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PERSPECTIVE

Recent deforestation drove the spike in Amazonian fires

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1. Introduction

Tropical forests are of global importance even though they only cover around 10% of the Earth's land surface. They store large amounts of carbon and host between one-half and two-thirds of the world's species (Lewis 2006). Small changes in the tropical moist forest—the most biodiverse biome within the tropical forests—may lead to global impacts on climate dynamics and warming, water cycles, and the loss of biodiversity. If the current rates of deforestation and clearing patterns continue, many tropical moist forests could face an imminent regime shift towards an alternative tropical scrubland ecosystem state (Lovejoy and Nobre 2018).

Over the last several months of 2019, there was a surge of headline news by global media of widespread wildfires in the Amazon rainforest, the largest remaining expanse of tropical moist forest on Earth. Smoke from Amazon fires, visible from space, engulfed cities thousands of kilometers away, including São Paulo, the largest South American city, which plunged into darkness at 3 pm on 19 August 2019. The long-term socioeconomic and environmental impacts of such fires could potentially be severe, not only in regards to the amount of particulate matter released into the atmosphere, but also contributing toward massive carbon dioxide emissions from fires. These will threaten biodiversity in one of the most megadiverse regions of the world, causing negative impacts on human health, and immense economic

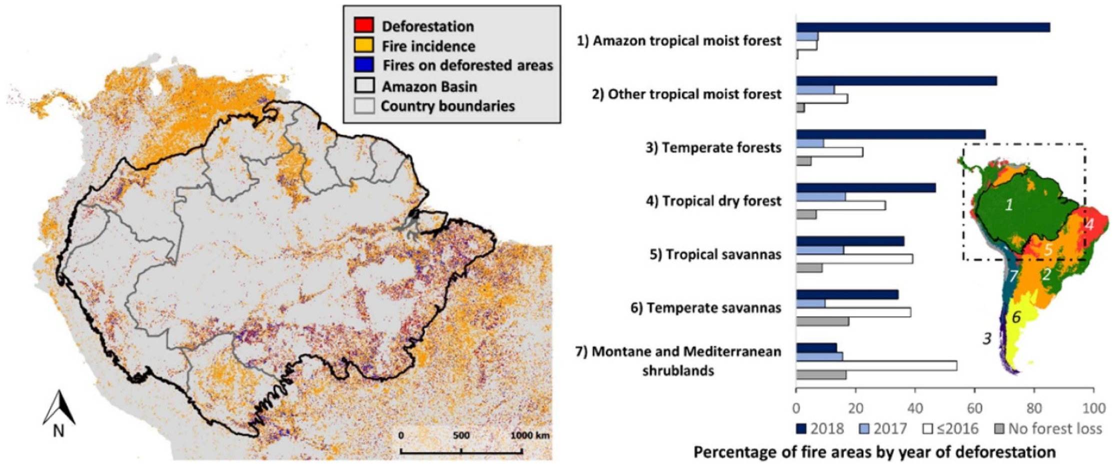

Figure 1. Geographic distribution of 2019 fires and deforested areas between 2000 and 2018 in the Amazon. (Left) The fire incidence map was derived from the Visible and Infrared Imager/Radiometer Suite (VIIRS) active fire detection records (Schroeder *et al* 2014). The original daily sensor detections at a 1 km resolution were aggregated to 0.05° × 0.05° pixels for this map. Deforested areas were also resampled from 1 arc-second (Hansen *et al* 2013) to 0.05° × 0.05° pixels. The Amazon Basin is outlined in black. (Right) Percentage of 2019 fires, by biome (Olson *et al* 2001), associated with deforestation in 2018 (dark blue bars), 2017 (light blue bars), and from 2000 to 2016 (white bars), as well as intact areas with no forest loss since 2000 (light gray). The numbers on the map represent the analyzed biomes and are linked with the bar chart.

damage (de Mendonça *et al* 2004, Aragão *et al* 2018, Smith 2019, Brancalion *et al* 2020).

Given these social and ecological losses, the ultimate reason behind the widespread fires in the Amazonian rainforest has become a focus of public inquiries. In the vacuum created by a lack of scientific assessments, contrasting narratives and polarized opinions have proliferated. Considering the fact that the doubling of fire incidence in August—the peak fire month in 2019—relative to the average August fire incidence over the last decade was not influenced by severe droughts or other climatic anomalies (Barlow *et al* 2020, Kelley *et al* 2020), what caused the 2019 Amazon fires anomaly?

2. 2019 fire incidence in South America

We analyzed the 2019 fire incidence, from 26 September 2018 to 25 September 2019, derived from the Visible and Infrared Imager/Radiometer Suite (Schroeder *et al* 2014), and its association with recent deforestation to disentangle the direct anthropogenic effect from a plethora of complex factors driving Amazon fires. The analysis was also performed for the whole of South America to compare these results across diverse biomes of the continent. Superimposing the spatial records of 2019 fire occurrences (Schroeder *et al* 2014) with maps of annual forest loss in the Amazon and other biomes of South America since 2000 (Olson *et al* 2001, Hansen *et al* 2013), we show a widespread sequence of fire events occurring in tropical moist forests directly after recent deforestation.

In 2019, more than 92 000 km^2 of tropical moist forest biomes were affected by fires, 69 000 km^2 of which were within the Amazonian basin according to the Moderate Resolution Imaging Spectroradiometer MCD64A1 global burned area product (Giglio *et al* 2016). We estimate the amount of vegetation carbon in the burned areas at 0.64 Gt C in 2019, equivalent to 0.63% of the carbon sequestered in vegetation biomass in the Amazon Basin based on the most representative global aboveground biomass models (Erb *et al* 2018). Brazil was the most affected country with 66% of the total burned area, located mainly in the south and southeast areas of the Amazon, followed by Bolivia (11%) and Colombia (7%). Notably, 85% of 2019 fires within the Amazon tropical moist forest occurred on areas deforested in 2018 (figure 1); surprisingly, less than 1% of fires spread to areas where no forest loss has occurred since 2000. We also found that the percentage of those fires that were located in tropical moist areas deforested in 2018 varied regionally throughout the Amazon basin. Thus, the countries with the most significant deforestation rates, such as Peru (95% of fires in 2018 deforested areas), Colombia (91%), and Brazil (88%), had higher values compared to other countries (59%) undergoing less deforestation. The effect of deforestation on fire activity in the tropical moist forest was more predominant than in all the other biomes in South America (figure 1). Only a small proportion of fires occurred on recently deforested areas in both the tropical and temperate savannas (35%) and montane Mediterranean shrublands (14%), where the conversion to agriculture areas is lower than in tropical moist forests.

2.1. Immediate fires after deforestation, footprints of land-use change

A possible consequence of anthropogenic deforestation increasing the number of human-made fires is

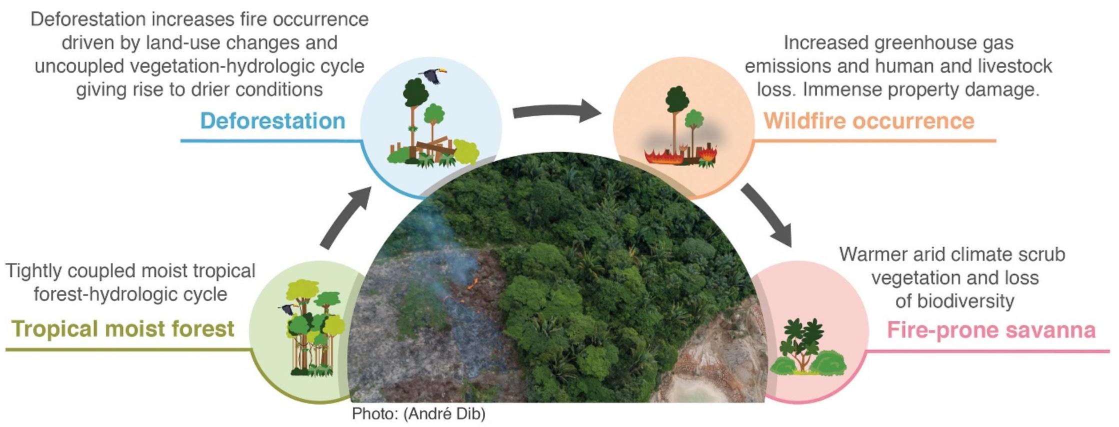

Figure 2. Cascade effects of deforestation and fire in tropical moist forests within the Amazonian region, representing that forest loss may lead to a tipping point entailing permanent changes and degradation of the ecosystem.

a loss of canopy cover and land use change. First, canopy closure reduction decreases fuel moisture and increases local temperature and wind speed. Reduced relative humidity above the Amazon tropical moist forest has been reported as a result of elevated demand for water and evapotranspiration losses of water due to increased human activities regionally (Barkhordarian *et al* 2019). Although wildfires within an intact tropical moist forest are historically rare, in line with our analysis for 2019, deforestation coupled with extreme droughts may create the conditions necessary for the expansion of fire into historically intact areas of the Amazon (Barlow *et al* 2020), exacerbating land cover conversion and even creating a dangerous positive feedback loop (Lovejoy and Nobre 2018). Also, our analysis points towards the 2019 Amazon fires as footprints of continued agricultural expansion (e.g. for cattle ranching and soybean farming Gibbs *et al* 2015), which is one of the main drivers leading to the highest rates of deforestation globally (7500 km^2 only in 2018), as opposed to induced direct consequences of climate change. Land clearing for livestock or food crops and the development of transport infrastructures contribute to improved access to forest areas, loss of canopy cover and increased fuel flammability. Together with an increasing potential for extreme weather events, this may create a 'perfect storm' for accelerated tropical moist forest transformation to cropland and, subsequently, to tropical scrub vegetation following the abandonment of agricultural land use (figure 2). Addressing forest degradation, agricultural expansion and preventing human ignitions will be critical to keeping this positive feedback under control.

2.2. Towards a tipping point

If left unchecked, the current trend of deforestation, fire expansion and forest degradation can cause catastrophic changes in Amazonia (Nepstad *et al* 2014), including human and livestock loss and property damage (figure 2). Many terrestrial species could lose their vital habitats, and a huge amount of carbon may be released to the atmosphere, further exacerbating global warming. Furthermore, such changes would likely modify Amazon's hydrological engine, which plays a major role in maintaining regional and global climate dynamics (Cox *et al* 2004); the current hydrologic regime sustains present-day agriculture production in the productive areas of Brazil, the second largest global food exporter. Forest cover reduction and changes in land use in the Amazon can create a cascading effect completely altering the planet's water cycle, climate, and food security.

Previous successful policies to protect the Amazon (Nepstad *et al* 2014), including law enforcement, interventions in soy and beef supply chains, restrictions on access to credit, and expansion of protected areas, are now at risk (Artaxo 2019). Defending their persistence and ongoing improvement will need to rely on a clear understanding of the driving forces of fires and deforestation. The underlying causes of Amazon fires are linked to deforestation and socioeconomic dynamics, with an interplay of past, current and future drivers that may contribute toward tipping points, namely, (a) deforestation may result in warmer and drier conditions at the local scale in the tropical moist forest (Lawrence and Vandecar 2015); (b) climate-induced drought may create conditions where wildfire behavior not only becomes more extreme within deforested and immediately adjacent areas, limiting suppression opportunities and increasing total burned area, but also allow wildfires to burn interior forests where wildfire has rarely occurred; and, (c) energy market deregulation and fiscal relaxation also contribute to expansion of land encroachment and, consequently, wildfires.

2.3. Policy implications

Given the increased forest loss and agricultural expansion since 2012 (INPE 2020), our analysis sounds the alarm bell for an even higher fire incidence in the Amazon tropical moist forest in the coming years. If this deforestation and clearing pattern continues, we could face an imminent regime shift toward the alternative ecosystem of tropical scrublands, affecting regional and even global climate (Lovejoy and Nobre 2018). To address the role of wildfire in increasing the potential for large-scale regime shifts in land cover and ecosystems, regulations should be deployed through executive policies aiming predominantly at incentivizing the conservation of existing forests and limiting human expansion and deforestation rather than on suppression-based wildfire management practices (Carvalho and Nobre 2020). The complex informal economy that has been established in many of the agricultural frontier regions has thrived on the weak presence of public engagement and law enforcement.

With the Amazon region being one of the most important carbon reservoirs and climate regulators, both regional political and international commitment will be needed to address deforestation. Despite the apparent disappointments, COP25 showed for the first time an overall agreement in positioning agricultural expansion as a driver for deforestation and seven different UN agencies indicated the need for 'turning the tide'. The combination of illegal logging and land encroachment is both the driver and passenger of a deficit of public will and relevant policies. Although the aforementioned factors justify strengthening protective policies for the Amazon, an opposite trend has been observed in recent years in Brazil, with the gradual dismantling of the policies that had previously made the country a success case for protecting tropical moist forest (de Area Leão Pereira *et al* 2019). The Amazon needs global compromises in governance and socioeconomics to safeguard humans and ecosystems worldwide.

Our analysis advocates for integrated forest management policies including environmental and economic regulation, social integration of stakeholders, and sustainable forestry practices across the Amazonian region. Such an integrated plan would go beyond the top-down reforestation plan announced by the G7 countries at the 2019 United Nations General Assembly. It seems evident that there is a need for implementing and harmonizing policies at local, national and international levels (e.g. REDD+; Articles 5 and 6 of the Paris Agreement) to enhance the effectiveness of local ecosystem payment schemes, improve the accessibility to technical assistance for capacity development, along with improved rural extension services. Monitoring and enforcing bans on human use of fire and achieving social acceptance of such policies, will make expanding biodiversity-based offsets possible to keep Amazon forest loss at bay. Such approaches could partially be funded by national initiatives such as a tropical carbon tax (Barbier *et al* 2020). Thus, a deep diagnosis of the socioeconomic sectors at play, together with an integration and reinforcement of education, public health and security structures, could regain a positive outlook for sustainable land management and forest conservation. Supported by fire-free practices adapted to changing environmental conditions, sustainable socioeconomic development seems imperative for preventing illegal logging, protection of indigenous rights of tenure and land governance, as well as sustainable development of agricultural and forestry sectors (Ferreira *et al* 2014, Artaxo 2019, Macedo and Pereira 2020). The Amazon fires of 2019 highlight the need for global solutions to address tropical rainforest loss. Actions and policies, however, must focus not only on the wildfires themselves but also on their root causes: the lack of appropriate policy, law enforcement, and socioeconomic drivers against deforestation and forest degradation in the non-fire adapted tropical moist forest in the Amazon.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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