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The 2023 Manaus smoke crisis and the role of highway BR-319 in a new Amazon fire cycle

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Abstract
In 2023, Manaus—the largest city in the Brazilian Amazon—experienced a severe smoke crisis linked to forest fires, extreme drought, and advancing deforestation. Using satellite imagery, atmospheric data, and field observations, we identified the municipalities of Manaquiri, Careiro and Autazes, along the BR-319 and AM-254 highways, as the primary sources of PM2.5 emissions. These fires, fueled by weak environmental governance and infrastructure-driven deforestation, led to PM2.5 concentrations exceeding 314 μg/m^3—more than 20 times the WHO limit. Our results show that plans to reconstruct BR-319 threaten to accelerate unsustainable land-use transitions, intensify fire outbreaks, and compromise climate stability, biodiversity, and public health. The findings highlight the environmental infeasibility of expanding road infrastructure in this region and call for alternative development strategies. Promoting low-impact options such as improved fluvial transport is essential to safeguard biodiversity, climate stability, and public health in the Amazon.

Keywords Air pollution, Brazil, Rainforest, Fire, Land-use change, Wildfires, Highways, PM2.5, Amazonia

1 Introduction

In 2023 a combination of El Niño and an Atlantic dipole caused a major drought in the Amazon [1]. Extreme droughts in the Amazon provide the conditions for forest fires, which release large quantities of smoke particles into the atmosphere, further exacerbating the drought. The particles act as cloud condensation nuclei, and when these particles are very abundant, they lead to the formation of water droplets that are too small to fall as rain [2–4]. This process inhibits rainfall, prolongs drought periods, and creates a positive feedback loop in which the lack of rain intensifies dry conditions, promoting more forest fires and, consequently, the release of more smoke [5, 6].

These events affected air quality and the health of Amazonian residents and highlighted the urgency of more effective environmental policies to control deforestation and fires in the Amazon [7, 8]. On average, a person inhales about 14 kg of air daily, in contrast to consuming only around 2 kg of water and 1.5 kg of food [9, 10]. People in tropical regions may inhale an amount of air greater than the global average due to the high temperatures, which affect their metabolism [10]. Each breath we take provides us with

essential oxygen, but it also introduces minute quantities of potentially hazardous gases and microscopic particles [11, 12]. These airborne elements can have a direct impact on our health, often without us even realizing it. The harmful health effects are not confined to immediate, acute incidents: prolonged exposure to polluted air can significantly harm long-term health, leading to a decrease in life expectancy [11]. On average, this reduction exceeds eight months, with the decline reaching over two years in areas suffering from severe air pollution, such as densely populated cities and industrial regions around the globe [12].

In 2023, Manaus (population 2 million), the capital of Brazil's state of Amazonas, faced alarming peaks of smoke resulting from fires in the Amazon region [13, 14]. During the dry season, especially between July and September, the city recorded high levels of air pollution. The governor of the state of Amazonas and the state's Secretary of the Environment declared that the smoke impacting Manaus did not originate in Amazonas, but rather from the east in the neighboring state of Pará [13]. We show that it is more likely that the smoke was linked to a new cattle ranching cycle that has advanced from the south along the BR-319 (Manaus-Porto Velho) highway to Manaus, in the still relatively intact central Amazon, from the AMACRO deforestation hotspot (the area around the junction of the states of Amazonas, Acre, and Rondônia). The BR-319 area is undergoing rapid deforestation due to illegal occupation of government land along the highway route, stimulated by the promise of reconstructing and paving the road [15–18]. Manaus, which is accustomed to enjoying quality air, except for pollution generated by its urban population, faced an exceptional deterioration in air quality [19].

In this study we investigate the causes and origins of the smoke that affected Manaus and test the hypothesis that the event was driven by the expansion of criminal fires and a complete absence of governance in the region surrounding highways BR-319 and AM-254, as well as the network of illegal side roads ("*ramais*") that spread from these corridors. This analysis contributes to the broader debate on sustainable development in the Amazon by highlighting the urgent need for integrated policies that consider the environmental infeasibility of major road projects and promote low-impact alternatives, such as the enhancement of fluvial transport systems.

2 Methods

To analyze the causes of the smoke peaks in Manaus, we used data from the Amazon Tall Tower Observatory (ATTO) of the National Institute of Amazonian Research (INPA), sensors from the State University of Amazonas (UEA) available on the AppSelva and PurpleAir platforms [19], records from the National Institute of Meteorology (INMET), and data from the Fire Monitoring Project of the National Institute for Space Research (INPE). The ATTO is a 325-m-high tower located east of Manaus, near the Uatumã River, where INPA and German partners have been monitoring atmospheric data since 2015. The analysis was based on measurements of PM2.5 particulate matter, wildfire incidents, wind patterns, and sea surface temperature anomalies. This provided a comprehensive dataset on the climatic, environmental, and meteorological conditions that influenced the observed levels of smoke in Manaus.

To assess the influence of oceanic phenomena, we used sea-surface temperature (SST) anomaly data from the US National Oceanic and Atmospheric Administration (NOAA) [20]. PM2.5 concentration data were obtained from air quality monitoring sensors

(PurpleAir) [19] and the AppSelva platform [21], supplemented by measurements from ATTO. PM2.5 was chosen as a relevant indicator of atmospheric pollution related to wildfires due to its impact on human health [6, 11, 12, 22].

Data on fire outbreaks were collected from INPE's Fire Monitoring Program database [13] using satellite images from the MODIS (Moderate Resolution Imaging Spectroradiometer) system to map the occurrence and intensity of wildfires during the study period. Data from METEORED were used to show emission concentrations and poor air quality over central and eastern Amazonia [23]. Information on wind patterns and meteorological anomalies was obtained from daily meteorological data provided by INMET [24–26].

Complementing the remote sensing and atmospheric data, field observations were conducted from May 2 to 5, 2024, in the municipalities of Careiro and Autazes, along segments of highways BR-319 and AM-254—previously identified as the primary sources of smoke emissions during the critical pollution episodes in Manaus. This temporal window was selected to enable on-site assessment of post-fire landscape transformations, such as the conversion of burned areas into pasture, and to document the presence of machinery and livestock in recently deforested zones. The methodology involved systematic inspections at access points along illegal roads and highway edges, photographic documentation, and conversations with local residents, including Indigenous Mura leaders. These observations provided qualitative and visual evidence that corroborate the spatial and temporal fire data obtained from remote sensing, allowing a direct association between the fire outbreaks recorded in 2023 and subsequent land-use changes observed in 2024.

3 Results and discussion

On October 12, 2023, Manaus experienced a PM2.5 particulate matter concentration reaching 314.99 μg per cubic meter of air (μg/m^3) (Fig. 1a), surpassing even the 2023 crisis in New Delhi, India, where this value reached 306 μg/m^3 [27]. The maximum value considered acceptable by the World Health Organization is 15 μg/m^3. From September through November 2023, the population of Manaus was living with smoke that forced residents to resume the use of masks, as during the COVID-19 pandemic. Events like these are extremely rare in Manaus, contrasting with the experiences of the inhabitants of the "arc of deforestation" in southern Amazonia, where smoke on this scale is normal for several months of the year and has negatively impacted people's life expectancy [8].

Most of the fires closest to Manaus were located to the south of the city, in the area south of the Amazon River (Fig. 1b). In a "normal" year, the smoke from fires does not reach Manaus, being carried westward towards Peru by the prevailing winds. But 2023 was not a "normal" year. Two types of El Niño (eastern and central) caused a severe drought in central Amazonia, including the Manaus region, which significantly increased the number of fires. In addition to El Niño, caused by warm water in the Pacific Ocean, there were also effects from an Atlantic dipole reducing rainfall in southern Amazonia [28]. The dipole results from the formation of a warm water patch in the tropical portion of the North Atlantic Ocean and a patch of cooler water in the South Atlantic Ocean. The dipole is evident in Fig. 2.

An Atlantic dipole (with higher SST in the tropical North Atlantic than in the tropical South Atlantic) can alter the wind patterns that bring moisture to Manaus, causing a reversal in wind direction. This occurred during the disastrous Atlantic dipole in 2005,

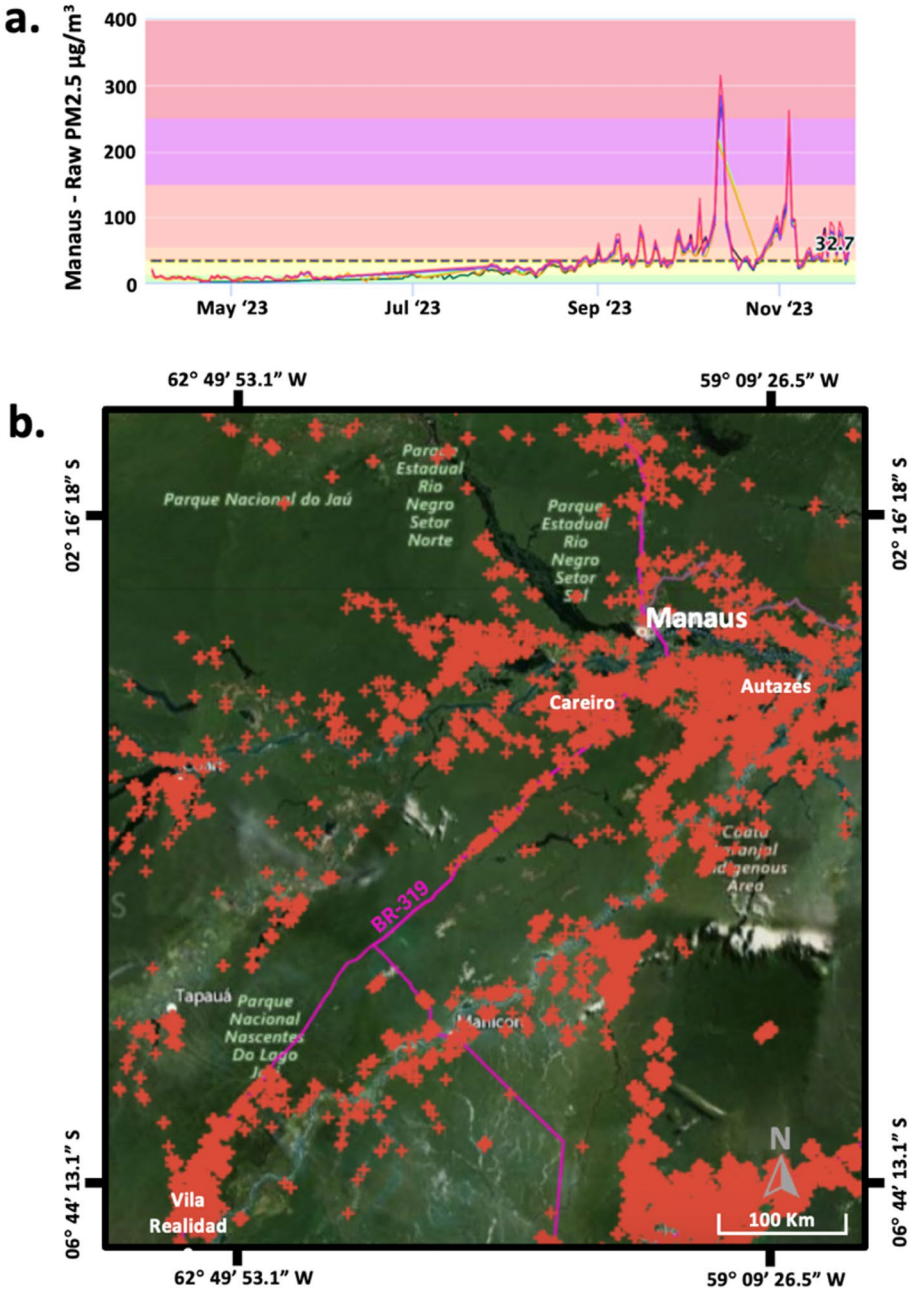

Fig. 1 **a** Levels of PM2.5 particulate matter (the most harmful to human health) in Manaus, according to the sensor network of the State University of Amazonas (UEA) (PurpleAir, [19]). The maximum value recommended by the World Health Organization is 15 µg/m^3. **b** The northern portion of BR-319, situated south of the city of Manaus: Fire hotspots in the BR-319 highway area between January 1 and November 30, 2023. The map shows two significant hotspots: one located between Careiro and Autazes, south of Manaus, and the other further south on BR-319 near Vila Realidade (Data from INPE, [14])

when the southwestern Amazon was hit by a severe drought [29, 30], leading to forest fires in Acre state [22] and in southern Amazonas [31]. Manaus experienced wind gusts from the west that felled forest areas [32].

The prevailing winds in Manaus blow from east to west. This results from the Earth's rotation and the effect of air movement at low altitudes from south to north across most of the Amazon (the return leg of the Hadley circulation). As air moves towards the

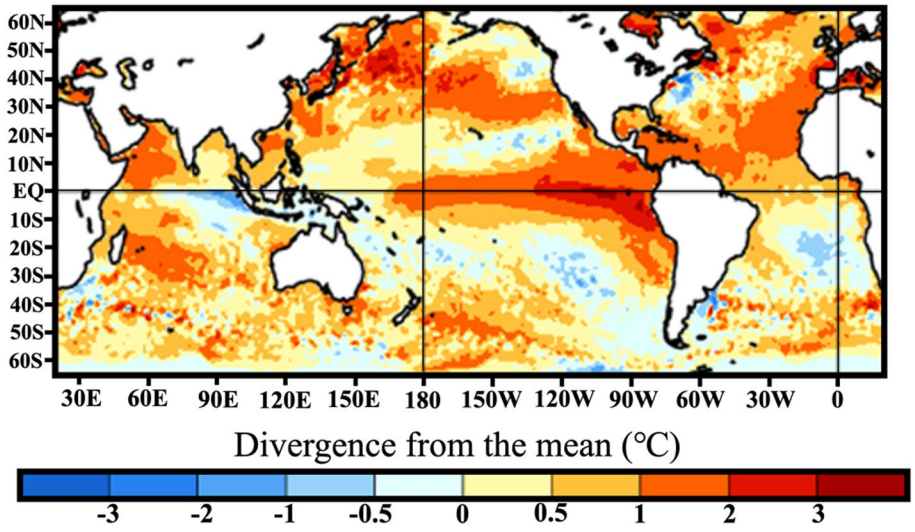

Fig. 2 Anomalies (divergence from the mean) in sea surface temperature (SST) in the oceans from 24 September to 21 October 2023. Tropical eastern Pacific (eastern El Niño) is very warm, and the warm-water patch is expanding to the central Pacific (central El Niño). The tropical North Atlantic is warm, while the South Atlantic is colder, forming the Atlantic dipole. Data from the US National Climate Prediction Center (NCEP) [28]

Intertropical Convergence Zone (ITCZ) near the equator, the speed at which the surface of the Earth is moving as the planet rotates increases, pulling air to the west as it is drawn towards the ITCZ. The ITCZ is a line that follows the latitude where the sun directly hits the Earth's surface, heating the air and causing it to rise, thus pulling air from the south and north. The exact wind direction depends on the season, which determines the more southerly or northerly position of the ITCZ. To reach Manaus, the prevailing east–west winds pass over a large area of forest with little deforestation north of the Amazon River.

Data from the ATTO Project confirm the role of fires near Manaus in explaining the large smoke peak in the city. The highest smoke peak in Manaus was recorded on October 12, 2023 with a PM2.5 particulate concentration of 314 μg/m^3 in the southern part of the city, according to sensors from the State University of Amazonas (UEA) accessible through the PurpleAir platform (See Fig. 1a). On the same date, the ATTO Project recorded 141 μg/m^3 (Fig. 3). Even if we assume that the smoke at the ATTO on October 10 (the ATTO's highest record) took two days to reach Manaus, samples in the city exceeded the ATTO's highest peak by more than 110 μg/m^3. Therefore, it is clear that smoke from Pará (the state neighboring Amazonas to the east) does not explain the high smoke levels in Manaus, even if all the smoke detected by the ATTO Project were carried to the city.

Additionally, PurpleAir sensors in Santarém, Pará, recorded the first peak after October 12, on October 13, reaching 205 μg/m^3, a much lower level than the maximum in Manaus. If smoke from Pará were responsible for the levels observed in Manaus, the peak there would have to be one or more days earlier and not one day later than the peak in Manaus, and the quantity of particulates recorded for Santarém would have to be much higher than that recorded in Manaus. The wind map from October 29 produced by Brazil's National Institute of Meteorology (INMET) shows Manaus in the middle of a large area of almost stationary air (Fig. 4a). This pattern had already changed to a more normal configuration with winds blowing from east to west on November 9, 2023 (Fig. 4b). On this date, Manaus showed improved air quality indices, and the sky over the

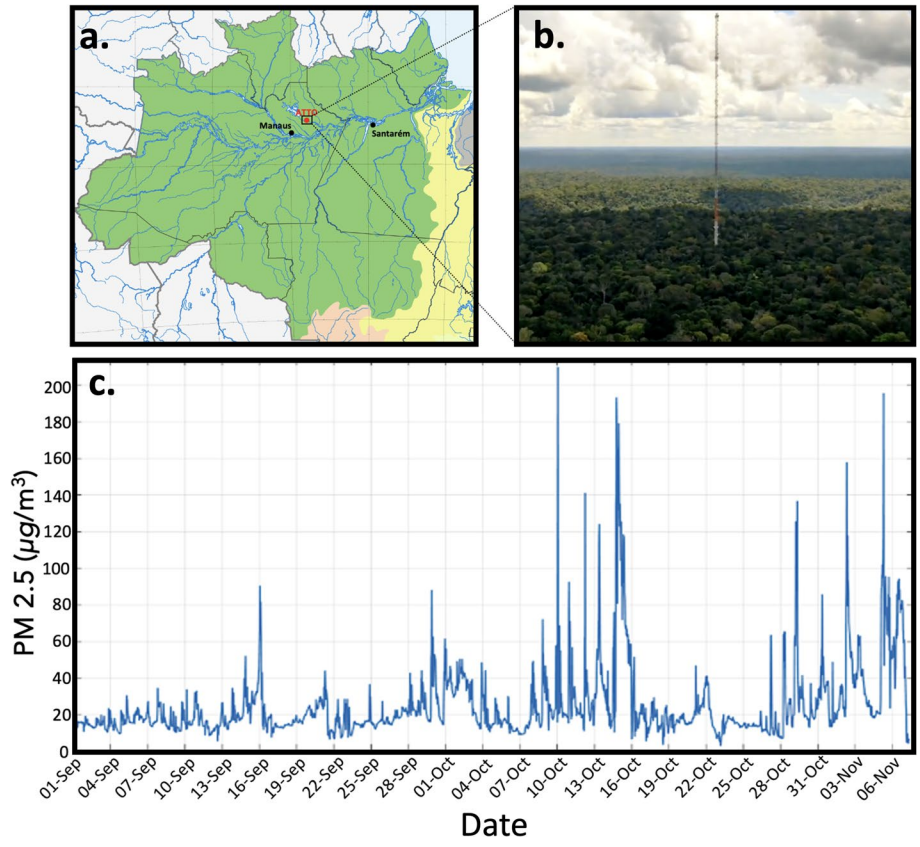

Fig. 3 **a** Map of Brazil's Amazon forest region (in green) and the locations of Manaus, Santarém and the ATTO tower. **b** The ATTO tower. **c** PM2.5 particulates measured in 2023 at the ATTO tower. The normal seasonal average is 4.3 μg/m^3

city was clear and clean (PurpleAir, [19]). Particulate emission and air quality data show a large smoke plume originating from the region south of Manaus. This was clearly separated from the plume over Santarém, Pará (Fig. 4c).

The fire hotspots between November 1 and 6 indicate fires in Autazes, Careiro, and other locations southeast of Manaus (Fig. 5). The municipality of Autazes, known for deforestation and forest fires [33], was prominent as a location of fires [34]. The Electronic Environmental Surveillance System (Selva) of the State University of Amazonas (UEA) indicated that the smoke in Manaus came from these fires south of Manaus, rather than originating in Pará [35]. On the other hand, some researchers at the National Institute for Space Research (INPE) highlighted the impressive amount of smoke over Pará and thought that it could indeed be transported to Manaus, in addition to the smoke produced by fires around the city [36]. However, these researchers pointed out that the images they had of the smoke peak on November 6, 2023 indicated that: "After the smoke 'burst' the scale limits, the equipment and the MODIS sensor could no longer identify what was smoke and what was cloud" [36]. INMET data corroborate the presence of clouds over the region, where Manaus recorded rain from 8 AM to 2 PM on November 7 [26].

Data from INPE's Fire Monitoring Project confirm that rainfall in the region extinguished the fire outbreaks, with no further fire occurrences recorded on November 7 [14]. The Manaus office of the Brazilian Institute of Environment and Renewable Natural

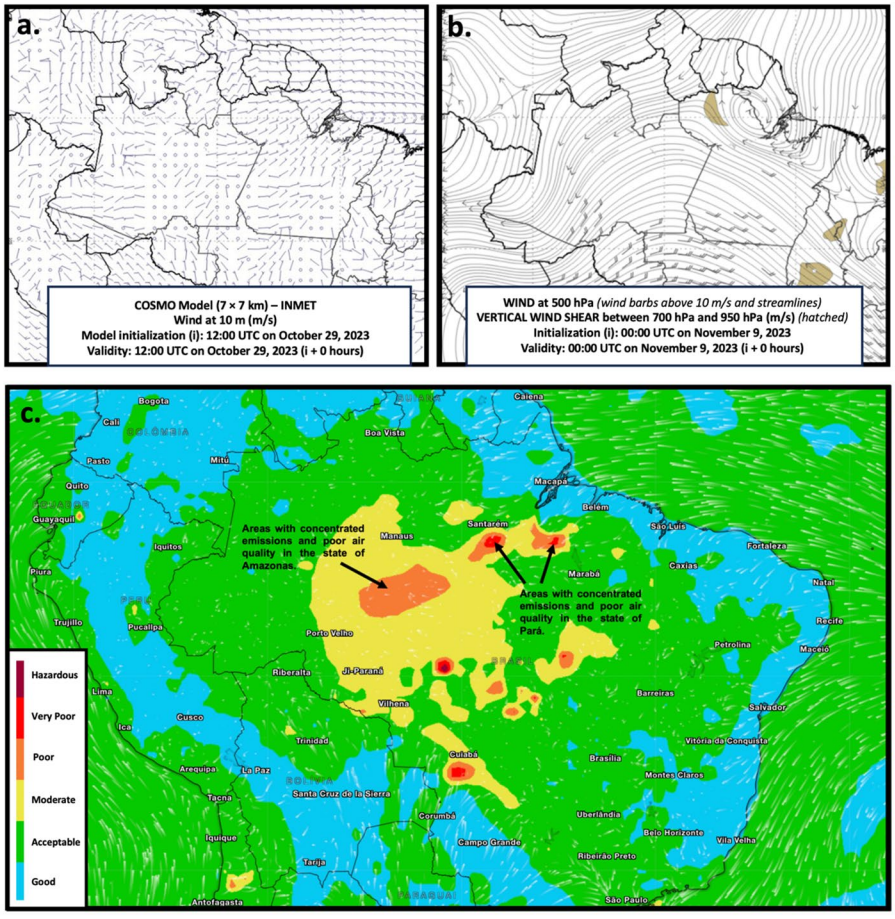

Fig. 4 **a** Atmospheric circulation on October 29, 2023. Arrows indicate wind flow, and circles indicate the absence of flow (INMET, [24]). **b** Winds on November 9, 2023, indicating a pattern change, with air from Santarém reaching Manaus (INMET, [25]). **c** METEORED data showing emission concentrations and poor air quality over central and eastern Amazonia. Warm colors indicate higher emissions, and cooler colors indicate areas with lower particulate concentration (Image for November 3, 2023 extracted from METEORED [23])

Resources (IBAMA) indicated that the locations with fires south of Manaus were the source of the smoke cloud that covered the city [37], but when the IBAMA headquarters in Brasília was questioned about the issue, the spokesperson did not answer the question, only providing a list of the agency's actions in fighting fires throughout the Amazon [36].

PurpleAir data show that, among all 14 air quality monitoring stations in Manaus, the easternmost station in the city (in the direction of winds from Pará) showed lower daily indices compared to the weighted average of the four southernmost stations in Manaus [19], which would receive greater impact from smoke coming from locations along Highway BR-319 (Fig. 5). Smoke from fires in Pará can, indeed, reach some points in the state of Amazonas, since the atmosphere is fluid, but the data demonstrate that the 2023 smoke crisis in Manaus cannot be attributed to fires in Pará.

The areas south of the Amazon River, where fires were generating smoke that reached Manaus, have been receiving population migration from the AMACRO region (e.g., Assayag, 2016 [38]). This could be just the beginning, as the impact will be much greater if Highway BR-319 is rebuilt and paved. Deforestation near Manaus is minuscule in comparison to the areas deforested in the AMACRO region at the southern end of Highway

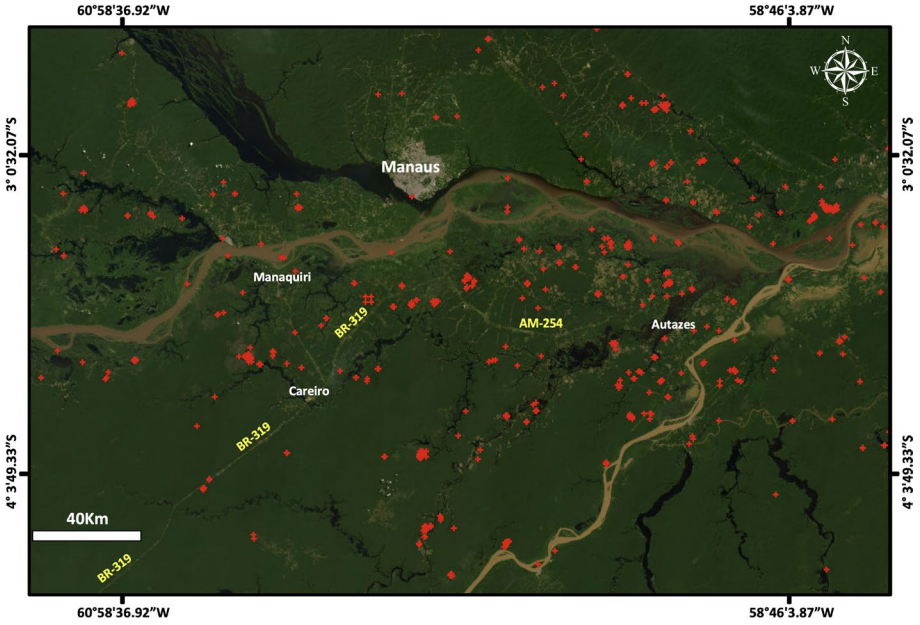

Fig. 5 The northern portion of BR-319, situated south of the city of Manaus. Image of alerts from the reference satellite of the Queimadas Project, from the National Institute for Space Research (INPE), between November 1 and 6, 2023 [14]. Fire hotspots appear in the municipalities of Manaquiri, Careiro and Autazes, an area impacted by Highway BR-319

BR-319 [39]. The population of Manaus is quite unaware of the risks and impacts of deforestation that could be generated by Highway BR-319, as the absence of paving is a factor that contributes to the central Amazon's environmental protection [17].

BR-319 was built in 1972-1975, inaugurated in 1976 and abandoned in 1988; since 2015 a "maintenance" program has made the road passible during the dry season, but the proposed "reconstruction" project has not yet received an environmental license to initiate construction [40]. The proposal to rebuild BR-319 would bring the processes and actors of the AMACRO region to the Manaus area and to all areas already connected to Manaus by roads, such as the state of Roraima, via the BR-174 (Manaus-Boa Vista) highway [41]. Huge areas of primary forest would also be opened by planned roads that would connect to BR-319, such as AM-366, which would provide access to the vast Trans-Purus region of intact rainforest west of the Purus River, which flows parallel to BR-319 [42–44]. Clearly, these impacts could reverberate in Manaus, with smoke similar to that which afflicts the AMACRO region every year. In 2023 Manaus was receiving a small warning of the impact expected if BR-319 is rebuilt.

A study conducted in the middle section of the Highway BR-319 in 2021 demonstrated that the deforestation rate within 40 km of the highway route was 2.5 times higher than the average for the Brazilian Amazon [18]. The same study also demonstrated intense land grabbing (illegal claiming of government land) in the area affected by Highway BR-319 [18]. A second study showed that the Institute of Environmental Protection of Amazonas (IPAAM) was illegally issuing licenses for forest management plans on undesignated public land in the BR-319 area, thereby facilitating this chain of land grabbing [45]. Highway BR-319 favored a new wave of deforestation driven by cattle ranching in the southern part of the state of Amazonas [46]. The advance of fires in the

municipalities of Autazes and Careiro in September and October 2023 resulted from the expansion of this deforestation wave into central Amazonia (near Manaus).

On November 17, 2023, Manaus again felt the effects of the smoke, recording PM2.5 particulate levels classified as "very unhealthy" to "hazardous" in some parts of the city. Again, the data showed a high concentration of forest fires south of the city, and in the interfluve between the Purus and Madeira Rivers that is cut by Highway BR-319, especially in the municipalities of Careiro and Autazes (Fig. 6a). The data again showed that the southernmost air-sampling stations in the Manaus area, which are the most influenced by the fires in Careiro and Autazes, recorded higher PM2.5 particulate levels than the other stations. Additionally, a control station in Itacoatiara municipality measured PM2.5 particulate levels lower than the southern stations, indicating that the smoke was not coming from the east (state of Pará). Data from the ATTO also pointed to lower levels than those recorded in Manaus. Wind flow data for the same period also rule out the possibility that the smoke could have come from Pará (Fig. 6b).

On November 21, the Amazonas State Department of Environment (SEMA) issued a statement on its official webpage stating that INPE satellite images showed that fires in western Pará and the Metropolitan Region of Manaus (RMM) were responsible for the smoke reaching the capital of Amazonas [47]. The images in question do not indicate the origin of this smoke as SEMA claimed, instead merely showing the locations of fire hotspots across Brazil. As shown by the data discussed above from east of Manaus at Itacoatiara and the ATTO, it is implausible that the smoke peak observed in mid-November 2023 can be attributed to the fires in Pará.

Estimates of PM2.5 particulate concentrations made by INPE on November 17, 2023, when the new increase in particulates in Manaus began, show that the emission cloud affecting Manaus was clearly dissociated from the PM2.5 particulate emissions from the fires in Pará, having as its real center the fires in Careiro and Autazes (Figs. 7). Thus, the official SEMA statement that INPE images indicated that the smoke affecting Manaus came from Pará [47] does not match what INPE's data show. Analysis of emission data from Brazil's National Institute for Space Research (INPE) indicates that the smoke plume covering Manaus originated within the state of Amazonas, particularly in the municipalities of Careiro and Autazes, as well as along the BR-319 and AM-254 highways corridor (Fig. 7). SEMA only officially requested support from the Federal

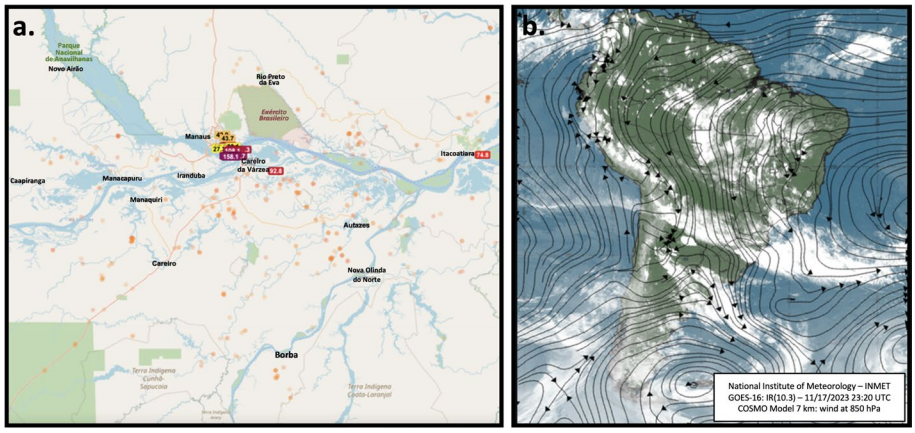

Fig. 6 **a** AppSelva data for November 17, 2023, collected at 11:36 PM. Fire data are from the NOAA20 and Suomi databases. **b** INMET COSMO model data for November 17, 2023

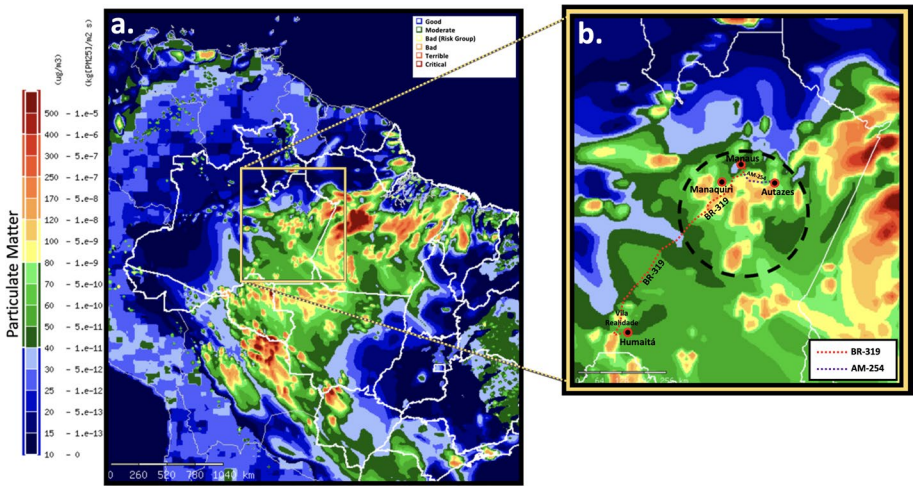

Fig. 7 INPE data on emissions and air quality for November 17, 2023. **a** The data show that the smoke cloud over Manaus was dissociated from particulate emissions from Pará. **b** The emissions image over the Amazonas region confirms that the smoke plume is distinct from the emissions originating in Pará and instead stems from fires occurring around highways BR-319 and AM-254. The southern portion of Amazonas—particularly the areas of Vila Realidade and Humaitá—also presents other significant emission sources. These data demonstrate that zones with higher traffic flow and paved segments along BR-319 concentrate the fire outbreaks responsible for the smoke that affected Manaus

Government on October 4th, when the situation was already extremely severe, coinciding with the official visit to Manaus of the Minister of Environment and Climate Change, Marina Silva [48].

Our findings support the hypothesis that the smoke event impacting Manaus originated predominantly from fire activity in areas influenced by highways BR-319 and AM-254 (Fig. 7b). Attribution of the smoke plume to the state of Pará is unequivocally refuted by emission data (Fig. 7b) and, in practice, served as a political maneuver by the Amazonas state government to divert attention from fires occurring within its own jurisdiction. The data highlight systemic governance failures and institutional neglect which enabled widespread fire propagation during an exceptionally dry season exacerbated by El Niño conditions (Fig. 2). Subsequent field surveys confirmed that extensive portions of the burned landscape were later converted into pasture, underscoring the instrumental role of fire as a mechanism for land appropriation and the expansion of cattle ranching in the region (Fig. 8).

On-site visits conducted in May 2024 in the areas along the BR-319 and AM-254 highways in the municipalities of Careiro and Autazes confirmed that the areas that experienced forest fires from September to November 2023 had undergone recent deforestation and burning (Fig. 8a). Along BR-319 in the municipality of Careiro and the area along AM-254, which connects BR-319 to Autazes, bulldozers and wheel-loader tractors were observed clearing land where remnants left by the fires indicated it had been burned (Fig. 8a, b), and some areas already had cattle (Fig. 8c, d) or water buffalo (Fig. 8e, f). Many of these areas overlap Indigenous lands and traditional Indigenous use areas (Fig. 8g). The chiefs of the Mura people in the municipality of Autazes have told us that water buffalo ranchers are increasingly encroaching on their land.

Access to these areas is being facilitated by illegal roads branching off the already paved AM-254 (Fig. 8i), cutting through the undesignated public land and approaching the Madeira River. These findings contradict the narrative that paving roads in the

Fig. 8 **a** and **b** Area with remnants of fires on AM-254 with a bulldozer and a pair of wheel-loader tractors clearing the area, Autazes municipality; **c** Area with cattle along the BR-319 highway, Careiro municipality; **d** Area with cattle along AM-254, Autazes municipality. **f** Water buffalo ranching along BR-319, Careiro municipality; **g** Water buffalo ranching along AM-254, in Autazes municipality. **h** Water buffalo ranching in an invaded area in the Mura Indigenous people's land, Autazes municipality. **i** Side road branching off AM-254, providing access to the undesignated public land. (Photos: L. Ferrante)

Amazon reduces deforestation by enhancing monitoring, as any such effect is overwhelmed by its facilitating the opening of illegal roads and subsequent land invasions and illegal deforestation that go unnoticed by authorities. These data confirm that the forest is being burned and replaced by a new wave of cattle ranching in the central Amazon. The Amazonas state government has been promoting the BR-319 reconstruction project and "development" (i.e., deforestation for cattle ranching) in the area.

The block of forest cut by Highway BR-319 and associated side roads plays a fundamental role in forming high-pressure cells that feed the winds known as "flying rivers" that carry water vapor from the Amazon to the southern and southeastern regions of Brazil [49]. The increase in fire and the conversion of forest to pasture in this area can be expected to further exacerbate climate change in central Amazonia, which is driving

an ongoing process of species extinction [50]. Continuation of these climate trends also risks collapse of the forest in the central and western Amazon [51], which would sacrifice this forest's essential ecosystem service in recycling water that is transported to the southern and southeastern regions of Brazil, where it is crucial for biodiversity, agriculture and the water supply of Brazil's largest cities [49].

The magnitude of these impacts, for which the 2023 "smoke crisis" in Manaus was a warning, indicates that the proposed reconstruction of BR-319 should not be licensed [52, 53]. Brazil's 2024 "fire crisis" has provided a second warning, with dangerous smoke levels in Manaus and in many other parts of Brazil [54]. Legislative initiatives that essentially force the approval of the highway project need to be defeated if not yet enacted or revoked if already enacted. These include proposed law PL 4994/2023 that has been approved by the federal Chamber of Deputies [55] and awaits approval by the Senate [52] and state law 6465/2023), which has already been enacted by the Legislative Assembly of Amazonas [55].

On June 25, 2025, the governor of the state of Amazonas, Wilson Lima, publicly challenged President Lula on the paving of the BR-319 highway, stating: "It doesn't make sense to me to argue that we shouldn't pave it because it can't be controlled. How can the federal government be unable to monitor a highway in the Amazon?" [56]. However, the state government did not call upon the federal government to respond to the escalating fire outbreaks in the BR-319 region, which was its responsibility [48]. Besides this, the state government has failed to enforce environmental oversight even in easily accessible paved sections, such as "Lot B" between Manaus and Careiro and the AM-254 between Careiro e Autazes (Fig. 1). This has enabled land grabbing to advance unchecked in this region (Fig. 8).

On August 6, 2025, the governor of Amazonas (Wilson Lima) signed Decree No. 52,216, officially presented as a measure of "environmental regularization" and forest restoration. The state government claims that the decree applies only to properties with pre-existing environmental liabilities, registered and validated in the Rural Environmental Registry (CAR), and located in municipalities with more than 50% of their territory under protection [57, 58]. It also argues that no new deforestation will be authorized and that the measure's sole purpose is to restore native vegetation. However, our field-based results documented in this study contradict this narrative [57, 58]. The decree opens a significant loophole for the legalization of already consolidated illegal deforestation, including in areas adjacent to Indigenous Lands and Conservation Units in ecologically sensitive areas along the BR-319 highway. It allows the "regularization" of environmental liabilities based solely on the CAR, a self-declaratory system without field verification, thereby favoring land grabbing (the illegal appropriation and sale of government land), which has been widely documented in Amazonas [18, 45]. The text also allows reducing the minimum legal reserve from 80% to as little as 50%, based on Ecological-Economic Zoning (ZEE) [57, 58]. In the municipalities of Autazes, Careiro, Careiro da Várzea, and Manaquiri, which are affected by the decree along the BR-319, pastures have expanded over the past five years to occupy 34%, 25%, 33%, and 33% of their territories, respectively [59].

This reveals a systemic, institutionalized process of state-level inaction in monitoring, followed by the subsequent legalization of illegally occupied areas.Although the federal government maintains a pro-environment discourse [60], monitoring data from the Fire

Monitoring Project of the National Institute for Space Research (INPE) indicate that fire outbreaks have intensified in Amazonas state, with a record number of fire outbreaks in 2024, reaching the highest level since the start of the monitoring program in 1998 [14]. Our data reveal a lack of environmental governance at both the federal and state levels, as well the unfeasibility of controlling fires in this area if the federal government rebuilds and paves the BR-319 highway. This implies both environmental impacts in a vast area of Amazon rainforest and impacts on public health in Manaus and other cities.

This smoke crisis exemplifies how infrastructure projects that disregard ecological thresholds—such as the proposed reconstruction of Highway BR-319—pose systemic threats to sustainability in the Amazon. In an ecosystem where climate stability, biodiversity, and the well-being of traditional populations are deeply interconnected, promoting large-scale road construction fosters deforestation, land grabbing, and recurring fire outbreaks. Recent studies have documented a widespread decline in Brazilian biodiversity, driven by climate change and El Niño-associated anomalies [49, 51, 61]. Both the climate disruptions induced by landscape-scale fire regimes and the elevated emission levels reported in the present study contribute directly to climate alterations [61], which in turn have accelerated biodiversity loss across Central Amazonia [51, 62] and other regions of Brazil [61]. These dynamics exemplify broader systemic patterns of ecological degradation, rooted in governance failures and the continued advance of the deforestation frontier [62]. In addition to the impacts of forest fires and associated climate change [61, 62], structural changes in the landscape—such as the expansion of pasture and other crops, along with the use of agrochemicals—are likely to intensify regional biodiversity loss [63, 64].

Such dynamics also undermine environmental governance and public health in urban centers like Manaus. Addressing these intertwined crises requires integrated policies that extend beyond reactive fire prevention. The underlying drivers of environmental degradation must be confronted. This includes acknowledging the ecological infeasibility of expanding major road networks through intact forest landscapes and instead prioritizing lower-impact alternatives, such as improving navigable waterways, which offer lower impact pathways for regional integration and economic development.

4 Conclusion

The 2023 smoke crisis in Manaus was mainly derived from fires south of the city, especially in the municipalities of Careiro and Autazes. The alarming smoke levels in Manaus reflect the lack of governance, especially in the area influenced by Highway BR-319. If reconstructed and paved, Highway BR-319 is likely to intensify fires in the region, adding to reasons for reconsidering this proposed highway project. The data also indicate a lack of sufficient effort by the Amazonas state government to control the fires in the region between the Purus and Madeira Rivers, where the state has instead been encouraging the expansion of cattle ranching.

The 2023 smoke crisis in Manaus serves as a harbinger of how infrastructure projects like Highway BR-319 can catalyze unsustainable land-use transitions, fueling deforestation, fire outbreaks, and public health emergencies. The data underscore how weak environmental governance and the promotion of road expansion threaten not only biodiversity and climate stability but also the sustainability of urban centers that depend on the ecological integrity of the Amazon.

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Author contributions
L.F. designed the research; L.F. conducted fieldwork; L.F. conducted statistical analyses; L.F. and P.M.F. interpreted the analyses; L.F., R.R.M. and P.M.F. wrote the manuscript; L.F., R.R.M. and P.M.F. revised the manuscript.

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Data availability
All data are available upon request to the corresponding author.

Declarations

Competing interests
The authors declare no competing interests.

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References

1. Fearnside PM, Silva RA. Amazon drought: Much damage still to come (commentary). Mongabay. 2023. https://news.mongabay.com/2023/11/amazon-drought-much-damage-still-to-come-commentary/
2. Andreae MO, Rosenfeld D, Artaxo P, Costa AA, Frank GP, Longo KM, Silva-Dias MAF. Smoking rain clouds over the Amazon. Science. 2004;303:1337–40. https://doi.org/10.1126/science.1092779.
3. Koren I, Kaufman YJ, Remer LA, Martins JV. Measurement of the effect of Amazon smoke on inhibition of cloud formation. Science. 2004;303:1342–5.
4. Pöschl U, Martin ST, Sinha B, Chen Q, Gunthe SS, Huffman JA, Borrmann S, Farmer DK, Garland RM, Helas G, Jimenez JL, King SM, Manzi A, Mikhailov E, Pauliquevis T, Petters MD, Prenni AJ, Roldin P, Rose D, Schneider J, Su H, Zorn SR, Artaxo P, Andreae MO. Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. Science. 2010;329:1513–6.
5. Rosenfeld D, Lohmann U, Raga GB, O'Dowd CD, Kulmala M, Fuzzi S, Reissell A, Andreae MO. Flood or drought: how do aerosols affect precipitation? Science. 2008;321:1309–13. https://doi.org/10.1126/science.1160606.
6. Lohmann U, Feichter J. Global indirect aerosol effects: a review. Atmos Chem Phys. 2005;5(3):715–37.
7. Artaxo P, Martins JV, Yamasoe MA, Procopio AS, Pauliquevis TM, Andreae MO, Guyon P, Gatti LV. Atmospheric aerosols in Amazonia and land use change: from natural biogenic to biomass burning conditions. Front Environ Sci. 2013;165:203–35. https://doi.org/10.1039/C3FD00052D.
8. Rocha R, Santanna AA. Winds of fire and smoke: air pollution and health in the Brazilian Amazon. World Dev. 2022;151:105722. https://doi.org/10.1016/j.worlddev.2021.105722.
9. Copernicus. Air quality. 2024. https://atmosphere.copernicus.eu/air-quality. Accessed 30 Sept 2024.
10. WHO (World Health Organization). Air Quality Guidelines: Global Update 2005. WHO Regional Office for Europe. 2006. https://www.who.int/publications/i/item/WHO-SDE-PHE-OEH-06.02
11. Brook RD, Rajagopalan S, Pope CA, Brook JR, Bhatnagar A, Diez-Roux AV, Holguin F. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation. 2010;121(21):2331–78. https://doi.org/10.1161/cir.0b013e3181dbece1.
12. Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature. 2015;525:367–71. https://doi.org/10.1038/nature15371.
13. Ferrante L. Dados mostram que fumaça em Manaus não veio do Pará, como diz governo do AM. Ecoa UOL, 2023. https://www.uol.com.br/ecoa/colunas/opiniao/2023/11/17/estudo-mostra-que-fumaca-em-manaus-nao-veio-do-para-como-diz-governo-do-am.htm
14. INPE (Instituto Nacional de Pesquisas Espaciais). Programa Queimadas do INPE, INPE, 2023. http://terrabrasilis.dpi.inpe.br/queimadas/portal/
15. Ferrante L, Fearnside PM. Amazon's road to deforestation. Science. 2020;369:634.
16. Ferrante L, Fearnside PM. Brazilian government violates Indigenous rights: what could induce a change? DIE ERDE J Geograph Soc Berlin. 2021;152(3):200–11. https://doi.org/10.12854/erde-2021-584.
17. Ferrante L, de Andrade MBT, Leite L, Silva Junior CA, Lima M, Coelho Junior MG, et al. Brazils Highway BR-319: The road to the collapse of the Amazon and the violation of indigenous rights. DIE ERDE J Geogr Soc Berlin. 2021;152(1):65–70. https://doi.org/10.12854/erde-2021-552.
18. Ferrante L, Andrade MBT, Fearnside PM. Land grabbing on Brazil's highway BR-319 as a spearhead for Amazonian deforestation. Land Use Policy. 2021;108: 105559. https://doi.org/10.1016/j.landusepol.2021.105559.
19. PurpleAir. Dados das estações em Manaus para Raw PM2.5 (μg/m^3). 2023. https://map.purpleair.com/1/a/ls/mPM25/a1440/p2592000/cC0#11.06/-3.1319/-60.0182
20. CPC (Climate Prediction Center). ENSO: Recent Evolution, Current Status and Predictions. Climate Prediction Center (CPC), National Centers for Environmental Prediction (NCEP) / National Weather Service (NWS), 2023. https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf
21. Selva. Sistema Eletrônico de Vigilância Ambiental. 2023. https://appselva.com.br/

22. da Silva SS, Fearnside PM, Graça PMLA, Brown IF, Alencar A, de Melo AWF. Dynamics of forest fires in the southwestern Amazon. For Ecol Manag. 2018;424:312–22. https://doi.org/10.1016/j.foreco.2018.04.041.
23. METEORED. METEORED, 2023. https://www.meteored.com/. Assessed 3 Nov 2023.
24. INMET (Instituto Nacional de Meteorologia). Previsão numérica. 2023. https://vime.inmet.gov.br/
25. INMET (Instituto Nacional de Meteorologia). Ventos em 500 hPa. 2023. https://vime.inmet.gov.br/
26. INMET (Instituto Nacional de Meteorologia). Tabela de Dados das Estações (Manaus A101), 2023. https://tempo.inmet.gov.br/TabelaEstacoes/A101
27. BBC (British Broadcasting Corporation). Air pollution: Delhi air turns very poor but 'worst is yet to come'. BBC, 2023. https://www.bbc.co.uk/news/world-asia-india-67166585
28. Fearnside PM, Silva RA. Amazon region hit by trio of droughts in grim snapshot of the century to come. The Conversation, 2023. https://theconversation.com/amazon-region-hit-by-trio-of-droughts-in-grim-snapshot-of-the-century-to-come-217652
29. Cox PM, Harris PP, Huntingford C, Betts RA, Collins M, Jones CD, Jupp TE, Marengo JA, Nobre CA. Increasing risk of Amazonian drought due to decreasing aerosol pollution. Nature. 2008;453:212–5. https://doi.org/10.1038/nature06960.
30. Lewis SL, Brando PM, Phillips OL, van der Heijden GMF, Nepstad DC. The 2010 Amazon drought. Science. 2011;31:554. https://doi.org/10.1126/science.1200807.
31. Vasconcelos SS, Fearnside PM, Graça PMLA, Nogueira EM, de Oliveira LC, Figueiredo EO. Forest fires in southwestern Brazilian Amazonia: estimates of area and potential carbon emissions. For Ecol Manag. 2013;291:199–208. https://doi.org/10.1016/j.foreco.2012.11.044.
32. Araújo RF, Nelson CBW, Chambers JQ. Regional distribution of large blowdown patches across Amazonia in 2005 caused by a single convective squall line: distribution of Amazonia blowdown damage. Geophys Res Lett. 2017;44(15):7793–8. https://doi.org/10.1002/2017GL073564.
33. dos Reis M, Graça PMLA, Yanai AM, Ramos CJP, Fearnside PM. Forest fires and deforestation in the central Amazon: effects of landscape and climate on spatial and temporal dynamics. J Environ Manag. 2021;88: 112310. https://doi.org/10.1016/j.jenvman.2021.112310.
34. Felizardo N. Avô de tiktoker da capivara está entre os causadores da fumaça em Manaus. The Intercept-Brasil. 2023. https://www.intercept.com.br/2023/11/06/fumaca-manaus-esses-sao-desmatadores-que-contribuiram-por-anos/
35. Sassini V. Cidade mais populosa da Amazônia vive de onda em onda de fumaça, e cotidiano é de área degradada. Folha de São Paulo, 2023. https://www1.folha.uol.com.br/ambiente/2023/11/cidade-mais-populosa-da-amazonia-vive-de-onda-em-onda-de-fumaca-e-cotidiano-e-de-area-degradada.shtml
36. Fatim B. Encoberta desde agosto, Manaus teve pico de fumaça na segunda (6), aponta Inpe. *g1*, 2023. https://g1.globo.com/am/amazonas/noticia/2023/11/07/encoberta-desde-agosto-manaus-teve-pico-de-fumaca-na-segunda-6-aponta-inpe.ghtml
37. Castro M. Fumaça que encobre Manaus vem da região metropolitana da capital e é causada por agropecuaristas, diz Ibama. *g1*, 2023. https://g1.globo.com/am/amazonas/noticia/2023/10/11/fumaca-que-encobre-manaus-vem-da-regiao-metropolitana-da-capital-e-e-causada-por-agropecuaristas-diz-ibama.ghtml
38. Assayag Y. MPF/AM cobra de órgãos ambientais e da polícia providências sobre denúncia de invasão na BR-319. Amazonas em Tempo, 2016. http://www.emtempo.com.br/mpfam-cobra-de-orgaos-ambientais-e-da-policia-providencias-sobre-denuncia-de-invasao-na-br-319/
39. Lima W. Queimadas batem recorde em agosto na Amazônia. Amazônia Real, 2022. https://amazoniareal.com.br/queimadas-batem-recorde-em-agosto-na-amazonia/
40. Ferrante L. Estradas. In: Atlas da Amazônia Brasileira: Fatos, dados e saberes da maior floresta tropical do mundo. Rio de Janeiro: Fundação Heinrich Böll, 2025. pp. 46–47. https://br.boell.org/sites/default/files/2025-04/atlas-da-amazonia-brasileira.pdf
41. Barni PE, Fearnside PM, Graça PMLA. Simulating deforestation and carbon loss in Amazonia: impacts in Brazil's Roraima state from reconstructing Highway BR-319 (Manaus-Porto Velho). Environ Manage. 2015;55:259–78. https://doi.org/10.1007/s00267-014-0408-6.
42. Fearnside PM. Oil and gas project threatens Brazil's last great block of Amazon forest (commentary). Mongabay, 2020. https://news.mongabay.com/2020/03/oil-and-gas-project-threatens-brazils-last-great-block-of-amazon-forest-commentary/
43. Fearnside PM. Amazon environmental services: why Brazil's highway BR-319 is so damaging. Ambio. 2022;51:1367–70. https://doi.org/10.1007/s13280-022-01718-y.
44. Fearnside PM, Ferrante L, Yanai AM, Isaac Júnior MA. Trans-Purus: Brazil's last intact Amazon forest at immediate risk (commentary). Mongabay, 2020. https://news.mongabay.com/2020/11/trans-purus-brazils-last-intact-amazon-forest-at-immediate-risk-commentary/
45. Andrade M, Ferrante L, Fearnside PM. Brazil's highway BR-319 demonstrates a crucial lack of environmental governance in Amazonia. Environ Conserv. 2021;48:161–4. https://doi.org/10.1017/S0376892921000084.
46. Ferrante L, Fearnside PM. Countries should boycott Brazil over export-driven deforestation. Nature. 2022;601:318.
47. SEMA (Secretaria Estadual do Meio Ambiente, Amazonas). Imagens de satélites do Inpe mostram que queimadas do oeste do Pará e RMM são responsáveis por fumaça que atinge capital do Amazonas. Sema Amazonas, 2023. https://meioambiente.am.gov.br/imagens-de-satelites-do-inpe-mostram-que-queimadas-do-oeste-do-para-e-rmm-sao-responsaveis-por-fumaca-que-atinge-capital-do-amazonas/
48. Santana F. Queimadas: Amazonas só acionou a União após visita de Ministra. Vocativo.com, 2023. https://vocativo.com/2023/11/26/queimadas-amazonas-so-acionou-a-uniao-apos-visita-de-marina-silva/
49. Ferrante L, Getirana A, Baccaro FB, Schongart J, Leonel ACM, Gaiga R, Garey MV, Fearnside PM. Effects of Amazonian flying rivers on frog biodiversity and populations in the Atlantic Rainforest. Conserv Biol. 2023;37: e14033. https://doi.org/10.1111/cobi.14033.
50. Flores BM, Montoya E, Sakschewski B, Nascimento N, Staal A, Betts RA, Levis C, Lapola DM, Esquível-Muelbert A, Jakovac C, Nobre CA, Oliveira RS, Borma LS, Nian D, Boers N, Hecht SB, ter Steege H, Arieira J, Lucas IL, Berenguer E, Marengo JA, Gatti LV, Mattos CRC, Hirota M. Critical transitions in the Amazon forest system. Nature. 2024;626:555–64. https://doi.org/10.1038/s41586-023-06970-0.
51. Ferrante L, Rojas-Ahumada D, Menin M, Fearnside PM. Climate change in the Central Amazon and its impacts on frog populations. Environ Monit Assess. 2023;195:1421. https://doi.org/10.1007/s10661-023-11997-x.

52. Fearnside PM. Race to destroy the Amazon forest: Brazil's National Congress set to force construction of Highway BR-319 (commentary). Mongabay, 2023. https://news.mongabay.com/2023/12/race-to-destroy-the-amazon-forest-brazils-national-congress-set-to-force-construction-of-highway-br-319-commentary/
53. Fearnside PM. Impactos da rodovia BR-319. Amazônia Real, (2024). https://philip.inpa.gov.br/publ_livres/2024/Fearnside-2024-Impactos_da_BR-319-Serie_completa.pdf
54. Lacerda L. Em meio a incêndios, qualidade do ar é considerada insalubre em oito estados e no DF. Folha de São Paulo, 2024. https://www1.folha.uol.com.br/cotidiano/2024/08/em-meio-a-incendios-qualidade-do-ar-e-considerada-insalubre-em-oito-estados-e-no-df.shtml
55. Amazonas. Lei Ordinária n° 6465, de 10 de Outubro de 2023. Dispõe sobre a flexibilização do licenciamento ambiental de competência estadual para incentivo à conclusão da rodovia BR-319. 2023. https://sapl.al.am.leg.br/norma/12714
56. Alves A. Wilson cobra Lula sobre BR-319: 'covardia'. A Crítica, 2025. https://www.acritica.com/opiniao/wilson-cobra-lula-sobre-br-319-covardia-1.376439
57. Azevedo LF. Decreto de governador do Amazonas favorece a grilagem e pressiona terras indígenas, avaliam pesquisadores. O Globo, 2025. https://oglobo.globo.com/brasil/meio-ambiente/noticia/2025/08/08/decreto-de-governador-do-amazonas-favorece-a-grilagem-e-pressiona-terras-indigenas-avaliam-pesquisadores.ghtml
58. Santana F. Decreto estadual abre brecha para legalizar desmatamento ilegal no Amazonas. Vocativo.com, 2025. https://vocativo.com/2025/08/08/decreto-estadual-abre-brecha-para-legalizar-desmatamento-ilegal-no-amazonas/
59. MapBiomas. Plataforma MapBiomas uso e cobertura. MapBiomas, 2025. https://brasil.mapbiomas.org/
60. Vilani RM, Ferrante L, Fearnside PM. The first acts of Brazil's new president: Lula's new Amazon institutionality. Environ Conserv. 2023;50(3):148–51. https://doi.org/10.1017/S0376892923000139.
61. Ferrante L, Baccaro FB, Kaefer IL, Diele-Viegas LM, Getirana A, Haddad CFB, Schiesari LC, Fearnside PM. Effects of climate change and El Niño anomalies on historical declines, extinctions, and disease emergence in Brazilian amphibians. Conserv Biol. 2025;39: e70024. https://doi.org/10.1111/cobi.70024.
62. Guimarães AF, Schietti J, Querido LCA, Nunes J, Santos P, Lagroteria D, Gordo M. Extreme drought and heat lead to alarming mortality of Amazon fauna. Acta Amazon. 2024;54: e20224053. https://doi.org/10.1590/1809-4392202404053.
63. Ferrante L, Baccaro FB, Ferreira EB, Sampaio MFdeO, Santos T, Justino RC, Angulo A. The matrix effect: how agricultural matrices shape forest fragment structure and amphibian composition. J Biogeogr. 2017;44:1911–22.
64. Ferrante L, Fearnside PM. Evidence of mutagenic and lethal effects of herbicides on Amazonian frogs. Acta Amazon. 2020;50:363–6. https://doi.org/10.1590/1809-4392202000562.

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