Environmental Research Letters

OPEN ACCESS

RECEIVED
8 September 2016

REVISED
23 March 2017

ACCEPTED FOR PUBLICATION
29 March 2017

PUBLISHED
8 September 2017

LETTER

Current and future patterns of fire-induced forest degradation in Amazonia

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Keywords: Amazon, climate change, drought, fire intensity, fire severity, CMIP5, fire modeling

Supplementary material for this article is available online

Abstract

Amazon droughts directly increase forest flammability by reducing forest understory air and fuel moisture. Droughts also increase forest flammability indirectly by decreasing soil moisture, triggering leaf shedding, branch loss, and tree mortality—all of which contribute to increased fuel loads. These direct and indirect effects can cause widespread forest fires that reduce forest carbon stocks in the Amazon, with potentially important consequences for the global carbon cycle. These processes are expected to become more widespread, common, and intense as global climate changes, yet the mechanisms linking droughts, wildfires, and associated changes in carbon stocks remain poorly understood. Here, we expanded the capabilities of a dynamic forest carbon model to better represent (1) drought effects on carbon and fuel dynamics and (2) understory fire behavior and severity. We used the refined model to quantify changes in Pan-Amazon live carbon stocks as a function of the maximum climatological water deficit (MCWD) and fire intensity, under both historical and future climate conditions. We found that the 2005 and 2010 droughts increased potential fire intensity by 226 kW m^{-1} and 494 kW m^{-1}, respectively. These increases were due primarily to increased understory dryness (109 kW m^{-1} in 2005; 124 kW m^{-1} in 2010) and altered forest structure (117 kW m^{-1} in 2005; 370 kW m^{-1} in 2010) effects. Combined, these historic droughts drove total simulated reductions in live carbon stocks of 0.016 (2005) and 0.027 (2010) PgC across the Amazon Basin. Projected increases in future fire intensity increased simulated carbon losses by up to 90% per unit area burned, compared with modern climate. Increased air temperature was the primary driver of changes in simulated future fire intensity, while reduced precipitation was secondary, particularly in the eastern portion of the Basin. Our results show that fire-drought interactions strongly affect live carbon stocks and that future climate change, combined with the synergistic effects of drought on forest flammability, may strongly influence the stability of tropical forests in the future.

Introduction

Shifts in fire regimes have driven landscape-scale declines in vegetation health in many of the world's ecosystems (Cochrane and Laurance 2002, Westerling *et al* 2006, Achard *et al* 2008, Alencar *et al* 2015, Trumbore *et al* 2015). This includes extreme cases of arrested forest succession, vegetation shifts to new states in arid western U.S. forests (Allen 2007), and catastrophic wildfires in temperate (Stephenson *et al*

2015) and boreal (Gauthier *et al* 2015) forests. These fire-induced shifts in vegetation conditions have reduced the capacity of natural ecosystems to store and cycle carbon, with important implications for the global carbon cycle (Trumbore *et al* 2015).

Anthropogenic changes are altering forest fire regimes in Amazonia (Morton *et al* 2013, Alencar *et al* 2015). Since the 1980s, human activities have increased forest fire occurrence by fragmenting forests and increasing sources of fire ignition (Nepstad *et al* 2001). Episodic droughts superimposed upon these activities create conditions for widespread, damaging forest fires (Aragão *et al* 2007, Brando *et al* 2012, Alencar *et al* 2015, Chen *et al* 2013, 2014). During the El Niño drought of 1997–98, 30%–40% of the Brazilian Amazon (5.5 million km^2) became flammable and a total of 39 000 km^2 of Amazonian forests burned, releasing 0.2–0.6 Pg of carbon to the atmosphere (Nepstad *et al* 2004). In the 2000s, more than 85 000 km^2 of forests burned, mostly during the dry and warm years of 2005, 2007, and 2010 (Morton *et al* 2013). During the 2007 drought alone fires burned ~12% of forests across the southeastern Amazon's arc of deforestation (Brando *et al* 2014). Projections of future climate for the Amazon suggest that the frequency and intensity of droughts and heat waves will increase as a result of greenhouse gas-driven climate change (Duffy *et al* 2015, Cox *et al* 2008, Malhi *et al* 2009). While these changes in climatic extremes will increase the likelihood of widespread tropical fires, the potential impacts of these changes on fire regimes and live carbon stocks in the Amazon are still poorly understood (Nepstad *et al* 2008).

Climatic extremes affect Amazon fire regimes both directly and indirectly (Cochrane 2003). Droughts directly increase forest flammability by increasing air dryness (e.g. vapor pressure deficit, VPD) and decreasing fuel moisture (Ray *et al* 2005). Indirectly, droughts cause reductions in soil moisture that often trigger leaf shedding, branch losses, and tree mortality (Pausas and Bradstock 2007). This process leads to more fuel accumulation and more direct sunlight reaching the forest floor (Nepstad *et al* 2001). As understory air dryness and fuel accumulation increase, three important predictors of fire intensity and severity are concurrently and positively affected: fuel consumption, fire spread rates, and burned area (Byram 1959). As a result, forests not only become more flammable during severe drought events, but also more prone to high-intensity fires (Cochrane 2003, Nepstad *et al* 2001, Brando *et al* 2014). These fires in turn drive non-linear increases in carbon emissions to the atmosphere (Brando *et al* 2016).

In this study, we modify a dynamic carbon model to include interactions between fire behavior, drought-induced tree mortality, and fire-induced biomass loss. We apply the model under historical climate conditions and future climate based on two Representative Concentration Pathways (RCPs 2.6 and 8.5) to address the following questions: (1) What are the effects of drought feedbacks on forest flammability and how do they impact fire behavior throughout Amazonia? (2) What are the potential effects of changes in fire intensity on carbon stocks and vegetation dynamics of the Amazon in future climate scenarios?

Data and methods

Model description

We used the Carbon and Land Use Change dynamic carbon model (CARLUC, described in detail in Hirsch *et al* 2004), which borrows its basic structure from the 3-PG model (Landsberg and Waring 1997). CARLUC estimates net primary productivity (NPP) from plant available water (PAW), photosynthetically active radiation (PAR), vapor pressure deficit (VPD), and air temperature. During each monthly time step, NPP is allocated to wood, leaf, and root carbon pools. Mortality creates dead organic matter that is placed in structural leaf litter, metabolic leaf litter, structural root litter, metabolic root litter, coarse woody debris and humus pools. We consider leaf litter and small woody fuels (i.e. 1 h fuels) as the fuel load.

To properly model forest flammability, fire behavior, and fire effects, we incorporated several new functions into CARLUC: (1) drought-induced loss of carbon stocks (AGB, above-ground biomass) as a function of the maximum climatological water deficit (MCWCD) (Phillips *et al* 2009, Lewis *et al* 2011) and associated changes in fuel loads and vapor pressure deficit (VPD); (2) litter moisture content (LMC, %), estimated from VPD; (3) fire spread rate (FSR, m·min^{-1}), estimated from LMC; (4) fire fuel consumption (W, kg·m^{-1}), estimated from LMC and fuel load mass; (5) fire line intensity (FI, kW·m^{-1}), estimated from FSR and W; and (6) fire-induced biomass losses, derived from FI from field measurements. Below we describe each one of these processes in more detail.

Several studies have shown that droughts can cause increased tree mortality and associated changes in fuel dynamics and microclimatic conditions in the forest understory (Cochrane *et al* 1999, Balch *et al* 2008, Brando *et al* 2008, 2012, Meir *et al* 2009). Therefore, we included in CARLUC the relationship between ΔMCWD and changes in biomass (Phillips *et al* 2009) (equation (1)). This relationship was derived from the Amazon forest inventory network (RAINFOR) based on changes in biomass and MCWD during the 2005 drought compared with the long-term average (Phillips *et al* 2009). When MCWD drops below −40 mm, this relationship predicts that as water stress increases (represented by MCWD) so do associated losses in aboveground biomass. To incorporate this equation into CARLUC, we first simulated forest carbon stocks and then

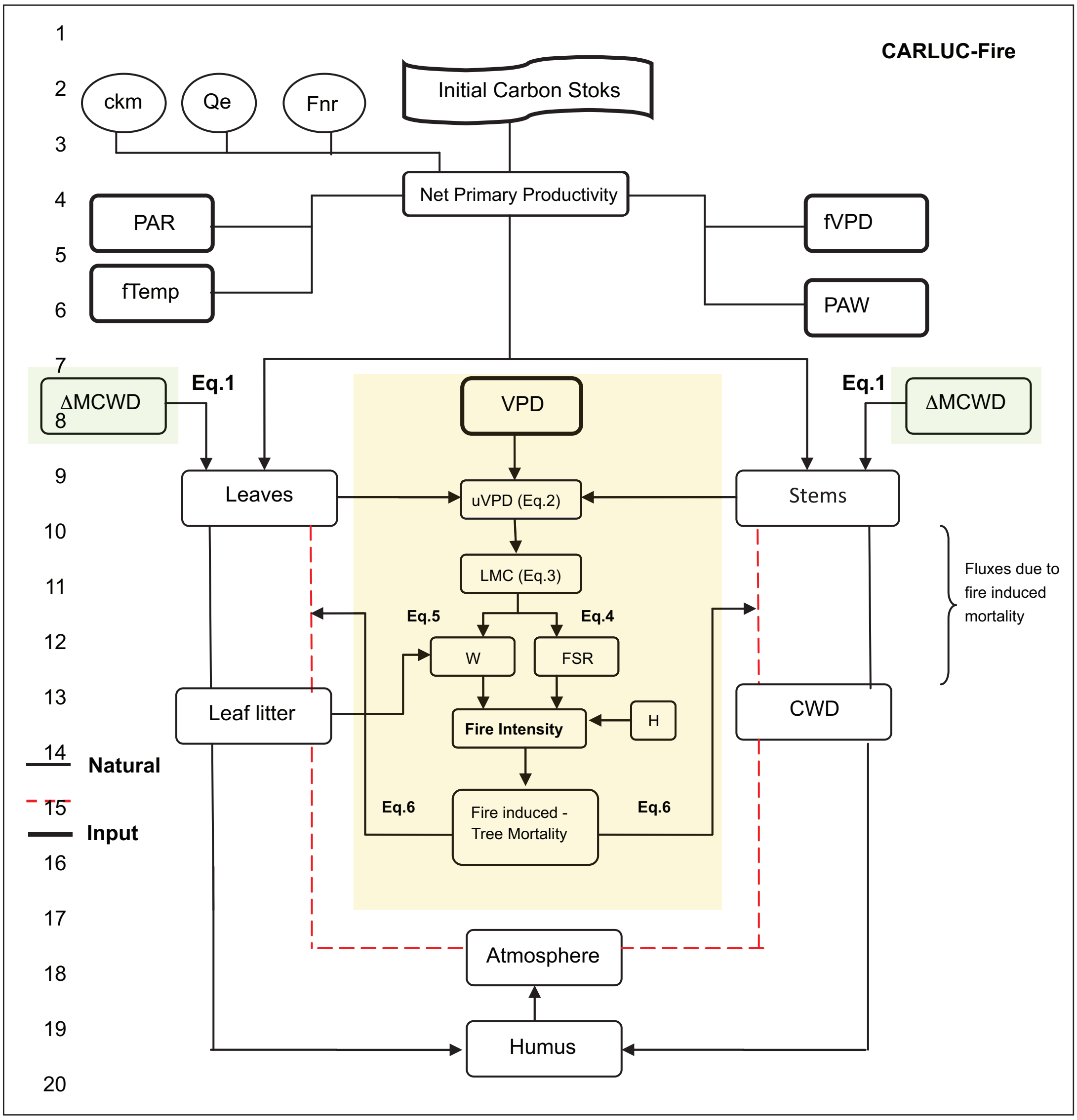

Figure 1. Flowchart of the CARLUC model, focused on in this study. The new fire component is highlighted in orange and the new drought component in light green.

added our drought component, expressed by the effects of MCWD on biomass turnover rates (proxy for tree mortality), into CARLUC. These drought effects essentially transfer part of the simulated live carbon stocks to litter material (i.e. fuel loads).

The biomass reference and fuel loads were generated by CARLUC under average climate conditions for the 2000s.

$$\Delta\mathrm{AGB} = 0.3778 - 0.052 * \Delta\mathrm{MCWD} \qquad (1)$$

where ABG represents predicted losses in ABG and MCWD the maximum climatological water deficit.

In the previous version of CARLUC, fire severity was based on uVPD alone (equation (2); Soares-Filho *et al* 2012), where uVPD was estimated from atmospheric VPD, standing aboveground live biomass (*Cstem*), and canopy cover (*Cleaf*). In this new version of CARLUC, referred to as CARLUC-Fire (figure 1), we included a new representation of fire intensity and severity. Fire intensity is now linked to litter moisture content (LMC) and fire spread rates (FSR) (equation (3) and equation (4)), such that increasing VPD leads to decreasing LMC and decreasing LMC leads to increasing FSR.

$$\begin{aligned}\mathrm{uVPD} = {} & 0.14049 - 0006 * \mathrm{Cstem}*10 \\ & - 0.5940 * \sqrt{\mathrm{Cleaf} * 10 + 0.5} \\ & + 1.505 * \sqrt{\mathrm{VPD} + 0.5} \qquad (2)\end{aligned}$$

$$\mathrm{LMC} = 80e^{-0.9\mathrm{uVPD}} \qquad (3)$$

$$\mathrm{FSR} = 0.043 + 0.838e^{-107(\mathrm{LMC})}. \qquad (4)$$

Fire intensity (FI) is defined as the energy released per unit length of fireline (kWm^{-1}). It is a key factor in determining how vegetation responds to fire events. Given that fire intensity and severity are highly correlated in tropical forests, a high value of FI indicates a high potential for fire-induced tree mortality and loss of live carbon stocks (Brando *et al* 2012, 2014). The representation of fire intensity in CARLUC is based on the product of three variables: FSR, which is derived from field measurements (equation (4)) (Ray *et al* 2005); the combustion heat (H), which is assumed to be constant at 18 700 kJ kg^{-1} (Van Wagner 1973, Albini 1976); and mass of fuel consumed by fire (W), which is based on the assumption that the proportion of each dead fuel class that is consumed by fire decreases as a function of its moisture content relative to its moisture of extinction (m_e; following Peterson and Ryan 1986).

$$W = \left\{ \begin{array}{l} 1.0, \frac{\mathrm{LMC}}{\mathrm{me}} \leq 0.18 \\ 1.2 - 0.62\frac{\mathrm{LMC}}{\mathrm{me}}, 0.18 \leq \frac{\mathrm{LMC}}{\mathrm{me}} \leq 0.73 \\ 2.45 - 2.45\frac{\mathrm{LMC}}{\mathrm{me}}, \frac{\mathrm{LMC}}{\mathrm{me}} > 0.73 \end{array} \right\}$$
$$* \text{1-h fuel} \tag{5}$$

W is the amount of dead fuel consumed per m^2. Therefore, if uVPD increases, fire intensity increases disproportionally due to decreases in LMC and increases in FSR.

To represent fire-induced tree mortality (i.e. biomass turnover) within CARLUC-Fire, we incorporated a new function accounting for carbon losses as a function of fire intensity (Brando *et al* 2014). This function was developed based on data collected in the context of a large-scale fire experiment located in southeast Amazonia. Brando *et al* (2014) conducted experimental fires from 2004 to 2010 and quantified the associated increases in tree mortality. We modified this relationship to estimate losses in aboveground carbon stocks (%) as a function of fire intensity (kW m^{-1}) (equation (6)). We assumed that fire-induced losses in belowground live carbon were 20% of aboveground losses. Ideally, this new equation should include data from other regions, but we could find none. Most studies on fire ecology in the Amazon are based on estimates of post-fire tree mortality, which lack information on pre-fire forest conditions and usually do not provide information on fire behavior (Cochrane 2003).

$$\text{Percent loss of ABG carbon} = 1/(1 + \exp(2.45 - 0.002373 * \mathrm{FI})). \tag{6}$$

Our simulations of CARLUC-Fire (modeling and analysis) were implemented using the Dinamica EGO software platform (Soares-Filho *et al* 2010) and R packages (Hijmans and Van Etten 2014).

Flammability and fire intensity

To assess forest flammability (i.e. potential fire intensity) as a function of historical drought, we performed three experimental runs of CARLUC-Fire for: (i) current conditions, using the average climate of the 2000s, excluding 2005 and 2010 (severe drought years in Amazonia); (ii) 2005 drought conditions, using biomass loss from our new drought component, derived from ΔMCWD (Lewis *et al* 2011), which promotes changes in simulated values of uVPD and fuel loads; and (iii) 2010 drought conditions, which was the same to the 2005 approach.

For calculations of potential fire intensity and severity, we ran CARLUC-Fire at 0.5° × 0.5° horizontal resolution, with a monthly time step from 2000 to 2010, using temperature and mean vapor pressure from the Climate Research Unit (CRU TS, v.3.22). Other required input variables (e.g. PAR, PAW) were derived from the Integrated Biosphere Simulator (IBIS) dynamic vegetation model, which was forced with the same CRU climate data (Panday *et al* 2015).

The result of these simulations are the fire behavior variables (LMC, FSR, W and FI), as well as fire severity and carbon stocks at 1/2-degree resolution for the entire Amazon Basin. From the forest carbon stocks, we can simulate Amazonian biomass under a given climate condition. To convert C to biomass, we used the relationship determined by da Silva *et al* (2007) for forests near Manaus, where one ton of biomass contains 0.485 tons of C. To constrain our analysis to where seasonality is large enough to allow for fires to spread, we estimate carbon emissions from fires mapped by Morton *et al* (2013) from 2000 to 2010. To do so, we ran CARLUC-Fire as described above but at 500 m × 500 m resolution.

Uncertainty analysis

While severe droughts can cause increased tree mortality in Amazonia, it is unclear how this process influences the timing of fuel accumulation and changes in forest microclimatic conditions. To quantify how these sources of uncertainty influenced our results, we performed two sets of simulations. First, we ran CARLUC-Fire assuming that (1) woody fuels would be evenly distributed throughout the year; (2) most of the woody fuel would increase during the fire season; and, (3) half of woody fuel would increase during the dry season and half throughout the year. These simulations provide information on how the timing of fuel availability resulting from droughts influences fire intensity and severity. Second, we ran CARLUC-Fire based on the assumption that drought-induced changes in uVPD lagged MCWD by one, two, and three months. This set of simulations quantifies how drought-induced tree mortality could influence uVPD and fire intensity and severity one, two, or three months after the drought.

Another potential source of uncertainty in calculating fire intensity and severity in CARLUC-Fire relates to the use of average climate data from 35 models to represent future climate change. We performed simulations based on the lower and upper quartiles of precipitation and temperature change to assess the uncertainties associated with the use of a multi-model ensemble. These analyses indicate that the difference between the upper and lower quartiles for the main CARLUC-Fire forcing data (VPD and MCWD) is relatively small (figure S4 and S5 available at stacks.iop.org/ERL/12/095005/mmedia).

Fires tend to burn hotter during the day than during the night. Therefore, our assumption that most fires occur during the day could lead to overestimation of fire intensity and severity. To address this potential source of uncertainty, we ran CARLUC-Fire simulations with low values of daily VPD (i.e. typical nighttime values) and high monthly VPD derived from maximum monthly temperatures. We assumed that the difference between these two simulations related directly to the uncertainty associated with using averaged monthly VPD in our simulations.

Climate change and fire behavior

To evaluate potential climate change impacts on fire intensity and severity, we performed three numerical experiments with future climate scenarios, considering near future (2010–2039), middle future (2040–2069), and distant future (2070–2099). We built these scenarios using maximum air temperature (related with air dryness, VPD) and precipitation (related with water stress, MCWD) from 35 climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5). We first performed CARLUC-Fire runs without the effects of MCWD on standing biomass. We then ran CARLUC-Fire including those MCWD effects using the 2005 generated MCWD but applying the RCP climate data. For 2010, we repeated this procedure but used 2010 conditions as our baseline.

We compare climate impacts as a function of two different levels of global warming at the end of the 21st century, the RCP2.6 and RCP8.5 scenarios. RCP2.6 is the best-case scenario (low emissions) and assumes an extreme reduction in fossil fuel use and rapid implementation of renewable energies, as well as carbon capture and sequestration. It is the scenario most closely mirroring the Paris (COP21) agreement, if fully implemented. RCP8.5 represents 'business as usual,' based on a fossil fuel intensive economy, consistent with present-day use and accounting for projected global demographic increases.

The resulting temperature and precipitation fields were used as input to the CARLUC-Fire model. Each simulation spanned the years 1950 through 2099. For 1950 through 2005, we used estimates of historical climate forcing (e.g. atmospheric greenhouse gas concentrations). After 2006, forcing was derived from the mean monthly simulated temperature and precipitation anomalies averaged for all 35 models and added to the CRU and Tropical Rainfall Measuring Mission (TRMM) data (figure 2). More specifically, we sliced the future CALRUC-Fire simulations into three time classes: '2010–39', '2040–69', and '2070–2099'. Applying these conditions to CARLUC-Fire, we simulated the effect of these two droughts (2005, 2010) under the two future changes in atmospheric composition (figure 6).

Results

Drought-induced changes in forest flammability

Our analysis of the climate data indicates that the 2005 and 2010 droughts impacted 47% and 60% of the Amazon, respectively, which is consistent with previous estimates (Lewis *et al* 2011). Our simulations show that these droughts caused reductions in live carbon stocks of 1.6 PgC and 2.1 PgC in 2005 and 2010, respectively (figure 3). In response to these droughts and the associated changes in forest carbon stocks, fuel loads and understory air dryness increased across the Amazon. We estimated that understory VPD (uVPD) was up to 20% and 13% higher than the long-term average, during the 2005 and 2010 droughts, respectively. Simulations with and without drought effects in CARLUC showed that canopy openness associated with drought-induced tree mortality (from equation (1) and equation (2)) accounted for 3%–5% of this increase, while higher atmospheric VPD (from climate data) in those years accounted for the remainder. In drought years, fuel loads were 4%–10% higher than in non-drought years.

The simulated changes in fuel and microclimate dynamics associated with the 2005 and 2010 droughts caused increased forest flammability across the Basin. Simulated potential fireline intensity (PFI) averaged 56 kW m^{-1} in non-drought years, but increased to 114 and 169 kW m^{-1} in 2005 and 2010, respectively (figure 4). Our simulations suggest that, if understory fires had occurred throughout the Basin (figure 5) during these droughts, between 1–1.5 million km^2 of the Amazon would have lost substantial live carbon stocks (e.g. considered here losses $\geq$ 12% of the initial carbon stocks), compared with a control simulation under average climate conditions. In non-drought years, the average area that could have experienced high fire-induced biomass losses was only 180 000 km^2.

Limiting our analysis to areas that burned between 2000 and 2010 (according to Morton *et al* 2013) (figure S6), we found that the fires of 2005 and 2010 directly increased fireline intensity by 109 $kW{\cdot}m^{-1}$ and 124 $kW{\cdot}m^{-1}$, respectively, and indirectly by 117 $kW{\cdot}m^{-1}$ and 370 $kW{\cdot}m^{-1}$ (compared with the long-term average). The direct effects were associated with increased understory air dryness (*uVPD*), while the indirect effects were mostly associated with increased fuel loads but also with increased *uVPD*. We estimate that the observed fires (Morton *et al* 2013) reduced live carbon stocks by 22% (in 2005) and 40% (2010) for a given burned area (figure 5). These estimates were much higher than in non-drought years, when fire-related losses in live carbon stocks averaged 9%. The greatest increases in fire-induced carbon losses were simulated for (1) southwestern

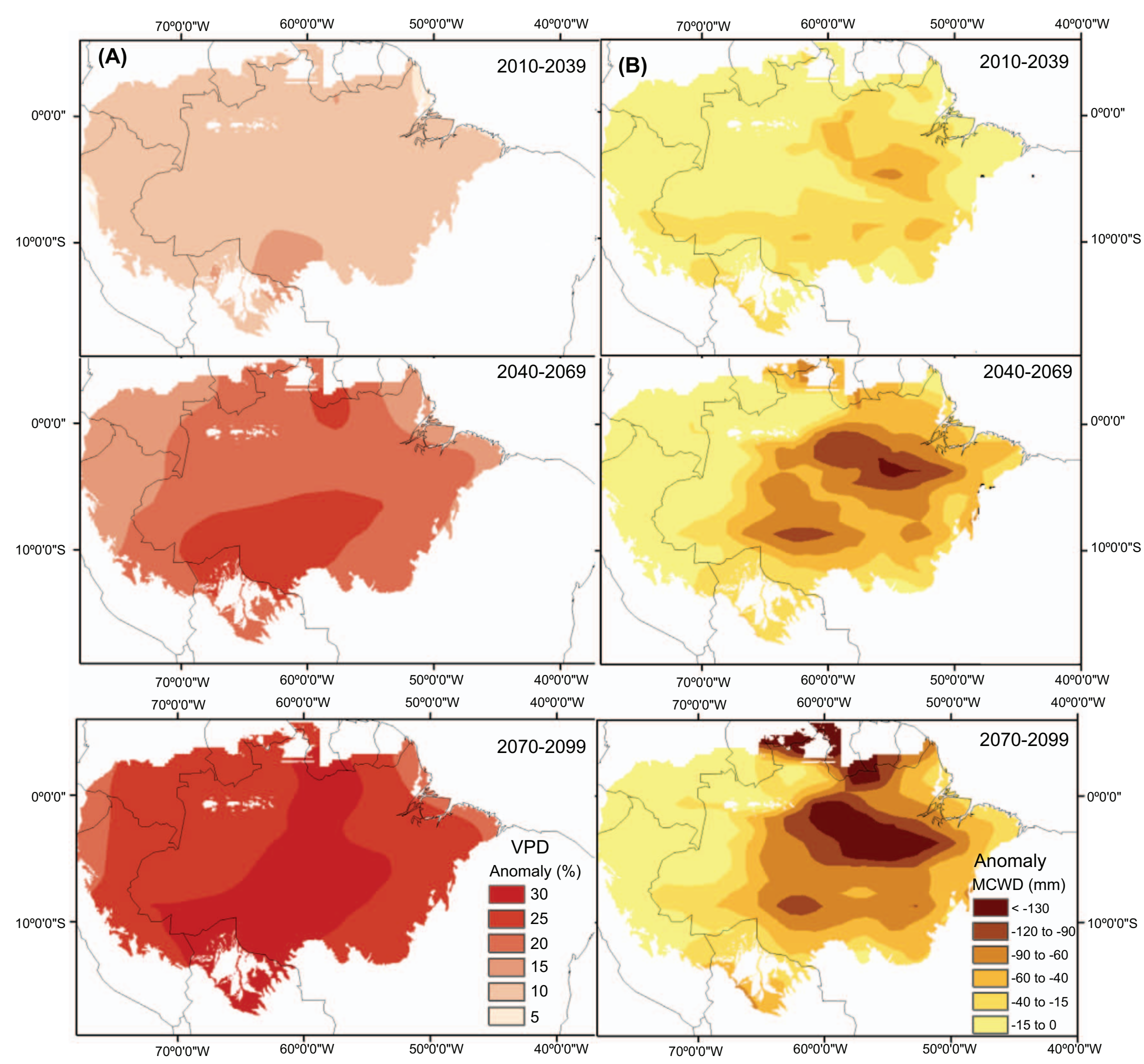

Figure 2. Projected dry-season changes in VPD (*a*) and MCWD (*b*), based on the multi-model ensemble for the RCP 8.5.

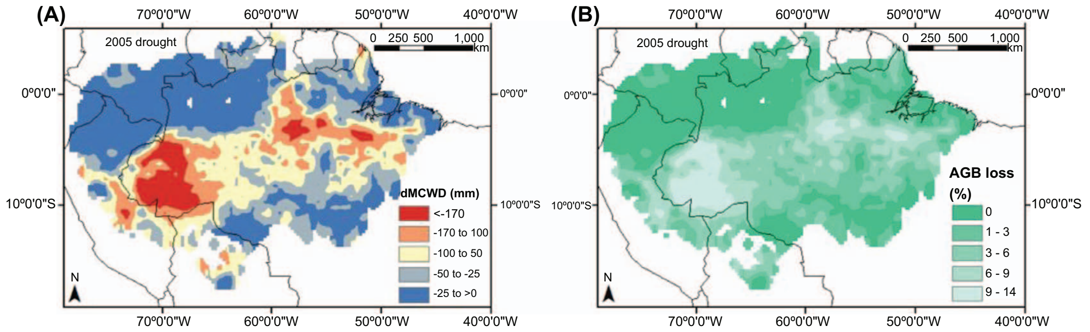

Figure 3. (*a*) Maximum climatological water deficit anomaly (ΔMCWD) (mm yr^{-1}) and (*b*) simulated percent aboveground biomass (AGB) loss from drought-induced tree mortality during the 2005 drought.

Amazonia during the 2005 drought and (2) southeastern Amazonia during the 2010 drought. We estimate that the 2005 and 2010 fires reduced carbon stocks of Amazonian forests by a total of 0.018–0.032 PgC.

Climate change and fire effects

Our simulations indicate that if future climate change follows a business-as-usual pathway of greenhouse gas emissions (RCP 8.5), fire regimes could change dramatically in Amazonia after 2050. Forest flammability, potential fireline intensity, and potential fire-induced losses in live carbon stocks would be much greater. Our simulations indicate that, under projected RCP 8.5 climatic conditions in the near (2010–2039), middle (2040–2069), and distant (2070–2099) future, droughts would cause Amazon fires that are 30%, 50%, and 90% more intense and severe than current non-drought fires (figure 6). Moreover, high-intensity

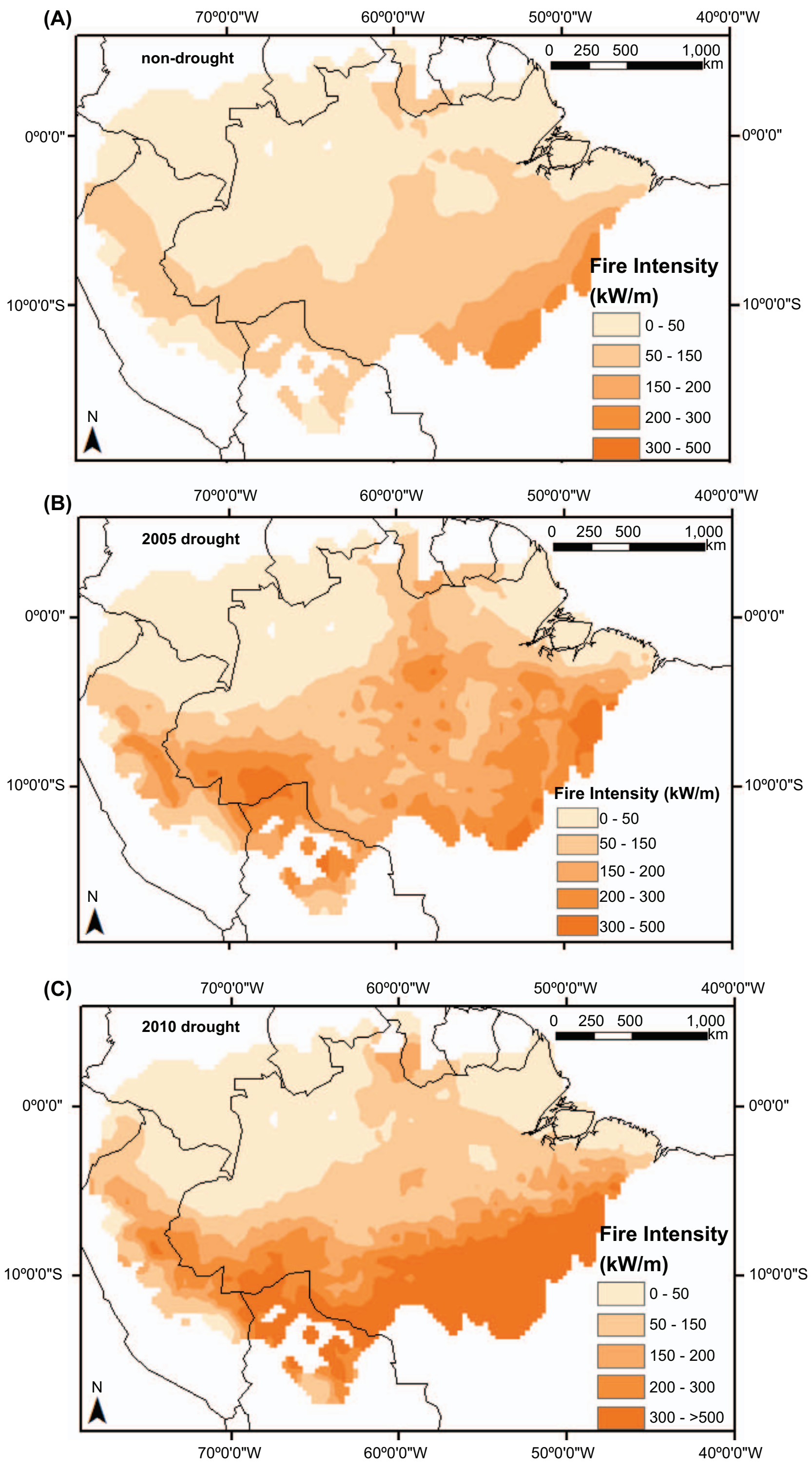

Figure 4. CARLUC-Fire simulated potential fire intensity (kWm^{-1}) for (*a*) non-drought years during the 2000s, (*b*) the 2005 drought, and (*c*) the 2010 drought. Dark orange indicates highest potential FI.

fires (i.e. FI $>$ 800 kWm^{-1}) during drought events could affect 196–550 thousand km^2 (2005, 2010) by mid-century, depending on the emissions scenario, compared to 0–76 thousand km^2 for the 2005 and 2010 droughts (i.e. under current climate conditions). As a result, fire-induced carbon emissions could double in the future, assuming the same amount of burned area as observed during 2005 and 2010 droughts.

In the RCP 8.5 scenario, air temperature is the most important variable driving changes in future fire regimes over the Amazon. In that scenario, air temperature increases by 5 °C–7 °C across the Amazon, driving increases in vapor pressure deficit, especially in the central-eastern Amazon (figure 2(*a*)). Future decreases in precipitation over the eastern Amazon are also predicted to increase forest flammability and potential fire intensity (figure 2(*b*)). Under a low-emissions

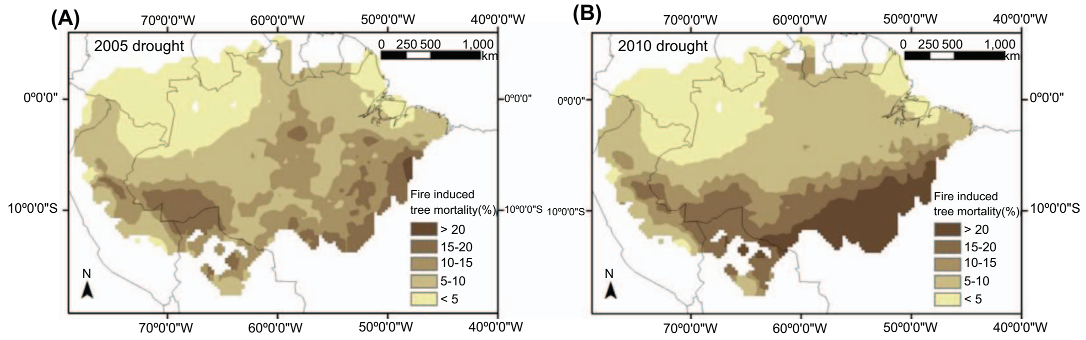

Figure 5. Potential fire-induced tree mortality prediced by CARLUC-Fire in (*a*) 2005 and (*b*) 2010 across the Amazon Basin.

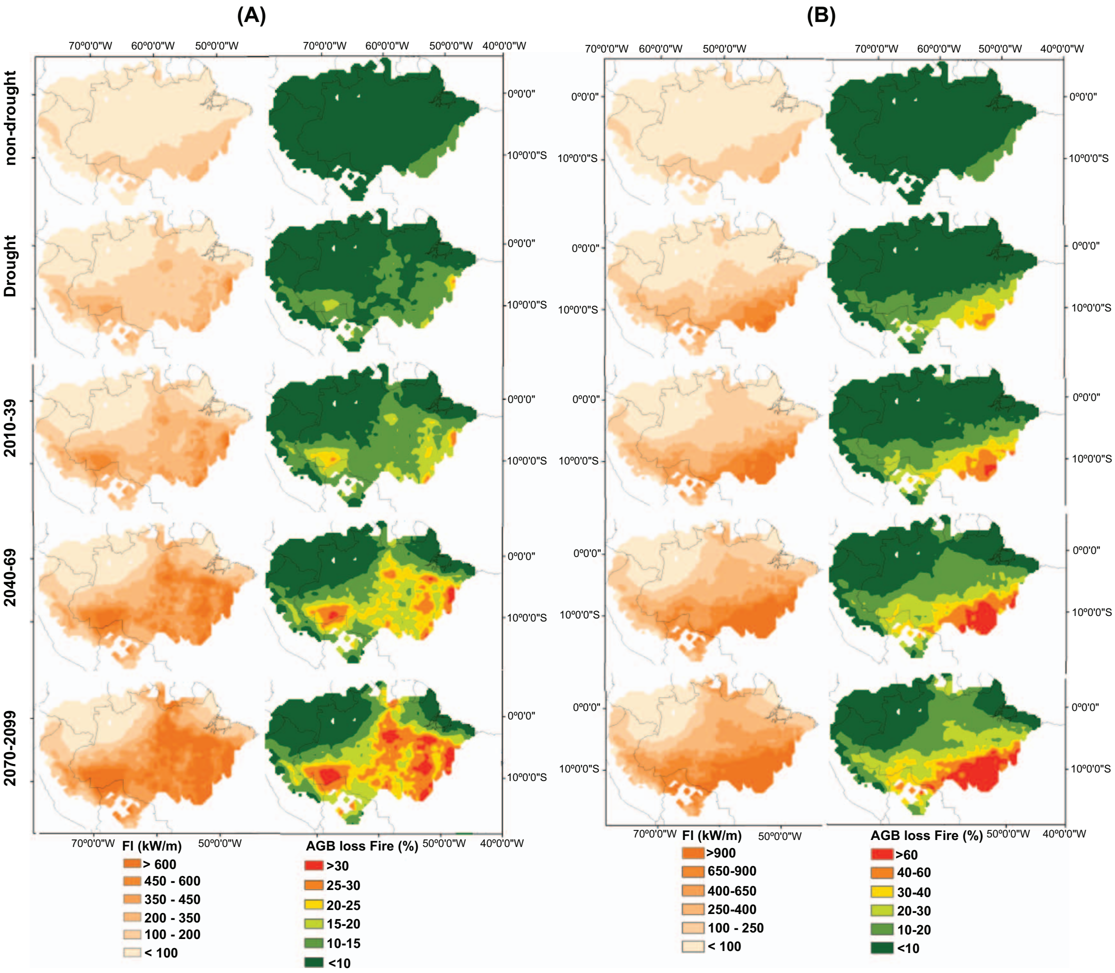

Figure 6. Projected changes in fire intensity and in fire-induced changes in aboveground biomass (fraction) according to two starting climatic conditions ((*a*) 2010 drought; (*b*) 2005 drought). We sliced the future projections into five groups: (1) current climatic conditions, assuming no drought-induced changes in live carbon stocks (*non-drought*); (2) current climatic conditions, assuming that droughts caused losses in live carbon stocks (*Drought*); (3) future climatic conditions for the period 2010–2039; future climatic conditions for the period 2040–2069; and future climatic conditions for the period 2070–2099. All future simulations were based on the RCP 8.5 and assumed that MCWD (our proxy for drought) could drive changes in live carbon stocks.

pathway (RCP 2.6), fire intensity and severity would be much lower compared with the RCP 8.5 scenario, especially after 2050 (figure 7).

Uncertainty analysis

In CARLUC-Fire, fire intensity and severity were highly sensitive to the timing of fuel accumulation resulting from drought-induced losses in aboveground carbon. Sensitivity analyses indicated that, when maximum fuel loads occurred during the peak fire season of a drought year (2005), fire intensity averaged 226 $\mathrm{kWm^{-1}}$. In contrast, when increases in fuel loads were evenly distributed throughout the year, fire intensity averaged 55 $\mathrm{kWm^{-1}}$ (figure S1*b*).

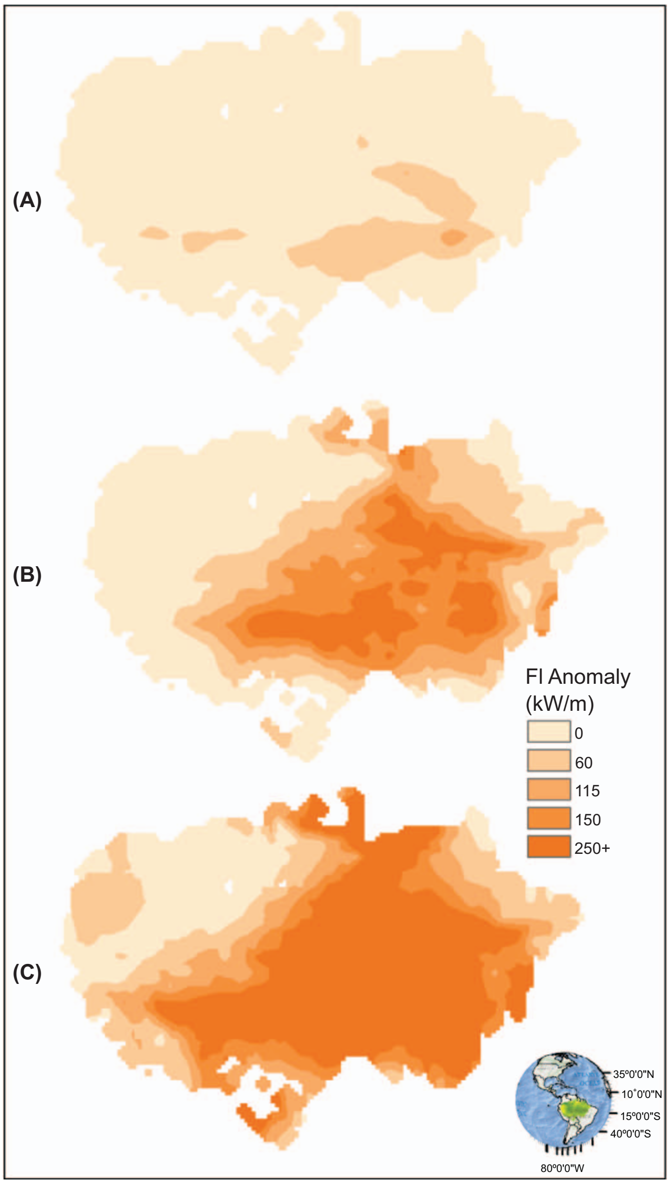

Figure 7. Difference in fire intensity (FI) between RCP8.5 and RCP2.6 with initial condition 2010. (*a*) Near future (2010–2039); (*b*) mid-future (2040–2069); (*c*) distant future (2070–2099).

Our sensitivity analyses also show that a delayed response of uVPD to drought-induced biomass losses influenced fire intensity and severity. For example, FI was 23% lower when VPD increased in the month before the drought, compared with the peak drought month. Simulations with longer lagged responses of VPD to drought (i.e. two and three months) (figure S3), led to lower FI. Finally, our sensitivity analyses show that the time of day could have a major impact on our estimates of FI. By using the monthly maximum air temperature, we may be overestimating FI by as much as 25% (figure S2).

Discussion

In this study, we modified a dynamic carbon-vegetation model (Soares-Filho *et al* 2012) to quantify the potential effects of drought-fire interactions on forest carbon dynamics in Amazonia. Our simulations suggest that the droughts of 2005 and 2010 increased fire intensity and severity in southern Amazonia, in agreement with previous studies (Chen *et al* 2011, Brando *et al* 2014, Chen *et al* 2014, Aragão *et al* 2016). Simulated increases in fire intensity and severity were primarily associated with greater fuel accumulation on the forest floor, which resulted from drought-induced changes in forest structure (considered an 'indirect' effect). Secondarily, fire intensity and severity increased in response to the direct effect of the droughts on understory air dryness (*uVPD*). These results suggest that drought-induced interactions during the 2000s greatly increased carbon emissions across the Amazon.

Our simulations suggest that future climate changes associated with large increases in radiative forcing (e.g. RCP 8.5) could nearly double fire-induced carbon emissions per unit area burned (figure S7), given projected increases in vapor pressure deficit (particularly after 2070). Increases in drought frequency and intensity, coupled with increased dry season length (Butt *et al* 2011), could exacerbate this process by killing trees and causing associated increases in fuel loads, which creates the potential for high-intensity fires. According to our results, sharp reductions in the rate of GHG increase (e.g. RCP 2.6) could mitigate these effects, reducing the area subject to 'dangerous' fire intensity by 68% (compared with RCP 8.5). However, the actual risk of future Amazon forest fires will depend on complex interactions among droughts, heat waves, and efforts to suppress fires when they start (Nepstad *et al* 2001, Cochrane 2003, Aragão and Shimabukuro 2010, Alencar *et al* 2015). The future area burned will also depend on spatial-temporal patterns in sources of fire ignition. Unlike systems where fires are naturally ignited by lighting (e.g. boreal forests), management fires in agricultural fields ignite most Amazon forest fires (Soares-Filho *et al* 2012).

Overall, our results suggest that modeling of fire in the Amazon could be improved by considering the direct and indirect effects of droughts on forest structure. Assuming no drought-induced effects on fuel loads and moisture, fire intensity decreased sharply across the Amazon according to our simulations. While several studies have shown that drought-induced tree mortality alters fire behavior by increasing fuel loads and decreasing fuel moisture (Cochrane *et al* 1999, Nepstad *et al* 2001, Balch *et al* 2008, Brando *et al* 2008, 2012, Meir *et al* 2009), most DGVMs lack representation of this process (Trumbore *et al* 2015, Powell *et al* 2013). Our empirical representation of biomass losses based on MCWD provides important insights into how drought-induced tree mortality may influence fire properties in Amazonia (Phillips *et al* 2009). However, our predictor of drought-induced tree mortality (i.e. MCWD) is coarse and has been shown to overestimate tree mortality in some cases (Feldpausch *et al* 2016). Existing process-based models (Zhang *et al* 2015, Castanho *et al* 2016) could be adapted to better represent this process based on recent findings on tree-water relationships (Rowland *et al* 2015, Sperry *et al* 2016).

In addition to quantifying the potential effects of fire on Amazon forests, we identified several key drivers of uncertainty in CARLUC-Fire. The first one is the timing of fuel accumulation following a drought, which strongly influenced fire behavior. Amazon droughts have been shown to drive short-term increases in fuel dynamics (Nepstad *et al* 2002, Brando *et al* 2008, Brando *et al* 2014), but it is unclear how this extra fuel is distributed throughout the year (Chambers *et al* 2000, Keller *et al* 2004, Nepstad *et al* 2002). Post-drought fuel accumulation depends on several factors, including plant phenology (Brando *et al* 2006, Restrepo-Coupe *et al* 2016), wood and leaf decomposition (Chambers *et al* 2000), blowdowns (Chambers *et al* 2013), and pre- or post-drought storms (Negrón-Juárez *et al* 2010). In our uncertainty analysis, fire intensity was highest under the assumption that drought-induced increases in fuel loads occur at the peak of the dry season of a given drought year. This assumption is probably unrealistic, given that dead branches and trees may take years to join the fuel pool. A more reasonable one is that a high proportion of the fine fuel becomes available during the peak fire season (Nepstad *et al* 2004), while larger woody fuels become combustible in the following dry seasons. The lack of field data on post-drought fuel production has limited our ability to accurately represent this process in our model (Brando *et al* 2008).

The second uncertainty relates to the timing of fire occurrence in tropical forests. Our simulations show that the common assumption that daytime and nighttime equally affect fire intensity could lead to an overestimation of fire severity. Nighttime fires tend to be less intense than daytime ones, leading to lower tree mortality and associated losses of carbon stocks, as supported by our simulations. Forest fires do occur mostly during the hottest parts of the day during average years (Cochrane *et al* 2003), but nighttime fires can burn large tracts of forests during drought years. Balch *et al* (2015) reported that during the peak fire season of the 2007 drought, low nighttime moisture levels in the forest understory sustained fires throughout the night, allowing fires to spread across large forested areas over multiple days (Brando *et al* 2014). If nighttime air temperatures increase faster than daytime air temperatures in the near future (Xia *et al* 2014), nighttime fires could become even more common (Donat and Alexander 2012). However, the lack of information on the extent of nighttime fires precludes a better representation of fires in our model.

In addition to the processes described above, CO_2 fertilization of Amazonian vegetation could play an important, and as yet unknown, role in shaping the region's future fire regime (Swann *et al* 2016). Theoretically, with increased atmospheric CO_2, fire intensity and severity could increase or decrease in the future. As CO_2 builds up in the atmosphere, Amazon trees may accumulate more biomass and have denser canopies (Hofhansl *et al* 2016). Thick canopies tend to retain more moisture in the forest understory, thereby reducing uVPD and associated forest flammability (Ray *et al* 2005, 2010). More CO_2 in the atmosphere could also increase the resilience of Amazonian forests to droughts by increasing plant water use efficiency (i.e. amount of water transpired per unit of CO_2 fixed)(Swann *et al* 2016). On the other hand, an increase in forest productivity could also increase forest flammability by increasing fuel loads particularly during severe drought years. These complex responses of tropical forests to droughts in a future with elevated CO_2 remain uncertain.

Conclusion

This study addressed a key aspect of Amazon fire regimes: how vegetation responses to drought may increase fire intensity and act synergistically with predicted climate changes. Our simulations indicated that fire-drought interactions can reduce live carbon stocks substantially. Climate changes, combined with the synergistic effects of drought on forest flammability, may strongly influence the stability of tropical forests in the future. Amazon fire models like CARLUC-Fire could be further improved to include the timing of drought-related increases in fuels; the relationship between changes in canopy structure and changes in microclimatic conditions; and the distribution of nighttime versus daytime fires to better represent drought-fire interactions in Amazonia.

Acknowledgments

This research was supported by a doctoral fellowship to Bruno L. de Faria, who conducted part of this work in residence at the Woods Hole Research Center, with support from CNPq. He would like to thank the IFNMG and CNPq for financial support, and the Federal University of Viçosa for the PhD opportunity. Funding for this study was also provided by NASA's Terrestrial Ecology Program (#NNX12AK11G), National Science Foundation (Grant #1146206), a CNPq scientific productivity grant to Paulo Brando (No. 307084/2013-2), CNPq (No. 400866/2014-5), Gordon and Betty Moore Foundation, the World Bank project 'Valuation of the Amazon Ecosystem Services and Interdisciplinary Research in Earth Science (#NNX14AD29G)'. The authors would like to thank Jennifer Balch, André C Silveira, and Marcos H Costa for their support and assistance with this research, as well as two anonymous reviewers who provided valuable comments on an earlier draft of this paper. The authors thank FAPEMIG (Minas Gerais State Foundation for Research Development) for the financial support.

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