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Amazon wildfires: Scenes from a foreseeable disaster

Paulo Brando[a,b,c,*], Marcia Macedo[b,c], Divino Silvério[d], Ludmila Rattis[b,c], Lucas Paolucci[e], Ane Alencar[b], Michael Coe[b,c], Cristina Amorim[b]

[a] Department of Earth System Science, University of California, Irvine, CA 92697, USA
[b] Asa Norte CLN 211 Bl B Sala 201 - Asa Norte, Brasilia - DF, 70863-520
[c] Woods Hole Research Center, 149 Woods Hole Rd., Falmouth, MA 02540, USA
[d] Universidade Federal Rural da Amazônia, Campus, Capitão Poço. Rua professora Antônia Cunha de Oliveira, Vila Nova, Capitão Poço, PA, Brazil
[e] Universidade Federal de Viçosa, Departamento de Biologia Geral, Peter Henry Rolfs s/n, Campus Universitário, Viçosa, MG, Brazil

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ABSTRACT

The Amazon forest's main protection against fire is its capacity to create a moist understory microclimate. Roads, deforestation, droughts, and climate change have made this natural firebreak less effective. The southern Amazon, in particular, has become more flammable and vulnerable to wildfires during recent droughts. The drought of 1997/98 first showed that fires could escape from agricultural fields and burn standing primary forests that were once considered impenetrable to fire. The spread of forest fires during other 21st-century droughts suggests that this pattern may well be the new normal. With the landscape becoming more flammable, reducing sources of ignition and the negative effects of deforestation is crucial for avoiding severe degradation of Amazon forests. Unfortunately, recent increases in deforestation suggest that Brazil is moving in the opposite direction. Keeping pace with the rapid changes in the region's fire regimes would require innovation; cooperation across political boundaries; and interagency communication on a scale never seen before. While Brazil's past success in reducing deforestation suggests that it could be an effective leader in this regard, its sluggish response to the 2019 fires tells quite a different story. But the fact remains that the future of the Amazon depends on decisive action now.

Every single day, several hundred hectares of primary forests are cleared in the Amazon (INPE, 2019). The loss of native neotropical savannas is even greater (Strassburg et al., 2017). By the minute, exotic African grasses and croplands replace native vegetation—a result of ferocious competition for land. Farmers have found in the tropics a place to expand commodity crop production, transforming the ecotone between Amazonia and Cerrado into one of the world's largest agricultural frontiers (Macedo et al., 2012) (Fig. 1). Several other tropical landscapes across the globe are undergoing similar transformations (Curtis et al., 2018). This rapid land-use change brings with it novel disturbances (Brando et al., 2019a). Fire is one that can rapidly damage Amazon forests, whose trees lack adaptations needed to resist fire-related damage (Barlow et al., 2003; Brando et al., 2012). Combined with global climate change, fire and other disturbances will determine what kind of forests will exist in the future – and whether these forests can sustain key habitat types and ecosystem services over the long term or will enter a downward spiral characterized by widespread degradation (Nobre et al., 2016).

But it was not always like this. During Pre-Columbian times, fire was rare in the Amazon. High moisture levels underneath the canopy of healthy forests largely prevented dead leaves, small branches, and twigs (the fine fuels that carry a fire) from reaching flammable levels (e.g., relative moisture ≤ 23%) (Ray et al., 2005). Even when moisture levels dropped unusually low – which can often be the case at the drier southern edges – the ignition sources to start widespread wildfires were probably scarce. At the time, ignitions were typically associated with slash-and-burn agriculture by indigenous peoples (Heckenberger et al., 2003) or lightning-related savanna fires (Bush et al., 2008). These characteristics help to explain why fire return intervals within Amazonia averaged several hundred years.

Beginning in the 1960s and 1970s, massive investments in infrastructure (for regional development) started a wave of environmental destruction (Nepstad et al., 2001). Legal and illegal roads opened the region to production, timber extraction, and deforestation, as well as malicious land-grabbing and land speculation (Sparovek et al., 2019; Azevedo-Ramos and Moutinho, 2018). By the mid-1980s, deforestation and associated forest degradation (i.e. via edge effects) were already taking a huge toll on the ability of forests to protect themselves against

* Corresponding author at: Department of Earth System Science, University of California, Irvine, CA 92697, USA.
E-mail address: pbrando@uci.edu (P. Brando).

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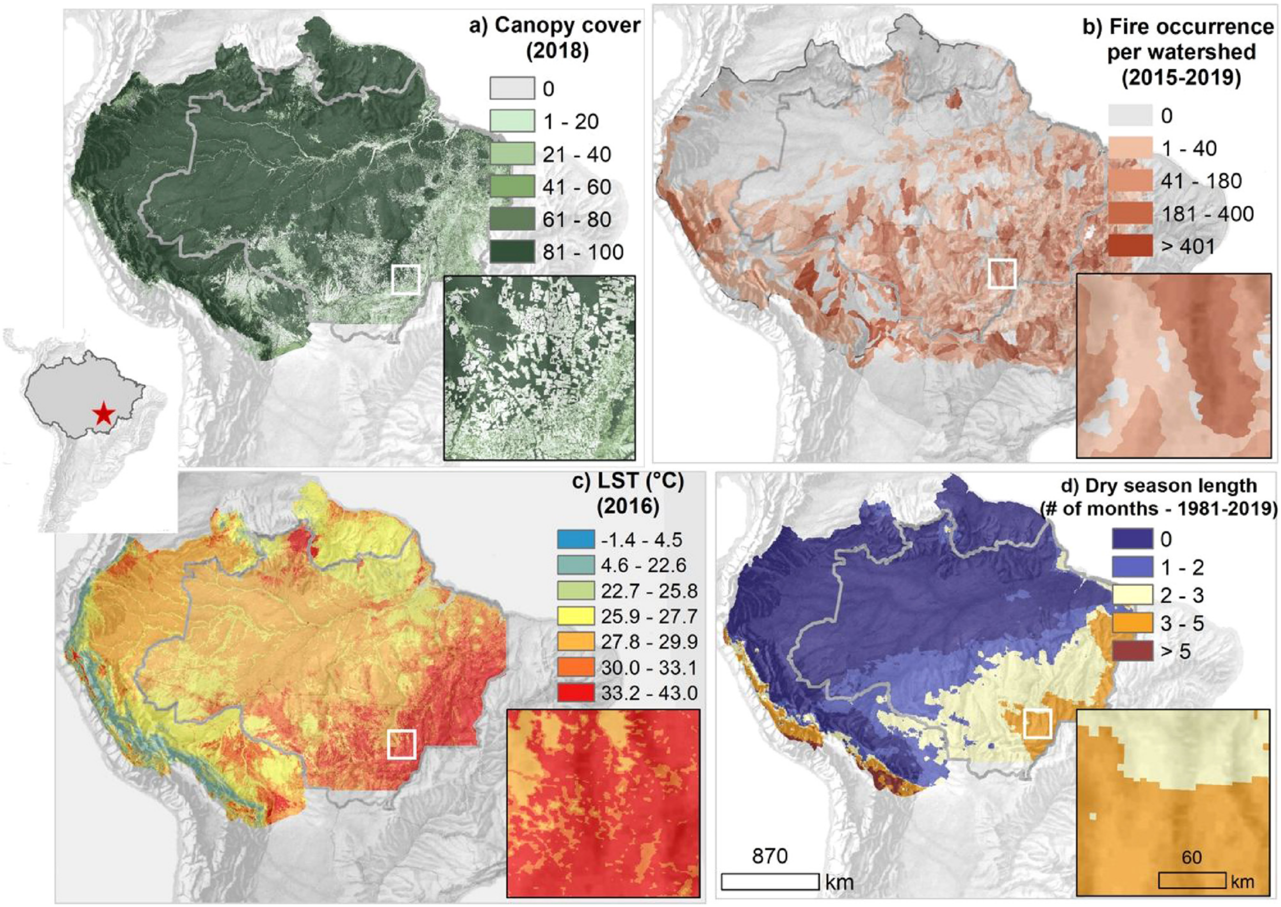

Fig. 1. Classes of canopy cover in percent (a), total number of fire occurrences ("hot-pixels") by micro watershed (b), land surface temperature (c), and dry-season length (d) across the Amazon basin. The inset maps for each variable show more detailed patterns for the southeast Amazon, where forest fragmentation is widespread. To produce these maps, we used the following datasets: The Global Forest Change (Hansen et al., 2013; panel "a"); thermal anomalies (MOD14A1; Giglio et al., 2016) from the Moderate Resolution Imaging Spectroradiometer (MODIS; panel "b"); MODIS Land Surface Temperature and Emissivity (MOD11A1; Wan et al., 2015; panel "c") and, the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS; Funk et al., 2015; panel "d").

fire (Nepstad et al., 1999). As deforestation soared in the 1980s and 1990s, people relied on fire as a management tool to clear deforested areas. It was just a matter of time before those management fires began escaping from open deforested fields into the degraded forest edges that connect agricultural fields to primary standing forests (Cochrane, 2003).

The thick canopies of Amazon forests act as an ecological firebreak. To maintain their canopy during dry-season months and avoid severe drought stress, many tree species tap into deep soil water, sometimes down to 15 m (Nepstad et al., 1994). During extreme drought conditions, tree water demand often exceeds the water supply, requiring trees to rely on more extreme strategies to avoid failure of their hydraulic systems (Nepstad et al., 2007; Brando et al., 2008). Shedding leaves, twigs, and branches allows trees to regulate their water balance and prevent severe damage (Cochrane, 2003). Yet a thinner canopy also invites more solar radiation to penetrate and can create dry and hot microclimate conditions in the forest understory. The leaves and twigs that accumulate on the forest floor are fuels that greatly increase forest flammability (Ray et al., 2005, 2010). These changes are compounded by edge formation during deforestation and logging, because they further thin the canopy and increase the likelihood of high-intensity fires (Alencar et al., 2006).

During 1997–1998, a severe drought disrupted much of the Amazon's ecological firebreak. The levels of drying and warming in that year stressed trees to the point that a disproportionate amount of leaves, branches and twigs dropped. Because sources of fire ignition were abundant that year, ≈39,000 km^2 of primary Amazon forests burned. Almost a third of the Brazilian Amazon became flammable (Nepstad et al., 2004) and the burning forests caught the world's attention. A *Time Magazine* article, dated September 18, 1998, posed the question: "Torching the Amazon: Can the Amazon be saved?". The Kayapó indigenous leader, Raoni Metuktire, and many other influential spokespeople echoed the message that deforestation and fires pose an existential threat to the Amazon's future. Although major droughts had stressed Amazonian trees before, the 1997/1998 drought was among the first to coincide with widespread sources of ignition and abundant forest edges.

When forests burn during unusually hot and dry years, the fires not only affect a much larger area but also tend to kill many more trees. In fact, the switch from a low- to a high-intensity fire can mean the difference between life and death for a tree. Experimental fires conducted in southeast Amazonia showed that post-fire annualized tree mortality rates jumped from 10% to 90% when wildfires occurred along hot, flammable edges during drought years, compared with non-drought years (Brando et al., 2014, 2019b). In other words, when coupled with severe droughts and forest edges, fires can be catastrophic and have long-lasting ecological effects (Silvério et al., 2019).

Changes in forest structure associated with fire-related tree mortality often cascade to faunal communities. Those same experimental fires that triggered widespread tree mortality following high-intensity fires caused the extinction of forest specialists and an influx of open-habitat specialists in ants (Paolucci et al., 2017) and butterflies (Andrade et al., 2017). There are also reports of wildfires driving the impoverishment of bird (Barlow and Peres, 2004) and dung beetle

(Andrade et al., 2014) communities in other parts of Amazonia. Since these organisms perform key ecosystem functions (Paolucci et al., 2016; França et al., 2020), their losses can cause important declines in forest resilience (Barlow et al., 2016). For instance, ants disperse seeds of Amazon tree species (e.g. Paolucci et al., 2016), while dung beetles remove dung and seeds (e.g. França et al., 2020), two important ecosystem functions. On the other hand, animal groups capable of persisting in degraded forests can help facilitate forest recovery (Paolucci et al., 2019).

If droughts occurred only occasionally, high-intensity wildfires would be extremely rare events in the Amazon, as in the past. The problem is that drought events like the one in 1997/1998 are becoming increasingly common in the region and interacting with land-use change and global climate change (Aragão et al., 2018). The clear-cutting of a few hectares of forest may have negligible effects on the regional climate, but when entire landscapes are cleared for the expansion of croplands and pastures, there is less solar energy available to drive the hydrological cycle (Coe et al., 2016). The Brazilian Amazon alone has lost close to 800,000 km^2 of forest as of March 2020 – an area larger than most countries (e.g. More than twice the size of Germany) (Fig. 1). This massive deforested area is altering the region's hydrological cycle (Nobre et al., 2016). When Amazon trees are replaced by shallow-rooted vegetation – generally with more homogenous canopies and lower evapotranspiration capacity – water cycling can drastically diminish, with direct consequences for the local and regional climate (Silvério et al., 2015). The dry season length over the southeast Amazon has increased by ≈ 0.6 days per year since the 1970s, in part because of these deforestation-related changes to the hydrological cycle (Lee et al., 2013; Fu et al., 2013; Leite-Filho et al., 2019). Together with the global rise in air temperature from climate change, this lengthening of the dry season is contributing to longer, hotter, drier fire seasons (Brando et al., 2020).

During the 21st century, the Amazon has already experienced three widespread droughts, all of which triggered massive forest fires (Morton et al., 2013; Aragão et al., 2018). With climate change and edge effects increasing forest flammability across the region (Fig. 1), the likelihood of catastrophic fires is poised to increase. The question now is what to do about it. A recent study projected that ending Amazon deforestation could reduce burned area by half. But if deforestation continues unabated, 16% of the region's remaining forests will likely burn by 2050 (Brando et al., 2020). These results suggest that curbing deforestation should be Brazil's top priority to reduce sources of ignition and avoid catastrophic wildfires in the near future. With less deforestation, there are fewer fires, a more stable regional climate, and fewer flammable edges (Fig. 2b).

The decade spanning 2004–2013 clearly demonstrated that Brazil has the capacity to fight illegal deforestation effectively. During this period, a combination of monitoring and enforcement, supply chain interventions, and the expansion of protected areas drove a 70% reduction in deforestation across the Brazilian Amazon (Nepstad et al., 2014). At the same time, agricultural production increased by 300% and cattle productivity by 150% in Mato Grosso, Brazil's most dynamic agricultural frontier at the time (Macedo et al., 2012). However, current political and economic forces have reversed this trend; recent rises in Amazon deforestation may be accelerating us towards an irreversible climatic tipping point (Nobre et al., 2016). Wildfires are the most pernicious symptom of this reversal, and will likely become the main catalyzer of forest degradation if this scenario continues (Nepstad et al., 2008; Brando et al., 2019b).

The events of 2019 provide a clear example of the potentially catastrophic feedbacks among deforestation, fire activity, and poor management. As deforestation began climbing towards the total of 9,762 km^2 cleared between August 2018 and July 2019, Brazil simply took no action at first. Furthermore, by August of 2019 (halfway through the dry season), the Brazilian Institute for Space Research (INPE) reported a three-fold increase in fire activity compared to the previous year. They warned that this was already a bad fire season, even in the absence of a drought. This was not a surprise. High deforestation rates detected by INPE in the previous months were generating huge amounts of necromass (dead trees, branches, leaves, and roots), and fire is the most common tool to remove biomass from newly cleared fields (Fig. 2a). By the end of 2019, INPE had detected the highest number of active fires in the Amazon since 2010 (Barlow et al., 2020).

Instead of leaping into action to control these illegal fires early on, the government got mired in a false debate about the facts – first denying the data, then arguing that the fires were normal or blaming it on the weather, and finally pointing to fires in other countries as a way to distract attention from Brazil. At the end of the day, all of those narratives proved false and the world was left with this simple fact: by willfully ignoring three independent systems for real-time monitoring of deforestation, Brazil missed the opportunity to avoid substantial emissions of both CO_2 and human-sickening smoke to the atmosphere. Most of the deforestation-related fires in 2019 did not escape into primary Amazon forests (e.g. Fig. 2c,d), at least in Brazil. But had 2019 been a drought year, Brazil's slow response to fighting deforestation and related fires would most likely have ignited catastrophic wildfires across the region, as was observed in drier regions of Bolivia and predicted by fire models (Brando et al., 2020).

If Brazil fails to take decisive action to stop deforestation, prevent associated fires, and encourage a transition towards fire-free land management, protecting the region's remaining forests will depend entirely on fire suppression to fight illegal wildfires. To achieve both goals, Brazil must: (1) rapidly increase command-and-control operations against illegal agricultural fires; (2) expand the existing network of well-trained and equipped fire brigades; and (3) improve specialized weather forecast systems and fire behavior models to guide fire suppression efforts, hopefully months before the fire season starts. Socioeconomic activities that depend on slash-and-burn systems will require new fire management techniques to prevent the escape of agricultural fires into neighboring forests, without placing an undue burden on the smallholders, traditional communities, and indigenous peoples that rely on these systems for their livelihoods.

Brazil is well-positioned to adapt to this new reality, and to implement innovative strategies to reduce fire activity. The country has the technology and proven scientific capacity to forecast, monitor, and verify deforestation and fire-related forest degradation. It also has a history of engaging the private sector in environmental solutions, evidenced by the key role of large farmers and commodity traders in reducing Amazon deforestation (Gibbs et al., 2015). This suggests that, with the right incentives, the private sector could make important contributions to curbing illegal deforestation and associated fires in the future (Stabile et al., 2020). Finally, Brazil has the world's largest network of protected areas and indigenous lands, both of which have proven effective in slowing deforestation and acting as firebreaks that buffer the region against further degradation (Walker et al., 2020). Maintaining these assets will no doubt require new investments and adaptions to cope with the rapidly changing Amazon landscape.

By ignoring its strengths, Brazil is squandering decades of efforts to strengthen institutions; historic engagement of the private sector; and the stewardship of indigenous peoples and traditional communities that have kept the Amazon from crossing a tipping point. We have never been so capable of identifying the problems haunting the Amazon as we are in 2020. Our challenge now is to act fast on the solutions, before climate change makes it much harder to solve the wildfire problem in the Amazon.

Author contributions

P.B., M.M., and D.S. conceived the study. P.B. wrote the manuscript with input from all authors.

Fig. 2. Examples of fire in the Amazon: necromass burning (a), burning forest edge (b), low-intensity understory fires (c), and high-intensity wildfires along a forest edge (d).

Declaration of Competing Interest

There is no conflict of interest.

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