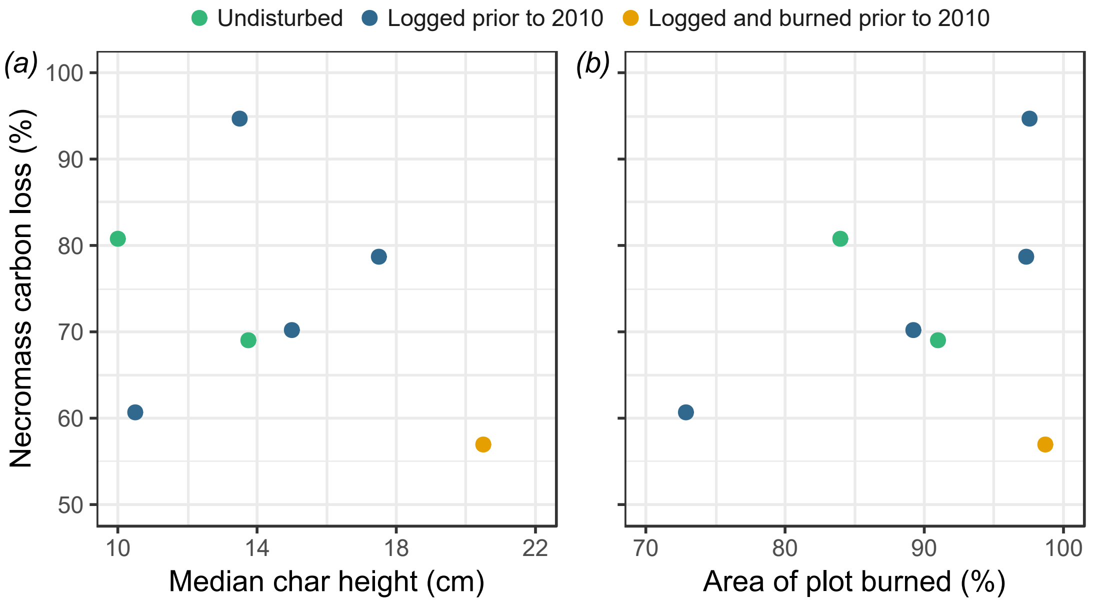
Table 1: Forest classifications for pre-El Niño forest disturbance classes and the plot samples in 2010, 2014-15 and 2017. The 2015-16 sample occurred after the extensive wildfires and is a subset of the 2014-15 sample.

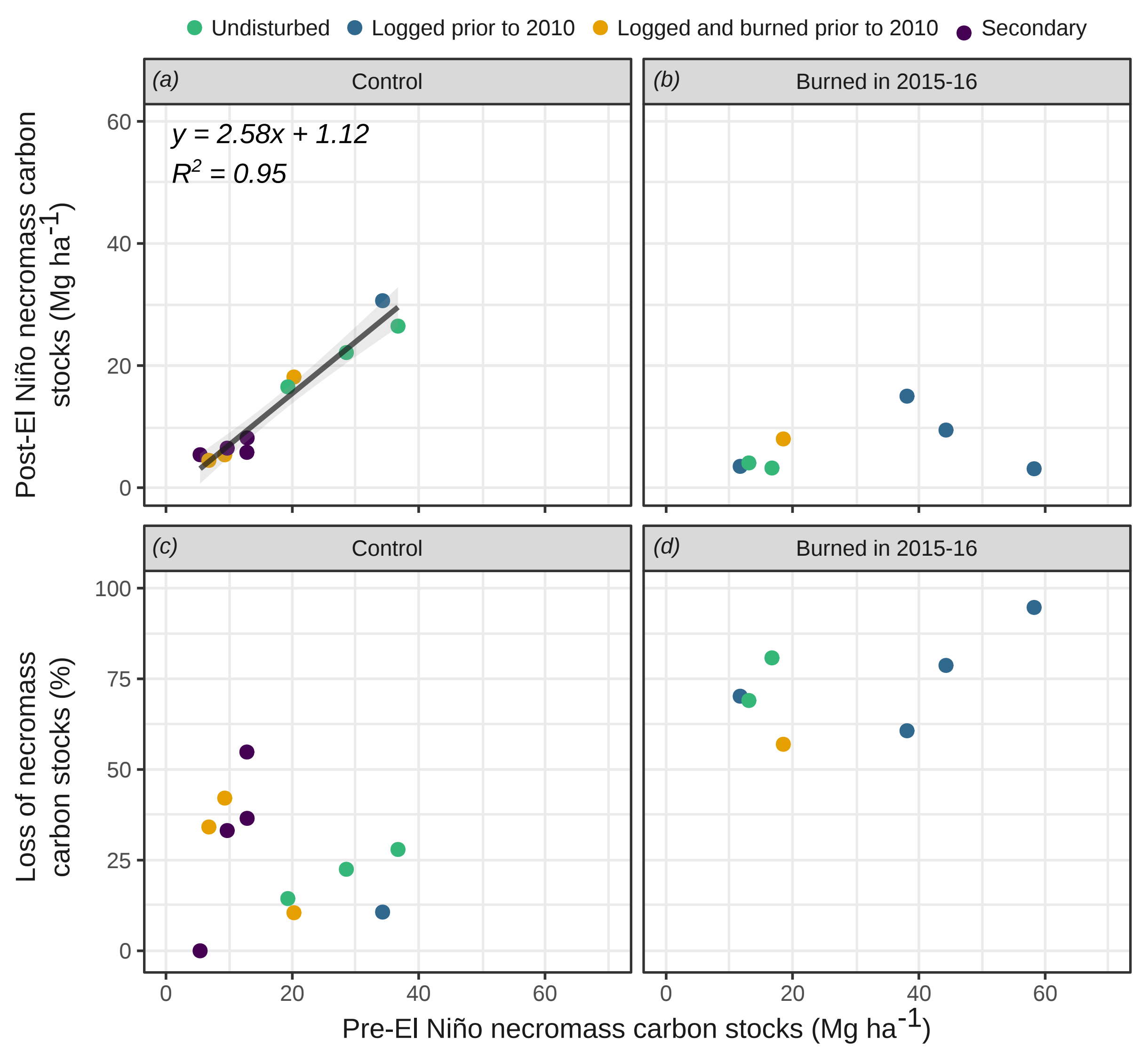
Pre-El Niño forest class	Definition	Necromass assessment (2010)	Monitoring of coarse woody debris (2014-2015)	Burned in 2015-16 and sampled in 2017	Fire intensity and plot burned area (2017)
Undisturbed primary forest	Primary forest with no evidence of human disturbance, such as fire scars or standing tree damage	17	5	2	3
Logged primary forest	Primary forest with evidence of logging, such as logging debris	26	5	4	1
Burned primary forest	Primary forest with evidence of recent fire, such as fire scars	7	0	0	0
Logged-and-burned primary forest	Primary forest with evidence of both logging and fire	24	4	1	4
Secondary forest	Forest regenerating after complete removal of native vegetation	33	4	0	1



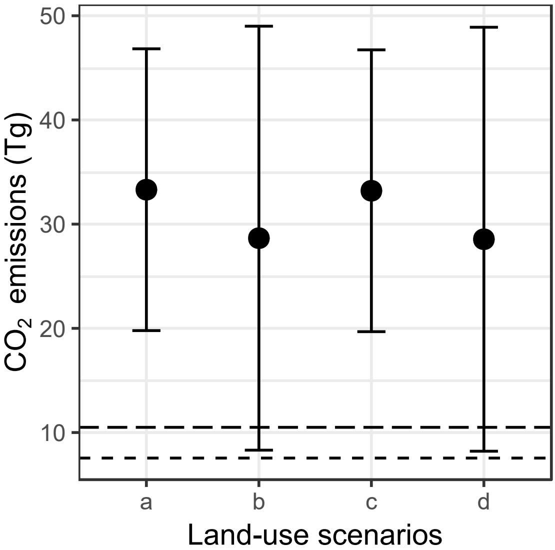
Primary forest
Secondary forest
Burned 2015-16
Water
Necromass monitoring
(a)
Tapajós Arapius Extractive Reserve
Tapajós National Forest
Amazônia National Park
0km
40km
80km
(b)


(a) Leaf litter
(b) FWD
(c) CWD
(d) Dead standing stems
(e) Total necromass
Carbon stock (Mg ha^{-1})
A AB AB B AB
A AB AB AB B
A A AB A B
A A A A B
A A A A B
U L B LB S
Forest class
U = Undisturbed
L = Logged prior to 2010
B = Burned prior to 2010
LB = Logged and burned prior to 2010
S = Secondary

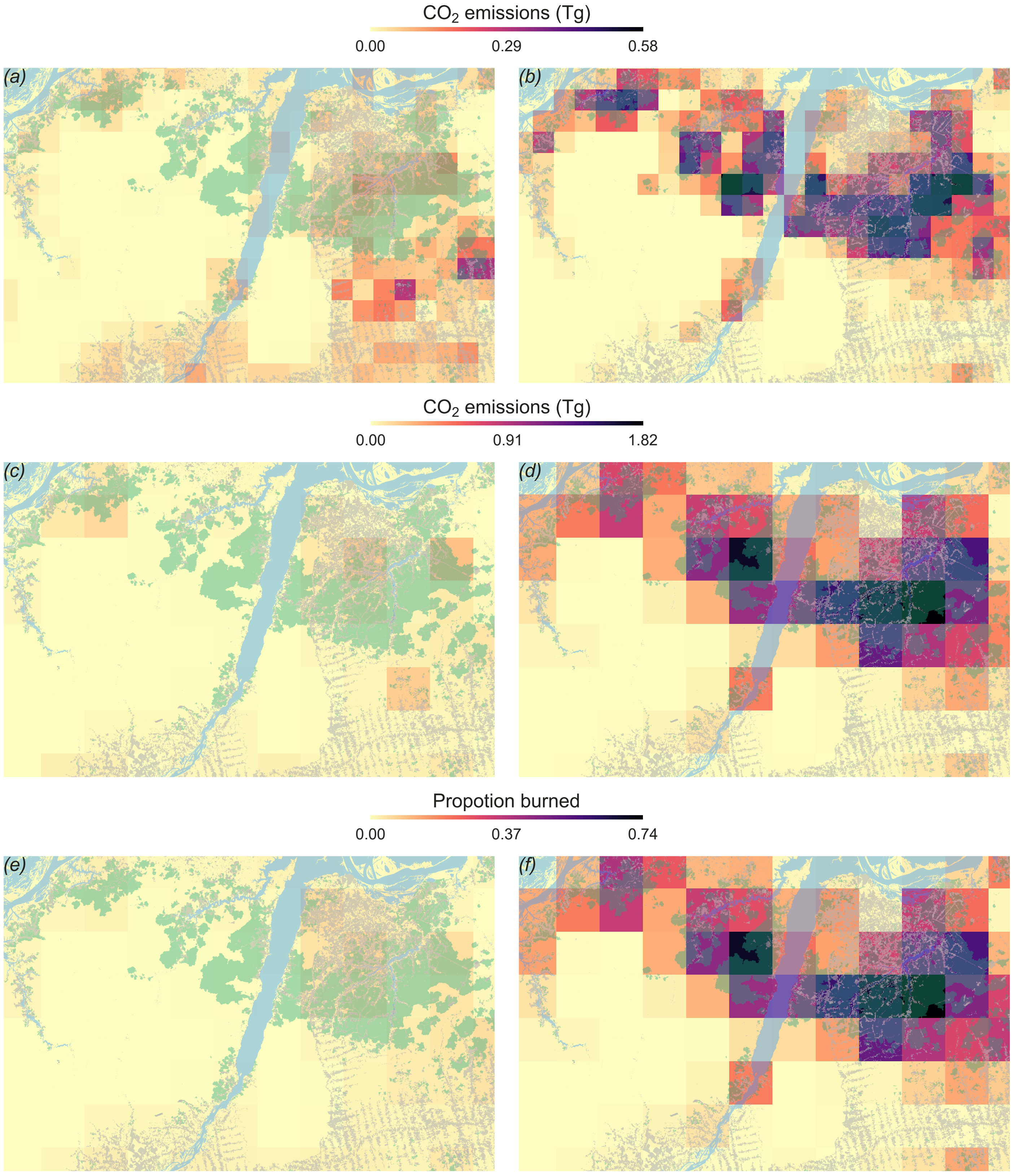

Undisturbed
Logged prior to 2010
Logged and burned prior to 2010
(a)
(b)
Necromass carbon loss (%)
100
90
80
70
60
50
10
14
18
22
Median char height (cm)
70
80
90
100
Area of plot burned (%)



Undisturbed
Logged prior to 2010
Logged and burned prior to 2010
Secondary
(a)
Control
(b)
Burned in 2015-16
(c)
Control
(d)
Burned in 2015-16
y = 2.58x + 1.12
R2 = 0.95
Post-El Niño necromass carbon stocks (Mg ha-1)
Loss of necromass carbon stocks (%)
Pre-El Niño necromass carbon stocks (Mg ha-1)
0
20
40
60
0
25
50
75
100



50
40
30
20
10
CO_2 emissions (Tg)
a
b
c
d
Land-use scenarios



CO_2 emissions (Tg)
0.00
0.29
0.58
(a)
(b)
CO_2 emissions (Tg)
0.00
0.91
1.82
(c)
(d)
Propotion burned
0.00
0.37
0.74
(e)
(f)