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Protecting Brazilian Amazon Indigenous territories reduces atmospheric particulates and avoids associated health impacts and costs

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Indigenous territories are considered important for conservation, but little is known about their role in maintaining human health. Here we quantified the potential human health and economic benefits of protecting these territories in the Brazilian Amazon, by using cardiovascular and respiratory diseases cases, pollutant and forest cover data. Between 2010 and 2019, 1.68 tons of Particulate Matter of small size ($PM_{2.5}$) were released every year, with negative effects for human health. A lower number of infections was also found in municipalities with more forested areas, and with a low level of fragmentation, which probably is related to the potential capacity of the Amazon Forest to absorb $PM_{2.5}$ (26,376.66 tons year^{-1}, 27% of this absorption capacity in Indigenous territories). Our estimates indicate that by protecting Amazon Indigenous territories, over 15 million of respiratory and cardiovascular cases could be avoided every year, with ~$2 billion USD being saved only in health costs.

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The Amazon rainforest, with half of the planet's remaining tropical forests, is the most biodiverse region on earth[1]. It is also megadiverse from a cultural perspective, with 1.7 million people belonging to 375 Indigenous groups, living within ~3344 Indigenous territories[2]. The protection of the Amazon is critical not only for biodiversity conservation[3] but also for the provision of key ecosystem services to humans, such as freshwater supply[4], carbon sequestration, and climate regulation[5,6]. However, this region is threatened by human actions and has some of the highest deforestation rates in the world[7]. Growing evidence points to the important role of Indigenous territories in buffering against these threats and preserving tropical forests and the ecosystem services they provide[8]. These territories can also play an important role in maintaining human health, bringing positive economic benefits to the municipalities where they are located. Nevertheless, this aspect has been studied rather infrequently. Considering the full ecological, human, and economic benefits that these areas can bring is vital to safeguard land tenure and to inform conservation and landscape management actions aiming at the maintenance of ecosystem services, particularly, health provision.

Between May 19 and October 31, 2021, 519,000 hectares of Amazon forest burned as a result of forest fires[9], with Brazil being responsible for the highest amount. In fact, the number of fires has been increasing in the last few years. In 2019 alone, more than 92,000 km^2 of tropical moist forest biomes were affected by fires[10], the highest number of active fires in the Amazon since 2010[11]. Following deforestation, these fires are usually lit deliberately to clear land for agriculture[11], a process known as slash-and-burn[12]. Although Brazil was once an example of the fight against deforestation, since 2013 the scenario has changed, and deforestation rates reached the highest levels of the decade in 2020[13]. In addition, the size of deforestation fragments is larger than before, suggesting a remarkable shift in deforestation patterns and a new wave of forest destruction[14]. In the Brazilian Amazon, annual deforestation rates are closely linked to the annual incidence of fires[11], with fires being the primary pathway for removing plant biomass and transferring associated carbon from tropical vegetation to the atmosphere[12].

Forest fires are also an important source of particulate matter (PM) and atmospheric trace gases. In tropical regions, they are the dominant source of PM pollution across much of the tropics[15], and are responsible for 90% of global $PM_{2.5}$ emissions[16], including over the Amazon basin[17,18]. In addition, the evergreen broadleaf forests of the Amazon have among the highest emission factors for black and organic carbonaceous aerosol[19], the primary components of fine particulate matter, plus the highest fuel loadings[20]. This forest characteristic leads to more severe fires that emit more carbonaceous aerosols.

Ambient $PM_{2.5}$ (PM with an aerodynamic median diameter smaller than 2.5 μm) can degrade regional air quality, disturb fauna communities by accelerating the loss of forest interior species[21], and affect the human population's respiratory health, exacerbating the vulnerability of Indigenous, traditional, and rural communities[22]. There is strong evidence of acute adverse health outcomes from exposure to $PM_{2.5}$ from forest fires, as particles easily penetrate the pulmonary alveoli and can pass directly through the lungs into the blood system[23]. Therefore, human population exposure to smoke from forest fires is associated with increased respiratory symptoms, heart disease, stroke, emphysema, lung cancer, bronchitis, asthma, chest pain, chronic lung and heart problems, and increases in the risk of death[24]. These effects can happen even in places far away from fire events[25]. Severe fires emit smoke particles that are lifted high in the air column and thus transported far distances from the fire source, affecting populated regions downwind[26]. In the Amazon, for example, smoke from forest fires has been shown to be related to an increase in the number of people hospitalized with respiratory system diseases[27]. The negative impacts of intense fire activity also extend to the socioeconomic sphere. Uncontrolled fires can bring financial losses to farmers by destroying crops, fences, and housing infrastructures[28] in addition to the costs associated with hospitalizations and treatment for each person hospitalized.

Greenspaces and forest areas are known to provide different ecosystem services, among them air quality regulation services[29], an ecosystem service still poorly estimated, especially outside urban areas, and which can consequently affect human health. This happens because foliage acts as a biofilter of air pollution[30] and improves air quality[31] due to the leaves' rough texture and large contact area[32], reducing the concentration of pollutants. Although several studies show the importance of these green areas for regulating air quality in urban areas, there is a knowledge gap about rural areas, especially in the tropics. In addition, few studies evaluated the forest spatial configuration that enhances the provision of health services. Here we account for this ecosystem service and tried to understand: (a) how much $PM_{2.5}$ is being released into the atmosphere in a 10-year period; (b) how much $PM_{2.5}$ could potentially be absorbed by forest areas and Indigenous territories; (c) how $PM_{2.5}$ affects human health; (d) what is the relationship between human health and forest structure; (e) the economic costs of forest fires; (f) the human health and economic benefits of protecting Indigenous territories. Because increases in $PM_{2.5}$ can harm human health[33,34], our hypotheses are that (I) forest areas, and the conservation of Indigenous territories can protect human health through the provision of air quality services and bring important economic benefits; (II) this ecosystem service can be maximized if forest areas are in a less fragmented state.

Results

How much $PM_{2.5}$ is being released into the atmosphere in a 10-year period. The $PM_{2.5}$ generated by the burned Amazon Forest presented a high correlation with the observed fires ($r = 0.89$) and had an impact on populations within 500 km of the fire event. This means that the $PM_{2.5}$ generated can disperse for up to 500 km from its fire source for one year. On average, 889,882.3 μg of $PM_{2.5}$ was accumulated every 500 km between 2010 and 2019 (with a total of 1.68 tons $year^{-1}$ for the entire region). The year 2010 had the highest concentration of $PM_{2.5}$, with 1,186,430 μg, followed by 2019, while all other years showed similar values. In addition, most of the pollution is concentrated in the western and southern Amazon, with small variations from year to year that probably occur given the direction and speed of the winds (Fig. 1). This pattern is confirmed when we see the ratio of the amount of $PM_{2.5}$ released for each hectare of burned forest, indicating that a large part of $PM_{2.5}$ moves to areas where there are no fires occurring (Supplementary Fig. 1).

How much $PM_{2.5}$ could potentially be absorbed by forest areas and Indigenous territories. During the analyzed years, the Amazon Forest had the potential capacity to absorb an average of ~8,5 billion μg of $PM_{2.5}$ (8,448,858,000) every 500 km $year^{-1}$, with a total of 26,376.66 tons $year^{-1}$ for the entire region. The Indigenous territories alone were responsible for 27% of this potential absorption (7192 tons $year^{-1}$), with only five territories (Vale do Javari, Yanomami, Alto Rio Negro, Mekragnoti, and Trombetas; numbers 1–5 in Fig. 3) being responsible for 8% of the total potential absorption capacity of the entire Amazon. Spatially, the lower absorption capacity was concentrated in the

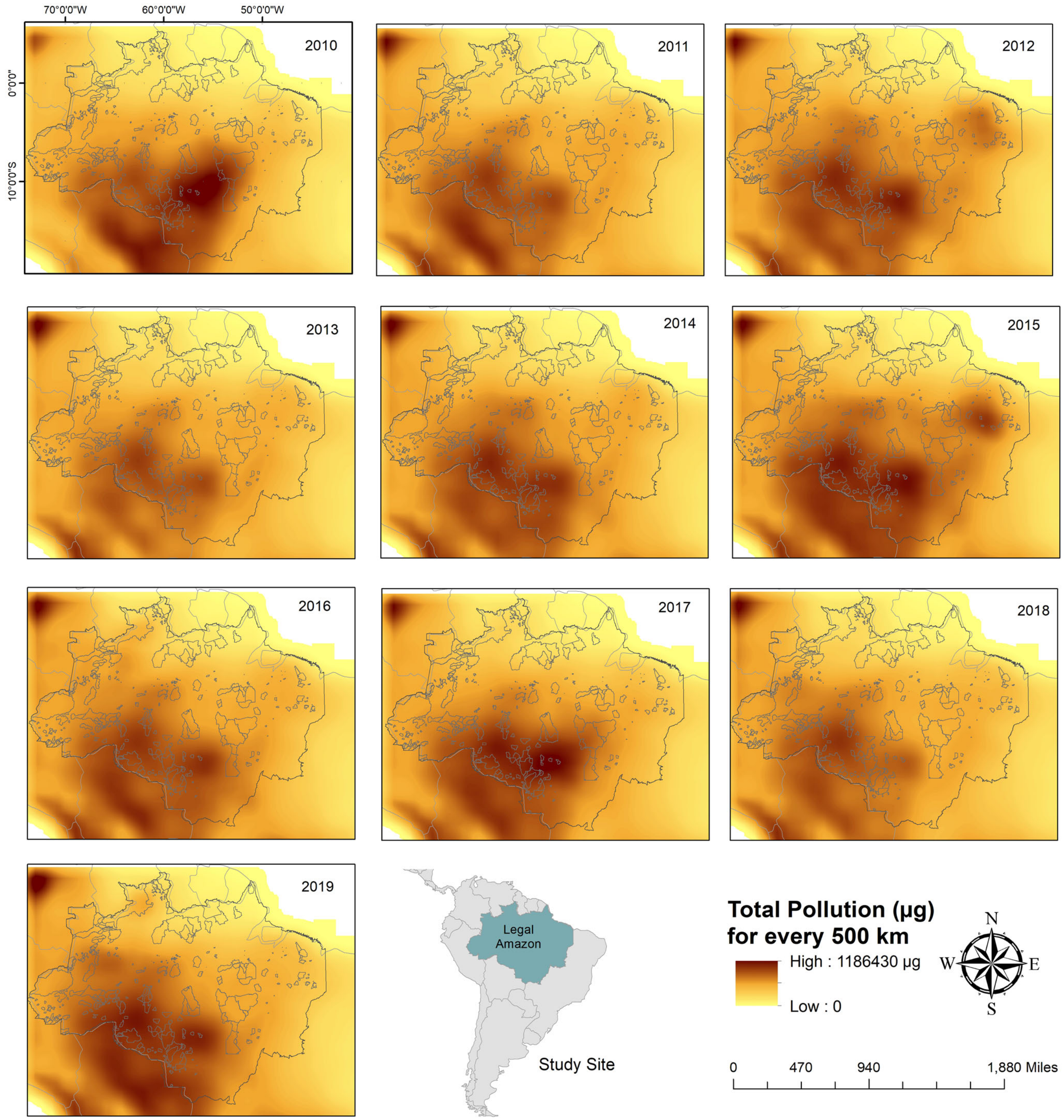

Fig. 1 PM$_{2.5}$ temporal trends. Temporal trends of PM$_{2.5}$ released by forest fires (in µg) in the Brazilian Legal Amazon, with the wind dispersion effect of 500 km square, and the study area location. The Brazilian Legal Amazon boundary is shown in gray on the maps, together with the Indigenous territories present in the region.

southernmost part, which corresponds to the Brazilian arc of deforestation region (Supplementary Fig. 2).

How is PM$_{25}$ affecting human health?. During the same period, there were 1,429,134 cases of respiratory and cardiovascular infections related to forest fires in the 772 municipalities that compose the Brazilian legal Amazon (an average of 142,913.4 cases per year), or an average of 586.87 cases per 100,000 population. In addition, 168,663 cases were reported in the Indigenous territories (227 cases per 100,000 population). The year 2011 had the highest number of cases and incidences (>160,000) within municipalities, followed by 2010 and 2013 (>150,000), while 2016 presented the lowest (119,123). For the Indigenous territories, 2019 showed the highest incidence of respiratory and cardiovascular diseases, while 2010 was the lowest (Figs. 2, 3), with an increase of 165% from 2010 to 2019. Spatially, the arc of deforestation part of the Amazon was the region with the highest average incidences of infections reported, while the west part had the lowest (Fig. 2). For the Indigenous territories, Kayabu (number 6 in Fig. 3) presented the highest incidences with 41,277 cases per 100,000 people, followed by the Panara

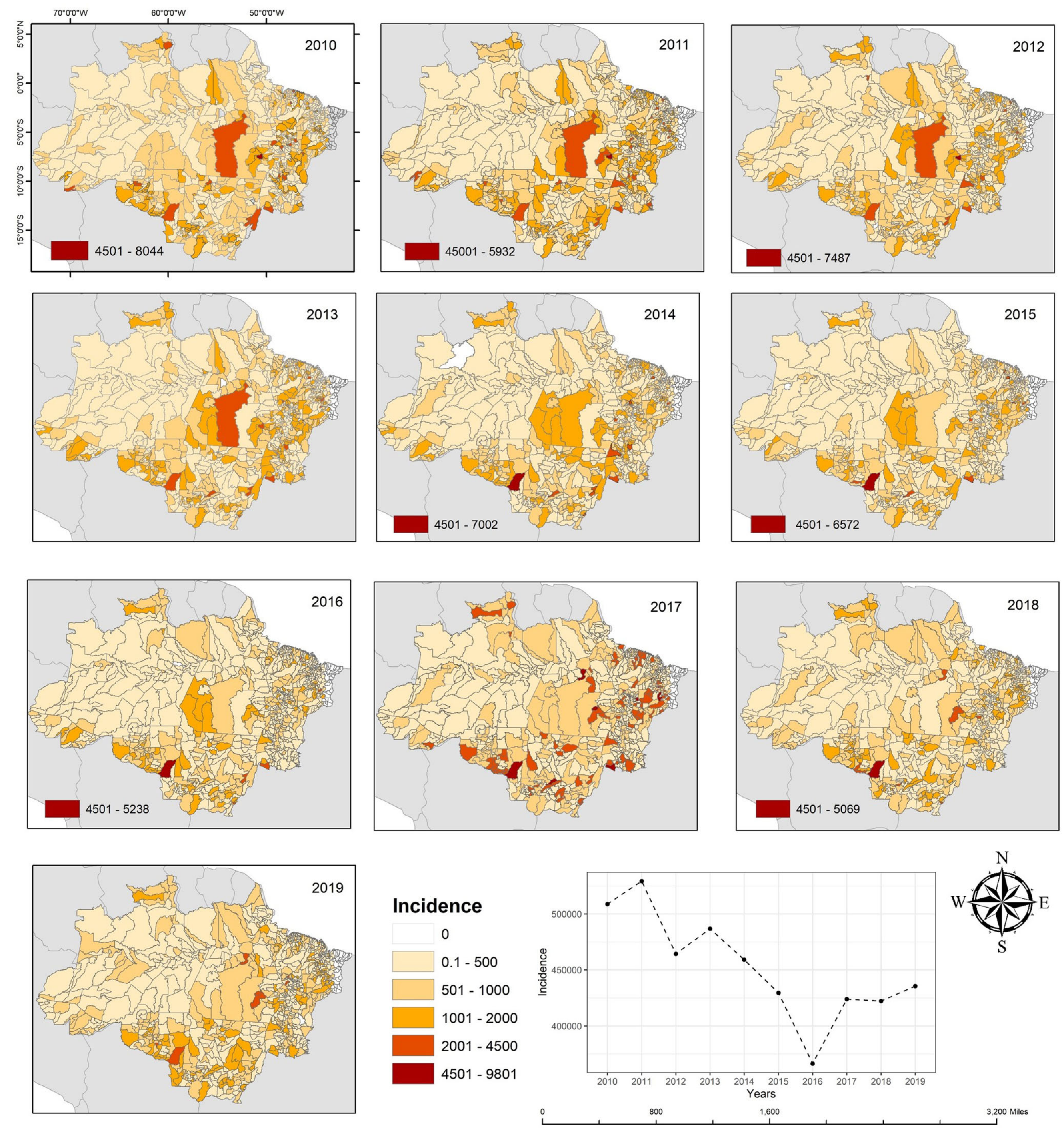

Fig. 2 Fire-related disease incidence. Incidence of respiratory and cardiovascular infections for the entire Legal Amazon on a municipality basis from 2010 to 2019.

(23,392; number 7 in Fig. 3) and the Sete de Setembro (14,939; number 8 in Fig. 3), all located in the arc of deforestation part of the Amazon (Fig. 3).

The number of respiratory and cardiovascular infections reported in both the Amazonian municipalities and in the Indigenous territories between 2010 and 2019 showed a positive relationship with the amount of $PM_{2.5}$ released in the atmosphere (Tables 1, 2 and Supplementary Fig. 3). Our model also indicated that for every increase of 1 kg of $PM_{2.5}$, there were 21 new infections reported in the entire Brazilian Amazon (with an error of ±0.1) and two new infections reported in the Indigenous territories (±1).

How is the relationship between human health and forest structure? The number of respiratory and cardiovascular infections reported in both the Amazonian municipalities and the Indigenous territories also showed a significant relationship with the structure of the forest areas. For the Amazon in general, only one model containing the amount of forest areas (present in the entire municipality and including the Indigenous territories) and the fragmentation index was selected to explain the variance in the number of infections, with a weight of evidence of 91% (Supplementary Table 2 shows the AIC and weight of evidence of all the models evaluated). Both variables presented a negative relationship, revealing that the more forested areas a municipality

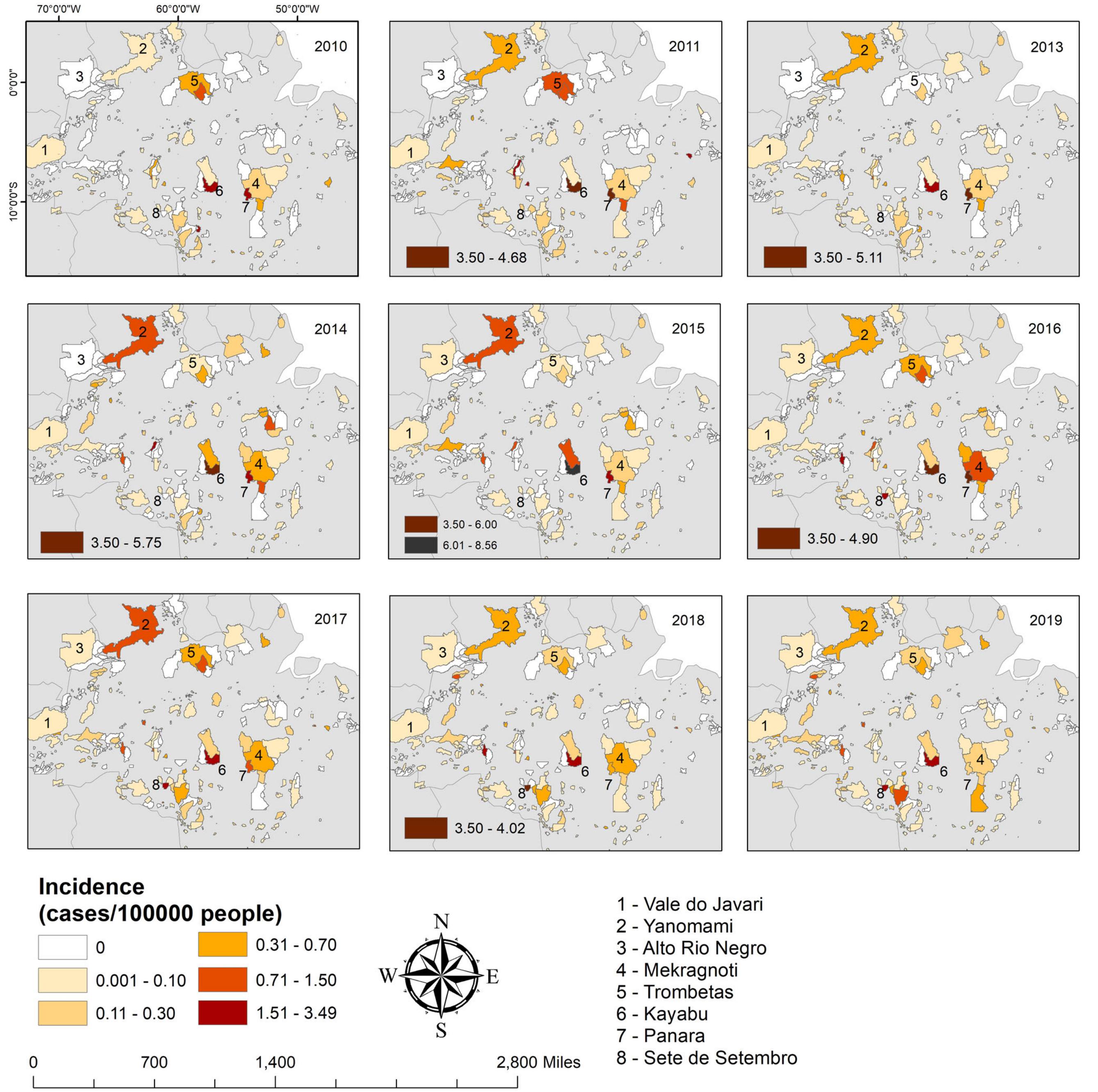

Fig. 3 Fire-related disease incidence for Indigenous people. Incidence of respiratory and cardiovascular infections for the Indigenous territories, from 2010 to 2019. The Indigenous territories 1–5 listed on the maps are the ones with the highest $PM_{2.5}$ absorption capacity, and numbers 6–8 are the territories with the highest incidences.

Table 1 Parameter and standard error (Sd) estimates for the entire Amazon-municipalities scale—Spatial model.

Parameter	Estimate	Std Error	*P* value
Intercept	5.119308	0.001485	$2^{e-16***}$
$PM_{2.5}$	0.232451	0.001124	$2^{e-16***}$
Year	2.04^{e-06}		$2^{e-16***}$
Gini Index	1		$2^{e-16***}$
Municipality (spatial effect)	2.9		$2^{e-16***}$

PM2.5 is the fixed effect, while Year, Gini Index, and the municipality centroids are the random effects.

Table 2 Parameter and standard error (Std error) estimate for the Indigenous territory model.

Parameter	Estimate	Std error	*P* value
Intercept	2.2670	0.2349	$2^{e-16***}$
$PM_{2.5}$	0.7166	0.1512	$2.15^{e-06***}$

has, and with a low level of fragmentation (<10 patches/100 hectares), the lower the number of reported infections (Supplementary Table 3 and Fig. 4). Our model also indicated that deforesting 1% of forest areas in each municipality could generate 82 new infections (with an error of ±4 cases). For the Indigenous

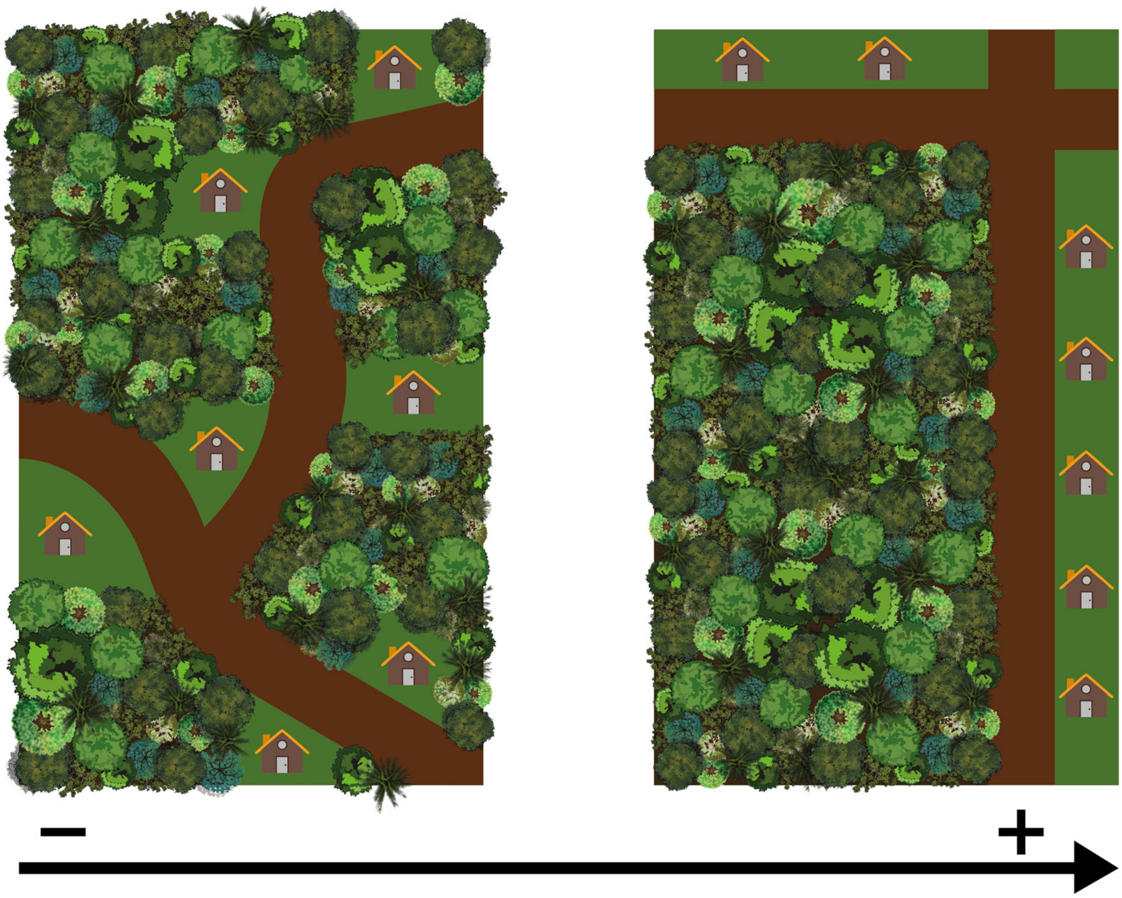

Fig. 4 Landscape structure and human health outcomes. Graph theory shows a landscape configuration that presents less pollution (–) and consequently is more beneficial to human health and more pollution (+) and is detrimental to human health considering fires-related infections.

territories, we also had just one model selected which contained the variables fragmentation and aggregation index. According to this model, the higher the fragmentation of the Indigenous territories, the lower the number of infections reported among Indigenous people. However, since the aggregation index was also selected, this indicates that forest fragments cannot have high isolation, showing that slightly fragmented but highly proximal forest fragments have an apparently suitable configuration for Indigenous health (Fig. 4).

What are the economic costs of forest fires? Using municipality-level data on total health costs obtained from the Brazilian Ministry of Health and total cases of fire-related diseases from our analysis, we completed a back-of-the-envelope calculation to find the average cost per hospitalization and treatment for each case to be R$ 635.34 (Brazilian Real) or $132.28 USD. This means that for every additional kilogram of $PM_{2.5}$ released into the atmosphere, there is an estimated cost of $2,777.90 USD every year. However, as these costs vary per municipality (i.e., the price of hospitalization and treatment are not uniform throughout the Amazon), some locations can present losses as high as $9,913 USD for one kilogram of $PM_{2.5}$ released (Fig. 5a).

It is worth noting that these values refer to an increase of only 1 kg of $PM_{2.5}$ in the environment. Some studies indicate that one hectare of Amazon Forest can release from 124 to 1926 kg of $PM_{2.5}$[35]. Assuming an average of these values—760.5 kg of $PM_{2.5}$, one hectare of Amazon burned could generate an estimated cost of $2,112,595 USD, only considering respiratory and cardiovascular infections. The maximum cost observed could reach $7,538,369 USD (Fig. 5b).

What are the human health and economic benefits of protecting indigenous territories? Our results indicate that Indigenous territories are responsible for 27% of the $PM_{2.5}$ absorption. Moreover, deforestation of 1% of each municipality could generate 82 new respiratory and cardiovascular infections (with an error of ±4 cases). This means that by maintaining the protection of these territories, 700,000 kg of $PM_{2.5}$ could be absorbed every year, which could avoid 15 million cases of respiratory and cardiovascular infections and could save $2,079,000,000 USD in health costs every year.

Discussion

We provide insights relating the presence of forest areas and Indigenous territories in the Brazilian legal Amazon to human health. Our results demonstrated that the Amazon Rainforest could absorb an average of ~26,000 tons of $PM_{2.5}$, with the Indigenous territories being responsible for 27% of these. Respiratory and cardiovascular cases were directly affected by the amount of $PM_{2.5}$, with an increase of 1 kg of $PM_{2.5}$ leading to 23 new infections. A key finding of our study is that one hectare of forest burned could generate an average estimated cost of $2 million USD. Human health was also affected by the amount and configuration of forest areas - municipalities with larger amounts of forests and low fragmentation presented better health outcomes. Our results indicate that maintaining the protection of the Indigenous territories could avoid 15 million respiratory and cardiovascular cases, saving $2 billion USD in health costs per year. These results can be used to promote conservation actions and guarantee the rights of Indigenous people in the Brazilian Amazon.

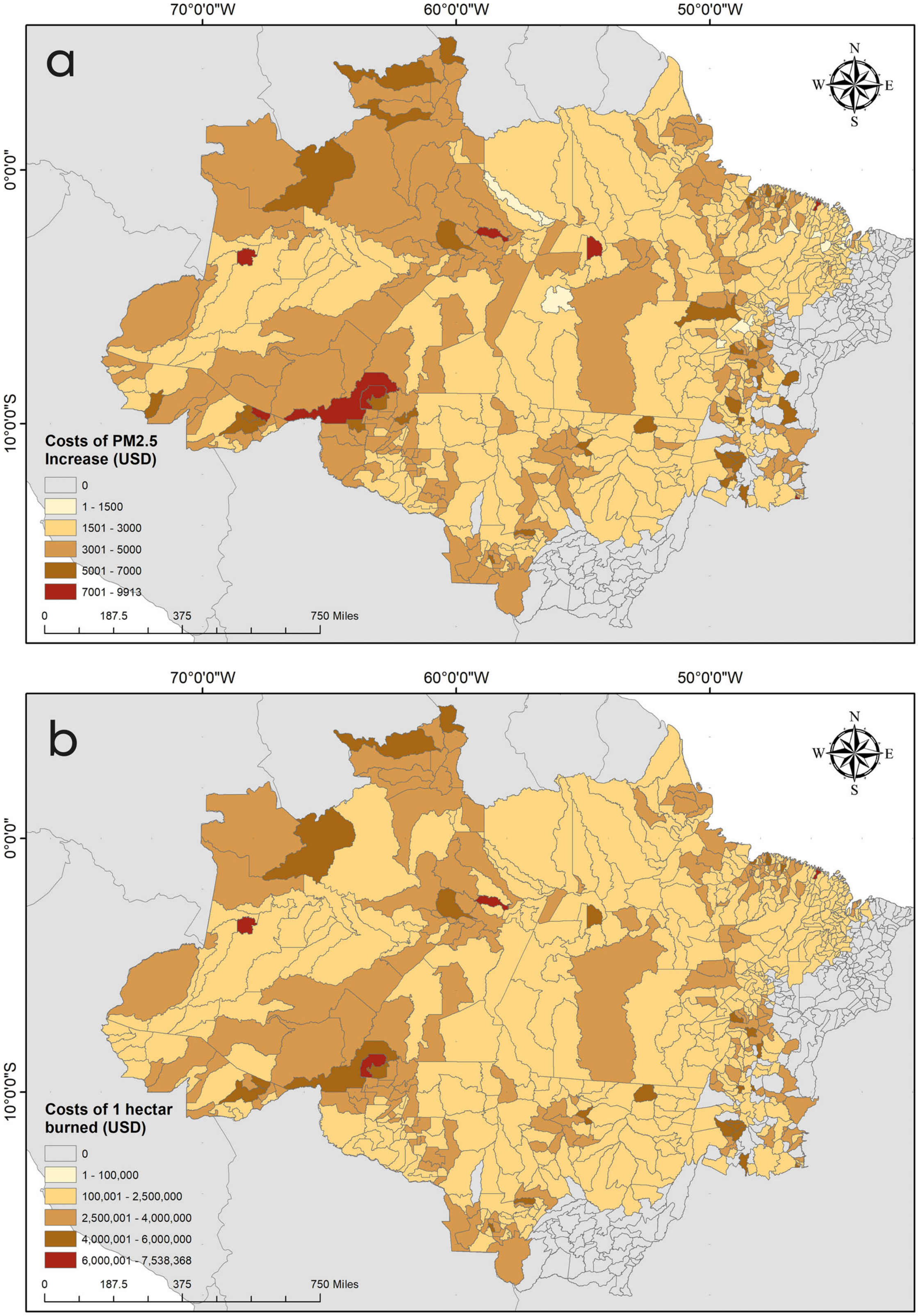

Fig. 5 Economic costs of forest fires. Economic costs associated with the increase of (**a**) 1 kg of $PM_{2.5}$ and (**b**) one hectare of Amazon burned, in USD.

Vegetation fires are an important source of particulate matter (PM) and trace gasses to the atmosphere[36]. For the Brazilian Amazon, studies have shown that biomass burning is the dominant particle source, accounting for more than 90% of the fine particles observed[17,36]. This happens especially during the dry season[17,37], when large parts of this region become among the most polluted places on Earth[37]. Our study corroborates these findings, with high correlations between the total estimated $PM_{2.5}$ and the number of forest fires. In addition, our results showed a high concentration of this pollutant in the western part of the

Amazon, as also found by ref. [36]. This could be explained by the wind speed and direction which play an important role in the atmospheric composition in the Amazon[38]. During the wet season, there is a northeastern wind from the Atlantic Ocean, while in the dry season, the predominant wind comes from Southeast[38]. Since our analysis had a time scale of one year, the result of $PM_{2.5}$ accumulation may be due to both wind streams, resulting in an annual accumulation in the westernmost region of the biome.

The concentration of pollutants in the ambient air depends not only on the quantities that are emitted but also on the ability of the atmosphere to either absorb or disperse these pollutants[39]. Forest areas remove gaseous air pollution primarily by uptake via leaf stomata[40], enhancing air quality. Because of that, several studies have tried to understand the effects of forest areas in removing air pollutants in an urban context[41,42], with a lack of studies for rural and non-urban areas. Our study tries to fill this research gap by providing an estimate of this ecosystem service for the entire Brazilian Amazon: 26,000 tons $year^{-1}$ is the potential absorption capacity of $PM_{2.5}$. A key finding of this study is that Indigenous territories are responsible for 27% of this absorption. This is probably related to the size of the territories and the presence of forest within them, since the greater the tree cover, the greater the pollution removal[40]. However, the Indigenous territories correspond to almost 22% of the Amazon region, presenting estimates of pollutant absorption greater than their corresponding area.

We have found no studies in tropical areas to compare with our values, but a study with urban trees in Barcelona found a potential of PM_{10} removal of 166 tons per $year^{-1}$ [43]. In comparison, another study found 711,000 tons $year^{-1}$ removed from USA urban forest areas[41]. Our numbers are probably underestimated because there are no pollutant deposition rates calculated for tropical trees. Vegetation characteristics are important factors defining pollutant absorption (i.e., as tree species, diameter at breast height, total height, and crown width), and since tropical trees are different from temperate trees by having overall larger values of diameter, height, and width, deposition rates may be larger too.

In addition, although the analyses were performed on an annual time scale, we are assuming that both forest fires and the absorption of pollutants are happening only during the dry season because pollutant dispersion depends greatly on meteorological variables, being negatively affected by wind speed, relative humidity, and precipitation[39]. During precipitation, particles can be washed off and either dissolved or transferred to the soil. Consequently, vegetation is only a temporary retention site for many atmospheric particles, and particles are eventually moved back to the atmosphere or moved to the soil[41]. Further research is needed to advance our understanding of the role of tropical trees in air purification[44], and how meteorological effects influence pollutant absorption in the Amazon. In addition, there is probably a limit at which the forest can absorb pollutants—above which the service is no longer performed—and very high pollutant concentrations could severely damage vegetation or lead to stomatal closure, reducing air pollution removal ability[45]. Unfortunately, these environmental thresholds have not been investigated yet.

Wildfires are a growing concern around the globe due to increasingly drier conditions brought on by climate change[46], and it is predicted that we will see an increase in morbidities and mortalities related to wildfires and smoke[47]. In South America specifically, modeling studies have estimated that regional fires are responsible for thousands of premature deaths per year[22,36], with various acute and chronic illnesses being associated with wildfire smoke[46]. $PM_{2.5}$ has been shown to cause endothelial and vascular dysfunction, oxidative stress, thrombosis, and metabolic dysfunction, all of which can contribute to cardiac effects[48]. For the respiratory system, toxicology studies have found that $PM_{2.5}$ from wildfires induces significant lung toxicity and mutagenic potency[49] and increases neutrophils and protein in lung lavage, as well as a histologic indication of increased cell influx and edema in the lung[50].

Due to the overwhelming evidence of harm caused to the cardiovascular and respiratory system by wildfires and smoke, we focused on disease types of that nature for our study (see Supplementary Table 1 for a list of diseases included). To capture the largest impact of $PM_{2.5}$ emission on disease occurrence, we grouped case numbers for an umbrella variable of cardiovascular and respiratory cases and found a positive relationship, as also evidenced by other studies[15,36]. This grouping causes our study to simplify the effects of fire on human health and lose nuance on which diseases may be more exacerbated by the presence of increased fires in the Amazon. However, due to the barrier to healthcare and lack of extensive healthcare for chronic illnesses experienced by many in the Amazon rainforest[51], we believe that publicly available health datasets are not capturing all respiratory and cardiovascular diseases caused by wildfires in the region, and that our modeled predicted increase in disease may be underestimated. In addition, not every person affected seeks medical care after symptoms of cardiorespiratory diseases during wildfire episodes, which contributes to potential underestimates of our case numbers and results.

Our results also established a significant relationship ($p \leq 0.05$) between human health and the presence and configuration of forest areas. According to our model, municipalities with larger amounts of forest in a slightly fragmented configuration, can have better health outcomes than municipalities with low amounts of forest cover. For the Indigenous health (that was associated with the forest areas of the Indigenous territories) the result was similar, with higher fragmentation but low forest isolation presenting better outcomes. Studies evaluating the effects of forest areas on human health are not new and have shown similar results, with positive effects of forests on human health[52].

Some studies have indicated that areas with large greenspaces or greater tree cover have a higher reduction of particulate matter concentrations[40,53], corroborating our results. However, the configuration of forest areas presents controversial results, with some studies indicating that less fragmented areas are better able to provide this service[53], while others found the opposite effect[54,55]. Here, we hypothesize that the ability of forest areas to absorb pollutants is related not only to the amount but also to the spatial arrangement of these forest areas. Thus, the larger the green area, the greater the provision of this service. However, a slight degree of fragmentation can contribute to a better flow of this service, since the population ends up being closer or even in between the forest areas, when compared to the less fragmented forest areas that consequently isolate human populations. For Indigenous health, since Indigenous territories have high amounts of forest cover, the hypothesis is the same, but it also includes a connection between forest areas. Furthermore, forest configuration can also have an impact on a deposition by assisting or altering wind profiles and therefore in pollutants' dispersion, since trees may act as physical barriers preventing pollutants' penetration into certain areas[56]. Thus, slightly fragmented areas may contribute to greater pollutant uptake compared to unfragmented areas.

It is worth pointing out that this result should not be seen as an excuse in favor of habitat fragmentation for a few reasons: (1) our results pointed out that such fragmentation can contribute to human health only in large amounts of forest cover and if it exists on a small scale (low number of fragments per hectare). So, this result only reinforces a pattern of forest area configuration and not quantity. Still, more studies are needed to corroborate this result and especially to find a threshold of coverage and fragmentation beyond which the provision of this service is lost; (2) more fragmented forest areas can also increase the transmission risk of zoonotic diseases[57,58]. Therefore, trade-offs within the human health maintenance service must be better balanced and evaluated. Further examinations of the relationship between forest structure, fire smoke-related illness, and zoonotic disease transmission risk may contribute to a better understanding of what a healthy landscape would look like in this region, leading to strategies that enable the formation of multifunctional and healthy landscapes.

Indigenous territories in Brazil are established by federal jurisdiction to guarantee the land rights of Indigenous people, their social organization, and the maintenance of their cultural values[59]. However, research has shown that they have a much broader role: they act as a buffer to frontier expansion by reducing deforestation[60] and fire occurrence[61], safeguard bat diversity[62], avoid millions of tons of carbon emissions[63], and contribute to effective conserve tropical forests and their ecosystem services[8,64,65]. These territories have a specific policy to prevent and combat fires, the Federal Brigades, which combines traditional knowledge to fire management and to reduce the impacts caused by uncontrolled fires. However, this program is not included in all territories, which increases fire vulnerability[64]. Here we show another still unstudied point of importance for these territories - their conservation can also contribute to the maintenance of human health. Forest areas of Indigenous territories, when added to models estimating the impact of municipality forest coverage on cardiovascular and respiratory diseases, become the most important variable to explain the number of disease cases reported within the entire Amazon population. Thus, the deforestation of these territories would lead to a reduction in the forest cover of the municipalities, a loss of the pollutant absorbing service, and an increase in the number of reported infections, generating economic costs. This is a preliminary estimate of the health service provided by these areas, so further studies should be carried out to corroborate our results and better understand the mechanisms associated with it.

Our results indicate that when one hectare of Amazon Forest is burned, it could generate a cost of ~$2 million USD considering only respiratory and cardiovascular infections and that by protecting Indigenous territories, 15 million cases could be avoided every year, saving $2 billion USD to the Brazilian government. Nowak et al.[66] found annual monetary values associated with $PM_{2.5}$ removal in the United States ranging from $1.1 million to $ 60.1 million USD, and $6.8 billion in another study considering the entirety of the United States[40]. Our values are not directly comparable to this study, but show similar results, especially when we look at the monetary value associated with the Indigenous territories' protection.

It is worth acknowledging that this is a first estimate of the cost associated with human health services for the Amazon Rainforest and Indigenous territories and can be viewed as lower bounds for total costs due to several reasons. First, the above costs are strictly morbidity related, and do not include mortality costs. Second, we currently have no data that accounts for the costs of lost working hours and disturbed livelihoods from destroyed forest areas, i.e., ecosystem services. Lastly, we do not have the costs associated with Indigenous people and thus, we can expect even higher associated costs than what are stated here. Still, it is worth noting that these costs were estimated based on the hospitalization and treatment costs provided by DataSus, and that they vary for each municipality. Therefore, although the average cost for all the municipalities in the region is almost $2 million USD for every hectare burned, the maximum cost observed could reach ~$8 million USD. Furthermore, these costs are not considering people who attend private healthcare systems or those who have mild infections and do not go to healthcare providers but still have treatment costs.

Conservation implication and limitations. Our study provides evidence that air pollution from forest fires is associated with a higher risk of respiratory and cardiovascular infections in the Brazilian Amazon, generating a high cost for the affected municipalities. In addition, it also provides evidence that forest areas can provide an ecosystem service of $PM_{2.5}$ absorption, contributing to the maintenance of human health and generating considerable economic benefits. Our results also support that conserving Indigenous territories can bring great human and economic benefits, providing a further argument in favor of Indigenous land ownership. In addition, our results could be used by Amazonian health agencies to better prepare health expenses and support the creation of public policies and regulations against forest fires.

However, our results have some limitations, part of which have already been commented on. Our estimates present a first-order approximation of the magnitude of $PM_{2.5}$ absorption capacity by the Amazon forest areas and should not be seen as a precise quantification of this ecosystem service because: (1) we are not estimating actual removal, but only theoretical deposition rates, because we are not including local meteorological factors and consequently the specific $PM_{2.5}$ real resuspension rate, which could affect results; (2) we decided not to include meteorological factors due to our time scale of one year masking any seasonality effects, causing added uncertainty due to the complexity of this process[67] such as non-homogeneity in the spatial distribution of air pollutants, particle resuspension rates, transpiration rates, or soil moisture status[44]; (3) our $PM_{2.5}$ estimation was done with satellite data, since meteorological stations are almost nonexistent for the Amazon region, which may lead to underestimates of the amount of pollutant that remains closer to ground height.

Despite the limitations, our results allow us to evaluate the contribution of the Amazon Forest and the Indigenous territories to the maintenance of human health, and the economic benefits that its conservation can bring, and could be used as evidence for forest and Indigenous territories protection.

Methods

Study area. We focused our analysis on the Brazilian Legal Amazon, which is a socio-political division that encompasses 772 municipalities, covering approximately 5 million km^2 and 59% of the Brazilian territory (Fig. 1).

Health data. Respiratory and cardiovascular infections cases for each Brazilian municipality, were obtained through the Brazilian Ministry of Health, the DataSus platform (available at http://tabnet.datasus.gov.br/cgi/deftohtm.exe?sih/cnv/nrbr.def). This data is organized by the municipality and for years between 2010 and 2019. In 1988, Brazil established universal and egalitarian access to health care as a constitutional right. In the following years the Unified Health System (the SUS) was introduced, guaranteeing free universal health coverage for the Brazilian population. Although the private health system still exists, the great majority of the population in the Amazon region are users of the universal health system, SUS, due to the lack of resources.

Respiratory and cardiovascular infections cases for the Indigenous population were available from 2010 to 2021 and organized by Indigenous territories; data was obtained through the Indigenous Health Division of the Ministry of Health and granted through the law of access to information (Law n° 12.527/2011; request number 25072.015598/2021-51). For both scales (entire Amazon and Indigenous territories), we decided to exclude the years of the COVID-19 pandemic, 2020 and 2021, to avoid any confounding factors. The diseases selected for the analysis were those associated with exposure to smoke from forest fires (see Supplementary Table 1 for a list of diseases).

Incidence was calculated by dividing the total number of cases in a specific year by the total population of each municipality in that same year and multiplying by 100,000. This data was obtained through the Brazilian official census— Brazilian

Institute of Geography and Statistics (IBGE, available at: https://sidra.ibge.gov.br/Tabela/136). However, as this data is only available for the years 1991, 2000, and 2010, we used the IBGE population projections for all the other years (available at https://sidra.ibge.gov.br/tabela/6579). For Indigenous lands, the incidence was calculated by dividing the number of cases by the total number of people in each Indigenous land, obtained also through IBGE (https://sidra.ibge.gov.br/pesquisa/censo-demografico/demografico-2010/universo-caracteristicas-gerais-dos-indigenas). Since this data is available only for the year of 2010, we used this data to calculate the incidence for all the years for which we have health data and had to assume that the population is static.

Land use land cover data and landscape metrics extraction. Land use land cover data was extracted from Mapbiomas mapping Collection 5 (Rosa 2016, available at http://mapbiomas.org/), with 30-m spatial resolution and available from 1985 to 2020. This mapping has 41 land cover classifications: forest, savanna, grassland, pasture agriculture, other non-vegetated areas and river, lakes, and oceans. A detailed methodology for the mapping can be found at https://mapbiomas.org/download-dos-atbds.

For each municipality and Indigenous territory of the Brazilian Amazon, we extracted landscape metrics of composition and configuration for years coinciding with health and pollution data (2010–2019). Landscape composition was measured considering the relative abundance of each landscape unit (percentage of forest cover and other agricultural uses), the diversity of land uses, and the percentage of forest loss in relation to the previous year. Landscape configuration refers to the degree of fragmentation, the size of the largest fragment present, the aggregation index (distance between forest fragments), and the area of forest edges. For every municipality, we also measured the amount of forest cover present only in the Indigenous territories in order to understand if these areas alone can provide health services for the entire population in each municipality. All landscape analyses were done in R, ArcGis 10.8.1, and Fragstats 4.2.

In addition to the landscape structure variables, we used the Gini index, available for the year 2010 for each municipality in the Legal Amazon territory, as a way to control for possible socioeconomic effects. This variable is available from IBGE (available at: http://tabnet.datasus.gov.br/cgi/ibge/censo/cnv/ginibr.def), and it measures how equitably a resource is distributed in a population[68].

$PM_{2.5}$ estimation. We used the NASA MODIS Active Fire (MOD14A1V6) and MAIAC Land Aerosol Optical Depth (MCD19A2 V6) products to assess fire frequency and spatial distribution between 2001 and 2020. MODIS Active Fire (MOD14A1V6) daily data at 1 km resolution was processed to keep only the best quality pixels (as defined by the QA band) and to extract the total number of fires per pixel and within each municipality per year. Daily MAIAC AOD images at 1 km spatial resolution from 2001 to 2020 were masked to keep only pixels deemed as best quality within the QA band (bits 8–11: 0). The mean yearly AOD was calculated at each pixel considering only those best quality values. MAIAC AOD is a good proxy for $PM_{2.5}$ ground concentrations[69]; however, it needs to be calibrated into $PM_{2.5}$ concentrations to be suitable for health impact analysis. Due to the scarcity of $PM_{2.5}$ in situ measurements, MAIAC was calibrated into $PM_{2.5}$ using concentrations from NASA's Socioeconomic Data and Applications Center (SEDAC, with 1 km resolution) as a reference through a pixel-level temporal OLS regression. For each 1 km pixel, a temporal linear regression was extracted between AOD (dependent) and $PM_{2.5}$ (independent). The results of this are, for each pixel, a slope and intercept coefficients that were then applied to the complete MAIAC AOD time series 2001–2020 to transform the AOD values into $PM_{2.5}$. Finally, the average $PM_{2.5}$ in each municipality was calculated. All analyses were done in Mollweide equal-area projection. The calibrated AOD-$PM_{2.5}$ product showed a high correlation with the SEDAC $PM_{2.5}$ for the years of overlap—Pearson $r > 0.85$. $PM_{2.5}$ analysis was done in TerrSet Geospatial Analysis Software.

Since the pollution generated by forest fires could be displaced by the wind over large distances, we performed a simple variogram analysis to identify how far this displacement occurred within a 1-year period. After identifying the radius of effect, which was 500 km, we calculated how much total pollutant accumulated within this radius as a proxy of total pollutants affecting human health by using a moving window approach. We also calculated the amount of forest cover and burned area within the same radius.

Ecosystem Service of $PM_{2.5}$ absorption by forest areas. One of the benefits of forest areas is the air quality amelioration function by altering the concentration of air pollutants[70]. To estimate this service and to calculate the total amount of $PM_{2.5}$ that is potentially absorbed by the Amazon Forest and Indigenous territories every year, we based our analysis on the UFORE-D model[71]. This model calculates the hourly dry deposition of pollutants by using meteorological data, tree cover data, and specific deposition rates for each pollutant[72]. We adapted the formula proposed in ref. [73] and considered that there is absorption only in the dry season—the same season in which fires occur, because there is no absorption on rainy days. For this, we calculated the area of forest present in a 500 kilometers radius by using a moving window approach. With the resulting map, we applied the formula:

$$\mathrm{PM2.5_{abs}} = \mathrm{A(m2)} * \mathrm{dv(ms-1)} * \mathrm{t(year)} \quad (1)$$

Where $PM_{2.5abs}$ is the potential pollution absorption capacity (unit m^3/year); A is the forest cover area, dv is the average dry deposition velocity for the pollutant (0.0043 m/seg), and t is the time step transformed for a 1-year period[73]. We are also assuming that the entire Amazon has a similar leaf area index, since studies using the normalized difference vegetation index derived from Advanced Very High-Resolution Radiometer data have shown little variation in the phenology of Amazonian forests[74].

We applied the same moving windows approach to the fire data, calculating the total area burned within a 500 km radius. Dividing the total amount of pollutants in this radius by the area burned in the same radius, we get the amount of pollutants generated for each hectare of forest burned. This allowed us to understand the areas with excess pollutants relative to the number of fires, indicating dispersion.

Statistical analysis. To understand how the health of Amazonian and Indigenous people is related to the amount of $PM_{2.5}$ released into the atmosphere by forest fires, we performed multiple regression analysis considering the number of cases as the response variable and the amount of $PM_{2.5}$ as the predictor variable. A multiple regression model is a theoretical statement about the causal relationship between one or more independent variables and a dependent variable[75]. For this first question, we hypothesized that the emission of $PM_{2.5}$ leads to an increase in cases of respiratory and cardiovascular diseases. Thus, we created a simple model with only the amount of $PM_{2.5}$ emitted year by year as the predictor variable. However, since there may be variations that are not captured by the model, which may be related to socioeconomic aspects, or the years of sampling, for the Amazonian model we included the year and the Gini index as a random effect. For the Indigenous territories, we included the year and the Indigenous territories as random effects since socioeconomic variables are not available for this spatial scale. Model fitting was done using generalized linear mixed-effect models (Glmer) with a Poisson family error distribution (lme4 package in *R* v. 2.1.0.1; R Development Core Team 2008) for the municipality scale and with a negative binomial distribution for the Indigenous land, and by using year and the Gini Index (only for municipality scale) as a random effect to account for differences among administrative units not captured in the fixed covariates. The choice of model to be used (Glmer) was made after comparisons with Glm models without the use of random effects. The best functional form used was chosen after performing a normality test (p <indicating non-normal data), and after different functional forms were applied to the same model (Poisson, zero-inflated Poisson, and negative binomial). The best link function was chosen using the model with the lowest AIC.

In both models (Amazon and Indigenous people), residuals were tested for spatial autocorrelation by calculating Moran's I with the inverted distance matrix. This test is commonly used and accepted as a fair evaluation of spatial autocorrelation and dependence, especially in disease studies[76]. For the municipality scale, the results showed spatial (Moran's I, $p = 0.0001$) autocorrelation. So, we modeled the effects of $PM_{2.5}$ on human health using a spatial model (*mgcv* package), maintaining the same structure of the previous model, with year and Gini Index as random effects, but including the spatial component. The Indigenous territories scale did not present spatial autocorrelation, so we used the Glmer results.

To understand how the health of Amazonian people is related to the amount and configuration of forest areas present in the Indigenous territories and the municipalities, we performed multiple regression analysis considering the number of infections as the response variable and the different landscape metrics as predictor variables. We conducted an exploratory data analysis to select only those explanatory variables with a relatively low correlation (Pearson's $r < 0.70$[77]). Model fitting was done using generalized linear mixed-effect models (Glmer) with a Poisson family error distribution (lme4 package in *R* v. 2.1.0.1; R Development Core Team 2008), and by using year and the municipality as a random effect to account for differences among administrative units not captured in the fixed covariates. The choice of model to be used (Glmer) was made after comparisons with Glm models without the use of random effects. We created seven models to test different hypothesis, which guided the choice of the predictor variables in each model: (1) null model: number of cases varies at random and has no influence of the forest areas; (2) the number of cases in municipalities is affected by the amount of forest areas present in Indigenous territories; (3) the number of cases in municipalities is affected by the amount of forest areas outside Indigenous territories; (4) the number of cases in municipalities is affected by total amount of forest areas present in the municipality (both inside and outside protected areas); (5) the number of cases is higher in municipalities with a higher number of land uses types; (6) number of cases is higher in municipalities with fragmented and isolated forest areas; (7) number of cases in municipalities will be affected not only by the amount of forest areas in Indigenous territories, but also by the fragmentation and isolation of these areas (see Supplementary Table 2 for a list of all models tested and their results). For model selection, we conducted a maximum likelihood model selection procedure, considering the second-order Akaike's information criterion (AIC)[78], and choosing the model with the lower AIC. With this approach, a lower AIC indicates the model better fits the data. We also calculated the difference between AIC for all the models and the lowest observed AIC. According to ref. [78], models with ΔAIC <2 are equally plausible to explain the observed pattern as the best model.

From the best-supported model, we extracted how much an increase in each variable could lead to an increase in the response variable (number of human cases), and from this, we estimated the economic costs involved. Base data on treatment hospitalization costs for the same diseases analyzed were obtained for each year and for each municipality from DataSus.

Data availability

The datasets generated during the current study are available at https://doi.org/10.17605/OSF.IO/T4H25[79].

Code availability

The codes generated and analyzed during the current study are available at https://doi.org/10.17605/OSF.IO/T4H25[79].

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Author contributions
P.R.P., F.S., M.d.C.V.-S., P.D., and C.Z.T. conceived and designed the research; P.R.P., F.S., M.d.C.V.-S., V.B., and N.P.-Q. were responsible for data analysis. P.R.P., F.S., and A.B. wrote the manuscript; All authors edited and approved the manuscript.

Competing interests
The authors declare no competing interest.

Ethics
The study included local researchers and took into consideration the research already done in the study area. In addition, no permitting was necessary because this work did not require data collection in the field.

Additional information
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