Title:	**Health in the Amazon: environmental, social and economic challenges**
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Abstract

The Amazon Basin, a critical region for global climate regulation and biodiversity, faces significant health challenges exacerbated by environmental degradation, climate change, and socioeconomic inequalities. Home to 47 million people, including two million Indigenous inhabitants, the region is experiencing a triple burden of climate change, biodiversity loss, and ecosystem pollution. These factors, coupled with weak governance and inadequate health infrastructure, contribute to a range of health issues, particularly among vulnerable populations such as Indigenous communities and those in remote areas. Environmental degradation, driven by deforestation, wildfires, illegal logging, mining, and agricultural expansion, has led to increased exposure to infectious diseases, respiratory and cardiovascular conditions, and mental health disorders. The climate crisis further intensifies these health risks through more frequent and severe wildfires, heatwaves, droughts, and floods, which disproportionately affect Indigenous and riverine communities. The Amazon is also a hotspot for Emerging Infectious Diseases (EIDs), with deforestation and habitat destruction increasing the risk of zoonotic spillovers. The COVID-19 pandemic highlighted the region's vulnerabilities and underscored the need for a One Health approach that integrates human, animal, and environmental health. Addressing these challenges requires strengthening health systems, improving epidemiological surveillance, and fostering transnational cooperation. There is an urgent need for climate change mitigation and adaptation measures, as well as investments in infrastructure and sanitation to improve health outcomes. Protecting Indigenous land rights and reducing deforestation are also crucial strategies for mitigating health risks and ensuring the well-being of Amazonian communities. This comprehensive approach is essential for safeguarding health and promoting sustainable development in the Amazon.

Key messages

- **Environmental Degradation and Health Risks:** The Amazon faces significant health risks due to environmental degradation, including deforestation, mining, illegal logging, and infrastructural development. These activities contribute to conditions, including (but not limited to) respiratory, cardiovascular, food insecurity, and infectious disease.
- **Climate Change and Health:** The climate crisis poses a triple burden on the Amazon, impacting health through pressures such as forest fires, high temperatures, air pollution, droughts, floods, microplastics and plastic pollution, among others.
- **Vulnerable Populations:** Indigenous and riverine communities are especially vulnerable to droughts, floods, and food insecurity, with Indigenous peoples facing high rates of malnutrition. Water scarcity and poor quality are pressing issues in vulnerable territories, such as black, *quilombola*, and indigenous areas. Additionally, individuals with pre-existing Noncommunicable Diseases (NCD), especially children and the elderly, are at heightened risk from air pollution and heatwaves exposure.

- **Health System Challenges:** The Amazon region suffers from inadequate health infrastructure, poor access to basic amenities, and weak governance, making it difficult to address the health impacts of environmental degradation and climate change effectively.
- **Emerging Infectious Diseases (EIDs):** The Amazon is a hotspot for EIDs due to environmental changes, deforestation, and illegal wildlife trade. The COVID-19 pandemic has highlighted the region's vulnerability and the need for a One Health approach that integrates human, animal, and environmental health.
- **Food Security and Pollution:** Food insecurity is a growing concern in the Amazon, driven by deforestation, monocrop farming, and contamination from pesticides and mercury. Plastic pollution and microplastics in waterways also pose significant health risks.

Key recommendations

- **Strengthen Health Systems:** Enhance health system management, improve epidemiological data integration, and ensure engagement with communities, focusing on community-based surveillance and inclusive risk communication strategies supported by primary care.
- **Promote Transnational Cooperation:** Implement a coordinated transnational and cross-sectoral response to environmental and health challenges in the Amazon. This includes unifying surveillance systems, reporting platforms, and prediction models across countries in the region.
- **Mitigate Environmental Impacts:** Reduce deforestation, protect Indigenous territories, and promote sustainable land use practices to mitigate health risks. Address the root causes of environmental degradation, such as illegal logging and mining, through stronger governance and enforcement.
- **Adapt to Climate Change:** Urgently implement climate change mitigation and adaptation measures across all sectors, with a focus on public health protection. Equip and train healthcare professionals to handle the health consequences of climate change, particularly in vulnerable communities.
- **Invest in Infrastructure:** Invest in basic sanitation, clean water access, and transportation infrastructure to improve health outcomes, particularly in remote and rural areas. This is critical for reducing waterborne diseases and improving overall public health.
- **Address Food Insecurity:** Promote local, sustainable agriculture, reduce reliance on Ultra-processed Foods (UPF), and support traditional fishing practices to improve food security and nutrition in the Amazon.
- **Tackle Pollution:** Implement measures to reduce air pollution, plastic pollution, and pesticide contamination in the Amazon. This includes expanding public transportation, using cleaner fuels, investigating criminal wildfires, and improving waste management systems.

- **Protect Indigenous Rights:** Ensure the protection of Indigenous territories to prevent health impacts from environmental degradation and promote their role in forest conservation. Strengthening Indigenous land rights could prevent millions of respiratory and cardiovascular cases annually.

1. Introduction

The Amazon, vital for global climate regulation and biodiversity, has an area of about seven million square kilometers across eight countries and home to 47 million people, including two million Indigenous inhabitants[1,2]. The climate crisis threatens human health in the Amazon basin, affecting all countries and their borders, including Bolivia, Colombia, Ecuador, Peru, and others. Health impacts vary due to population size, density, location, time and frequency of exposure, and wealth. Amazon basin countries have not historically emitted large amounts of Greenhouse Gases (GHGs), except for Brazil, which significantly contributed through deforestation and degradation. Despite low emissions, the global effects of climate change impact every region and country[3]. The region endures a triple burden of climate change, biodiversity loss, and ecosystem pollution marked by socioeconomic inequalities; lack of access to basic amenities; violence; and difficulties in implementing public policies[4]. Urban communities suffer from socioeconomic insecurity, climate crisis, and poor sanitary conditions, while rural and remote populations face inadequate health services and infrastructure. Indigenous communities are particularly vulnerable due to their reliance on forest resources and exposure to these environmental changes; immune issues, high exposure to extreme weather events, income poverty, and low education levels[5,6]. Environmental degradation poses significant health risks in the Amazon, such as increased wildfires releasing pollutants causing respiratory and cardiovascular diseases; changing precipitation patterns affecting water availability and quality; and increasing of vector-borne diseases, such as: yellow fever, dengue, malaria, Saint Louis encephalitis, Mayaro fever, and Oropouche. The impacts of climate change are strongly influenced by social vulnerabilities and adaptive capacity, requiring timely and adequate responses to both rapid and slow-onset climate risks. Weak governance, limited disaster risk management policies, and inadequate and limited climate adaptation, combined with social inequalities, high poverty levels, informal employment, and health systems gaps, contribute to the devastating health impacts of climate change. These impacts disrupt daily life, affecting health, well-being, social development, and human capital[7,8]. In the Brazilian Amazon, primary care is the most present type of healthcare facility and the main point of access for the Unified Health System in the region, making it an essential strategy for addressing regional inequities and overcoming these obstacles. However, it is well known that the health sector is not capable of combating the driving forces and their pressures on health on its own. Therefore, what we need to work better is in how to work together. It is essential to establish intersectoral synergies between institutional agendas, enabling government, research institutions, and monitoring agencies to collaborate effectively[9].

2. Driving forces, political and historical context

For a long time, despite its biodiversity and indigenous cultures and richness, the standing forest in the Amazon was seen as a territory that was not economically advantageous, leading to exploitation activities such as logging, mining, wildlife smuggling, and deforestation, negatively impacting ecosystems and human health[10–12]. Some actors continue exploiting protected areas and indigenous territories, ignoring biodiversity conservation, despite the potential for a sustainable bioeconomy to reduce poverty and support climate commitments[13]. In recent years, deforestation and forest degradation have increased in the Pan-Amazon region, with a 14.9% rise in 2022 (35,480 km^2) compared to 2021 (30,089 km^2), and varying trends across different countries in the region[14–17]. If these disturbances persist, the forest could become degraded and resemble a savannah, which would have catastrophic global effects on ecosystems, carbon sequestration, and biodiversity[15–17].

Cattle ranching is the primary driver of deforestation in the Amazon, exacerbated by illegal invasions of protected areas and Indigenous territories, though Amazonian countries exhibit distinct characteristics. The Brazilian Amazon, for instance, is notable for extensive soybean cultivation and heavy pesticide use, with residents of Mato Grosso exposed to 65.8 liters of pesticides in 2018 and urban dwellers exposed to over 300 liters annually. In Colombia, coca cultivation remains a persistent challenge, while in the Ecuadorian Amazon, small-scale farming systems contribute significantly to agricultural expansion[18–21]. Weak enforcement of environmental laws and high market demand drive illegal logging, particularly for valuable timber species like mahogany, degrading ecosystems, reducing biodiversity, and impacting resources critical to Indigenous populations[22]. Both legal and illegal mining for minerals like gold and iron ore cause deforestation, water pollution, and soil erosion, violating Indigenous rights and disrupting traditional ways of life. Illegal mercury use in gold extraction contaminates fish, a crucial dietary resource for urban and rural communities[22].

Infrastructure projects such as road construction and hydroelectric dams provide access to remote forests, accelerating deforestation, fragmenting habitats, and displacing Indigenous communities. These projects also bring an influx of people, spreading pathogens and disrupting local ecosystems[22,23]. Governance issues, including corruption and insufficient resources, allow illegal logging and mining to proceed with little resistance, undermining legal frameworks and Indigenous rights. Political lobbying often favors resource exploitation over forest conservation, reducing regulatory enforcement in the Amazon[22]. Socioeconomic pressures, including high poverty levels and limited sustainable economic opportunities, push some community members toward illegal mining, logging, or unregulated agriculture, leading to environmental degradation[22]. Additionally, global market demand for commodities such as beef, soy, and minerals further incentivizes illegal and unsustainable exploitation of forest resources, contributing significantly to deforestation and degradation[22].

3. Health impacts, anthropogenic and economic pressures in the Amazon

Deforestation and ecosystem degradation contribute to major health issues, including, infectious diseases, respiratory, metabolic and cardiovascular impacts, skin diseases, heat stress, mental health issues, mercury contamination from gold mining, and pesticide and other metals exposure, all exacerbated by climate change[24]. NCDs and communicable diseases have an overlap of classic risk factors contributing to the double burden of diseases in several regions of the Pan-Amazon, which acts as a driver of epidemiological transition. Amazon states have the lowest life expectancy in Brazil[25,26]. Extreme events harm traditional communities, particularly indigenous peoples who depend directly on the territory. Economic activities threaten these communities, leading to conflicts, environmental degradation, and increased health risks, causing ecosystem loss at various scales[27]. Besides government action, civil society and non-governmental organizations' mobilization is crucial. Immediate action is needed to protect traditional communities' health and well-being, improve quality of life, and preserve forest habitats.

Box: Importance of the territory for health and *buen vivir* in the Amazon: Pamiwa's ecological calendar

For the Pamiwa people of the Colombian Amazon, the territory is a vital space where visible and invisible beings coexist. Cultural and ancestral norms guide sustainable resource use, promoting buen vivir and health, understood as physical, spiritual, and emotional well-being in balance with biodiversity. Disruption of this balance leads to diseases imposed by the seres dueños de la naturaleza (masters of nature). To understand the movement of the territory and the actions of the seres de la naturaleza, the Pamiwa create ecological calendars. These collectively developed graphic tools illustrate how the environment interacts across the three realms to produce health and disease as seen in Figure 1.

The ecological calendar for the Pamiwa people of the Colombian Amazon tracks seasonal changes in the environment, marked by the positions of constellations and water levels. The year is divided into five periods:

1. January and February
2. March, April, and May
3. June, July, and mid-August
4. August, September and October
5. October, November and December

These periods correspond to natural droughts and floods, with traditional activities like agriculture, fishing, and hunting depending on these observations. Diseases related to these environmental changes are recorded in the calendar's inner circle. The dueños de la naturaleza regulate human-nature interactions through animals and phenomena like snakes, spiders, lightning, and winds, with traditional experts performing protective rituals to maintain harmony. Recent disturbances include diseases introduced by foreigners, such as measles and COVID-19, viewed as evils. Climate change affects this system with altered rain patterns, rising river levels, extreme temperatures, and droughts, leading to increased mosquito populations and the spread of diseases like malaria and dengue. Environmental changes are indicated by shifts in animal behaviors, such as the timing of ants, birds, and frogs. Ecological calendars help to understand health impacts of anthropogenic activities for Amazonian indigenous peoples, preserving indigenous knowledge. It holds an importance for public policy, allowing broader frameworks in the face of global challenges such as capitalism and climate change.

3.1 Climate change and Noncommunicable Diseases (NCDs)

NCDs are the leading cause of death in Brazil, accounting for 74% of all deaths, and in the Amazon region NCDs are probably underestimated, because of their geographical isolation, and due to its limited access to health facilities and precarious mobility of riverside communities. Important risk factors, such as genetic susceptibility, remain undetermined for the indigenous, quilombolas, riverine population and remote communities. NCDs, such as cancer, diabetes, and hypertension are highly prevalent in the Amazon. Between 2010 and 2021, cardiovascular disorders were the leading cause of death in the Amazon, accounting for 23% of all deaths. Respiratory conditions and external causes accounted for 9% and 16% of deaths, respectively. In Brazil, the amazonian riverine population has higher rates of hypertension, insulin resistance, overweight, obesity, and cardiometabolic disturbances compared with the south of Brazil and capital cities like Rio de Janeiro e São Paulo[28,29].

3.2 Forest fires, high temperatures and air pollution

The population's exposure to the toxic effects of biomass burning resulting from forest fires in the Amazon is an important risk factor for cardiovascular and respiratory diseases[30,31]. The dry season in the Amazon occurs between June and November, when drought, extreme temperatures and biomass burning is more commonly experienced and pollutant levels, like Particulate Matter 2.5 (PM2.5) often exceed World Health Organisation (WHO) limits[32,33]. In recent years, heatwaves have occurred more frequently in the Amazon with an intense burning period extending from March to December[34,35], depending on variations in rainfall[36].

Heatwaves in the Amazon increase morbidity and mortality due to metabolic conditions, particularly cardiovascular and respiratory diseases such as ischemic heart disease, stroke, heart failure, Chronic Obstructive Pulmonary Disease (COPD), and Chronic Kidney Diseases (CKD)[37,38]. The risk of mortality from cardiovascular disease rises with more intense heatwaves, affecting the elderly and women the most[39,40]. High temperatures increase heart and respiratory rates, dehydration, blood viscosity, and blood pressure, stressing the heart and lungs, especially in the elderly[40,41]. Prolonged heatwaves exacerbate cardiovascular stress, amplify air pollutants, and worsen existing respiratory and cardiovascular conditions[37]. Future projections for Amazonian capital cities indicate a significant increase in years of life lost due to heat-related cardiovascular diseases between 2040-2069 compared to 1970-2005, assuming rising emissions[39]. By 2100, the savannization of the Amazon could expose over 11 million people to heat stress[42]. Skin cancer and cataracts related to Ultraviolet (UV) radiation are reported in riverine communities, with significant research gaps on UV exposure and health effects in the Amazon. Monitoring solar UV radiation is crucial due to its impact on health and ecosystems. UV-related diseases are largely preventable with proper sun protection, but indigenous, riverine, and rural communities may be at higher risk[43,44].

Deforestation, precipitation, and temperature account for 80% of the variability in forest fire seasons in the Amazon, with most wildfires being anthropogenic, often set to clear land for agriculture and cattle ranching. Between 2012-2019, deforestation increased by 39%, leading to more dry season fires[45]. In 2019, total costs associated with hospitalizations due to deforestation-related fires were estimated at R$ 5.64 million (USD 1.4 million)[46,47]. And the estimated costs are even bigger because of the historical criminal Amazon wildfires in 2024. Early 2024 saw 7,861 fire outbreaks, the highest in the first three months of the year since 2016[48]. These fires release substantial pollutants, significantly affecting indigenous communities' health. In 2019, wildfires caused an estimated 3,400 additional deaths due to increased air pollution[45]. In the Brazilian Amazon, wildfire-related air pollution is linked to higher hospital admissions for respiratory conditions, especially among children and the elderly[46,49]. PM2.5 from wildfires is associated with a 38% increase in respiratory admissions and 27% increase in circulatory admissions[50]. Air pollutants and wildfires are also linked to asthma[51], COPD[52], lung cancer, brain tumors[53], suffocation, burns, and cerebrovascular events[54,55].

3.3 Droughts and Floods

The Amazon rainforest has experienced severe drought and flood events in recent decades, disproportionately affecting indigenous and riverine communities. These events increase the risk of water-, food-, and vector-borne diseases, malnutrition, traumatic injuries, chemical exposures, cardiovascular and respiratory illnesses, mental health disorders, and mortality[56,57]. Floods lead to dermatological illnesses due to physical trauma, stagnant water, exposure to pollutants and wastewater toxins, crowded shelters, and inadequate sanitation. The highest risk of wound infection and disease transmission occurs during the post-impact phase[58]. Deforestation exacerbates floods in the Amazon River. Prolonged flooding destroys crops, contaminates water, and affects lives and health in rural and urban areas[59,60]. Children and the elderly are the most vulnerable[61]. Long-term precipitation increases the risk of pesticide exposure from agriculture, particularly relevant due to soybean monoculture expansion in the Amazon, raising concerns about drinking water contamination[62,63].

3.4 Microplastics and Plastic Pollution

New evidence shows the Amazon Basin is highly polluted, with birds incorporating plastic into nests and aquatic plants retaining microplastics, leading to biomagnification. Due to inadequate water and sewage treatment, tons of plastic enter the Amazon waterways annually. The plastic industry contributes significantly to GHG emissions and environmental pollution. The food and beverage sector is a major source of single-use plastic packaging, linked to UPF, posing a significant threat to biodiversity, freshwater resources, and traditional fishing activities. Research gaps on plastic pollution in the Amazon need to be addressed[64,65]. Plastic polymers have been found in human organs, and plastic additives, known as endocrine-disrupting chemicals, contribute to infertility and NCDs, including obesity, diabetes, cardiovascular disease, and some cancers[66–69].

3.5 Food insecurity and threats to food sovereignty

Food security in the Amazon is threatened by monocrop farming, concentrated land ownership, intense pesticides use, deforestation, biodiversity loss, extreme events, restricted access to healthy food and water, unhealthy diets, and loss of traditional practices, as presented in Figure 2[70,71]. Vulnerable groups such as indigenous peoples, pregnant women, low-income families, children, and adolescents face disproportionate effects[72]. Indigenous people face significant nutritional challenges, like high rates of malnutrition, anemia, and stunting among children and maternal populations[73–76]. Undernourishment weakens the immune system, increasing susceptibility to infectious diseases[77]. High consumption of UPF contributes to energy use, biodiversity loss, GHG emissions, land use, food waste, and water use[78–80]. Limiting UPF and encouraging local, seasonal, organic food improves health and sustainability[81,82]. Fishing is vital for food security in the Amazon, as a primary source of protein in many communities. Climate change, contamination of aquatic ecosystems with pesticides and mercury, illegal and overfishing, and the construction of dams reduces fish diversity, harming fishing communities and their cultures, poses significant health risks, like malnutrition and metabolic disorders[83–86].

Box: Connecting climate, sanitation and health

One of the most critical areas at the nexus of climate and health is access to safe drinking water. The solutions are known, but there is a need for committed funding to implement them[87]. National, state, and municipal efforts are needed to increase awareness of the critical role of water in climate, health, and economic development, particularly to reduce mortality and morbidity rates among children and the elderly in the Amazon basin.

Basic sanitation services are vital for human development, promoting health, preventing the spread of waterborne diseases, and supporting climate adaptation. These services are included in SDG 6, which aims to ensure the availability and sustainable management of water and sanitation for all[88]. SDG 12 focuses on sustainable consumption and production patterns, while SDG 11 emphasizes making cities inclusive, safe, resilient, and sustainable. It is crucial for developing nations to provide reliable public information on water and sanitation services at the local level[89]. As of 2022, 2.2 billion people lacked safely managed drinking water, 3.5 billion lacked safely managed sanitation, and 2 billion lacked basic handwashing facilities around the world[90]. In Brazil, the situation in the Amazon is particularly concerning, with almost half of the 20 cities with the worst basic sanitation indicators located in this region[91].

The Amazon region presents high risk for waterborne disease due to inadequate water, sanitation, and hygiene (WASH) infrastructure. According to the 2010 Census, 68.2% of the population in the Brazilian Amazon lacked access to adequate sanitation[92]. This lack, combined with the significance of rivers in the local context, contributes to higher mortality rates in the region. The pandemic has further exposed the dire impacts of poor access to clean water and sanitation, particularly in vulnerable Amazonian communities[93].

The climate emergency exacerbates water quality and scarcity, requiring urgent action, especially in vulnerable territories such as those of black, quilombola, and indigenous populations[94]. As an example, the May 2024 floods in Rio Grande do Sul, in southern Brazil, highlight the severe consequences of inadequate sanitation infrastructure. These floods disrupted water supply systems, sewage collection and treatment, as well as solid waste management, exacerbating public health risks and environmental contamination.[95].

Considering this scenario, children live in a state of "multiple deprivation," facing severe health risks due to poor sanitation, especially during flood seasons[96]. The infant mortality rate in the Amazon region is persistently higher than in the rest of the country, with waterborne diseases being a significant cause. Simple solutions like water chlorination and drilling micro water systems could greatly improve health outcomes in Amazonian communities[96].

Key strategies include raising awareness of the importance of water in climate and health actions, achieving universal sanitation coverage by 2030, ensuring that water access is recognized as a human right, and investing in infrastructure and management to prevent water-related diseases and improve quality of life in the Amazon. Civil society organizations should hold governments accountable, invest in water technology research, and promote inclusive governance of water resources[97].

4. Risk of Emerging Infectious Disease (EID)

The Amazon is a significant arbovirus reserve[98], with potential global health impacts[99]. Climate change, biodiversity loss, and land-use changes have increased social and environmental vulnerability, disrupted ecosystems, and heightened pathogen transmission risks[100–105]. Deforestation for agriculture, extractive industries, biomedical uses of biodiversity, road construction, habitat destruction, trade, hunting, and wildfires, combined with climate change, have all contributed to this increased risk, suggesting that spillover events may become more frequent. While historically, more spillover events have occurred in Asia and Africa, the

Amazon's high biodiversity increases the likelihood of pathogen presence and mutations, especially with the growing presence of livestock in the region[6,106]. Examples of EID include Nipah Viral Encephalitis (NVE), Severe Acute Respiratory Syndrome (SARS), Hantavirus Pulmonary Syndrome (HPS), highly pathogenic avian influenza H5N1, influenza virus H1N1, and HIV[107–109].

The COVID-19 pandemic and the rise in EIDs have emphasized the importance of the One Health approach, integrating human, animal, and environmental health as you can see in Figure 3[110–112]. Historically, over 60% of new human pathogens have animal origins, with 75% stemming from wildlife through zoonotic spillover[6,113]. Anthropogenic impacts contribute to increasing EID rates in the Amazon. Covering 40% of South America and 7% of the planet's surface, Amazon faces significant EID risks due to land use changes, environmental degradation, global trade, climate change, habitat destruction, and pollution[100,110,114,115].

These stressors disrupt forests, leading to edge effects that impact biodiversity and pathogen transmission cycles. Forest clearing and degradation increase human and domestic animal contact with wildlife, facilitating pathogen transmission[106,116]. Biodiversity decline reduces the ability of ecological communities to provide essential ecosystem services[117].

Figure 4 presents projected mean number of spillover events per capita and change in cover between 2020 and 2050 (deforestation). Areas that presently have a high cover of trees (> 60%) and will experience low deforestation will have low levels of spillover (< 0.12, lower left corner cell in the inset color code) and should be protected from deforestation. Areas of high spillover and high deforestation cluster around population centers and should be prioritized for land use planning and community health support. Many areas in the Amazon are already deforested and will have a high level of spillover (> 0.3) even if they suffer little additional deforestation (< 40%) up to 2050 (lower right corner cell in the inset color code panel). These areas should be considered in restoration programs such as the Brazilian Native Vegetation Recovery Plan (PLANAVEG).

EIDs linked to IWT have significantly increased over the past decade due to human-environment interactions and better diagnostic testing. There is an urgent need to monitor and enforce IWT regulations to protect public health, especially as globalization increases disease risks[118]. Data on IWT in South America is limited[119]. In Brazil, more than half (55.8%) of wild animals rescued from illegal trafficking were infected with at least one zoonotic parasite. Non-human primates had a higher infection rate (58.3%) compared to carnivores (41.7%). The zoonotic parasites detected included helminths (33.5%) and protozoa (66.5%), with 20.8% of infected animals having coinfections[120]. Despite the significant health risks from pathogens in bushmeat, public awareness of these risks remains low[118]. Increasing extreme weather events due to the climate crisis are expected to heighten the risk of outbreaks of existing vector borne diseases and the emergence of new ones. These climate effects will interact with ongoing urbanization in areas like Manaus, necessitating a precautionary approach focused on surveillance, preparedness, and alert systems. These measures should be integrated into broader efforts to address environmental changes, including deforestation and climate change, to ensure regional sustainability[27].

4.1 Challenges for predicting the risk of future epidemics in a megadiverse region

Predicting future epidemics in the Amazon is challenging due to the complex interplay of ecological and socioeconomic factors. Human activities have created fragmented landscapes where high-density animal populations in degraded habitats are prone to epidemics. Anthropogenic agroecosystems attract wildlife, increasing disease spillover risks as interactions between wildlife, humans, and domestic animals rise. Common activities like logging, hunting, agriculture, and cattle breeding modulate conditions for zoonotic disease (ZD) outbreaks.

Despite advances in understanding drivers of emerging and reemerging infectious diseases, predicting zoonotic risks and outcomes in the Amazon remains difficult. Factors such as the effectiveness of healthcare systems and the pathogen's spread potential lead to varied hospitalization and mortality rates. Surveillance data often focus on introduced diseases, with limited knowledge of native pathogens. The COVID-19 pandemic highlighted the need for preventive strategies for new pathogens.

The Amazon is identified as a hotspot for emerging ZDs, but COVID-19 revealed deficiencies in the region's preparedness for epidemiological emergencies. Urban centers have well-structured public health systems, but rural areas are under-resourced. A new framework predicts ZD risks in Brazil, considering land use changes, mammalian species richness, social welfare, and geographic connectivity[100]. Data gathered based on the INFORM protocol assessed exposure, vulnerability, and coping capacity. The model showed significant associations between zoonotic epidemic risks and vegetation loss, mammalian richness, and remoteness, while urban afforestation and vegetation cover were negatively related to ZD cases. Only 29.63% of Brazilian states are at low risk of zoonotic outbreaks, with the Amazon region being a major concern due to low urban afforestation, high mammal richness, and significant vegetation loss. High-risk states, primarily in the Northern region, exhibit these characteristics, while low-risk states have better urban connectivity and healthcare access.

Human mobility is crucial in spreading epidemics, connecting ZD sources to densely populated regions. Six high-risk Brazilian states in the Northern region and one in the Central-Western region have been identified, all partially or entirely covered by the Amazon rainforest. These states have low urban afforestation and high levels of remoteness and mammal richness. Low-risk states in the Northeastern and Southern regions show better urban connectivity and lower vegetation cover and loss. Bushmeat hunting and trading increase ZD risks by promoting direct human-wildlife contact.

A database of frequently poached mammal species in Brazil and their zoonotic parasites highlighted key species for monitoring[100]. Network analysis revealed that bacteria, protozoans, and viruses are the main parasite groups, with species like the crab-eating fox, opossums, and armadillos serving as central hosts. While introduced pathogens have historically caused major outbreaks in Brazil, the risk of ZDs emerging from native biota is significant, particularly in the Amazon. These findings emphasize the need for integrative public health policies combining human and wildlife monitoring, reflecting the One Health paradigm. Effective prevention and response strategies require collaboration across governmental, agricultural, and societal sectors, promoting sustainable practices and informed community engagement to mitigate zoonotic risks.

In summary, predicting and mitigating the risk of future epidemics in the Amazon involves understanding the complex interplay of ecological degradation and socioeconomic activities. Preventive strategies should integrate ecosystem and urbanization characteristics, improve public health infrastructure in remote areas, and promote sustainable practices. The One Health paradigm provides a holistic approach to managing interdependencies among human, animal, and environmental health, necessitating cross-sector collaboration and comprehensive public policies to address zoonotic risks effectively.

4.2 Risk of diseases outbreaks and its costs

The current state of health in the Amazon is complex and hampered by incomplete data due to gaps in surveillance and diagnostic capacities in regions with weak or nonexistent health systems. The COVID-19 pandemic highlights the critical need for ongoing investment in Global Health Security (GHS) preparedness, as previously demonstrated by outbreaks of Ebola, Zika, and H1N1[121,122]. Enhancing GHS requires greater regional cooperation and improved infectious disease surveillance systems. Frameworks like the International Health Regulations and the GHS Agenda provide a foundation for strengthening health systems. International cooperation is essential to enhance surveillance, build trust among partner countries, and improve health security systems and practices to effectively respond to and mitigate infectious disease outbreaks. Health systems must be a priority for governments in Amazonian countries, and financing must be increased. However, health systems in Latin America are highly fragmented and segmented, leading to significant challenges in providing quality care and ensuring equity. Market, social, and political pressures drive poorly regulated privatization of public healthcare, undermining public services where management capacities are already limited[123]. Historic data from The Global Health Observatory of the WHO indicate that Amazonian countries have very weak health systems compared to the most developed countries.

Figure 5 shows that current health expenditure per capita in Amazonian countries ranges from $330 to $984, compared to $575 to $1,406 in Latin America and the Caribbean and $594 to $1,639 in the world average (from 43 to 67% less). On the other hand, this situation is also observed at sub-national levels. For example, in Brazil, the expenditure in Amazonian states is much less than in states from other biomes as shown in Figure 6.

The green bars in Figure 6, are the states that belong to the Legal Amazon in Brazil. These numbers highlight the need for more prioritization and investment in health systems in Amazonian countries and regions due to their higher vulnerability and increasing pressures. Future risks of disease outbreaks and negative health impacts, driven by combined stresses like climate change and land use changes, are challenging to assess in detail but could be substantial. Certain areas, particularly in the Cerrado, are identified as "disease hot-spots" prone to high risks of ZDs from anthropogenic land use changes[121]. Disease risks and impacts on human health are likely to be significant even before reaching the Paris Agreement's 2-degree target, necessitating immediate action.

5. Recommendations to improve health in the Amazon

Health systems:

- Learn from the COVID-19 pandemic how to access capacities that allow us to respond to disasters that affect health, such as the climate crisis in the Amazon River basin.
- Identify needs to improve health system management, epidemiological data integration, and community group engagement.
- Strengthen community-based surveillance in vulnerable communities and develop inclusive risk communication strategies[8,124].
- Strengthen health system to ensure preparedness, resilience, and crisis management capabilities, promoting health and well-being by identifying trends and proposing actions, strategies, and policies[8].
- Implement climate change mitigation and adaptation measures as public health protection policies crossing all ministry projects (e.g. health, environment, work) coordinated by health sector[39].
- Improve access to primary care, especially in lower population density areas, where facilities are located far from people's homes. Improved logistics are required for more effective transportation, better distribution of supplies like medicines and tests for diseases like Human Immunodeficiency Virus (HIV) and malaria, which can have a substantial impact on the care provided to vulnerable populations like children and pregnant women[125,126].

Health facilities:

- Ensure health service delivery during extreme weather events by implementing solutions such as mobile health units equipped with boats or amphibious vehicles, which can maintain access during floods[127].
- In addition to primary care investment, it is necessary to reassess access to hospitals and specialized care beyond the capital cities, given the limited and time-consuming mobility in the region[128].

Heatwaves:

- Develop and implement localized heat stress indices, such as a region-specific Wet Bulb Globe Temperature (WBGT) and heat index, tailored to the Amazon population. This adaptation is crucial as existing parameters are based on extra-tropical regions and do not accurately reflect the unique conditions of the Amazon.
- Develop and improve advanced alerts and communications by mobile devices to provide lead-time to deploy appropriate preparedness measures and responses.

- Develop climate policies addressing the health impacts of heatwaves, focusing on the elderly, children, people with NDC and women, and considering heatwave intensity in both rural, remote and urban settings [40].
- Ensure availability of electricity, clean water, sanitation, and hygiene (WASH) and health services to promote thermal comfort and cooling strategies[129].
- Promote environmental urbanism creating greener spaces and strengthen local strategies for adapting to high temperatures, such as architecture and materials used by remote communities to build their homes[130].

Air pollution:

- Reducing deforestation is crucial for improving air quality and public health in the Amazon[131]. Other measures include expanding public transportation, using cleaner fuels, and changing building construction standards to reduce energy consumption. These could reduce annual mortality from air pollutants by up to 60% by meeting WHO and Paris Agreement standards.
- Invest in green urbanism, promoting green infrastructure[130].
- Adaptation measures like early warning systems, air quality monitoring, the establishment of clean air shelters, and the distribution of masks or air purifiers, restricting outdoor activities, are required to improve air quality, especially for susceptible individuals during high pollutant events like wildfires[54].
- Inform communities about air quality levels (e.g., Air Quality Index) to reduce exposure to polluted areas. An improved air quality monitoring network is recommended to fill research gaps[132].
- Prioritizing the use of High Efficiency Particulate Air (HEPA) filters in key locations, such as Primary care facilities, to ensure clean air and protect vulnerable populations from the harmful effects of air pollution, especially in seasons with high biomass burning[133].

Microplastics:

- Implementing comprehensive policies to mitigate microplastic pollution and its impacts on public health and the environment.

Food security:

- Protect biodiversity, fishing resources, and communities.
- Invest in conservation and support traditional structures to prevent severe food insecurity[134].
- Promote food sovereignty for sustainable resource management[135].
- Prioritize biodiversity conservation programs, especially those with a gender perspective, to achieve Sustainable Development Goal (SDG) 2[136,137].

Emerging Infectious Diseases (EID):

- Implement integrated land-use planning and sustainable development practices to avoid alter pathogen transmission cycles and increase human-wildlife interactions to reduce the risk of disease spread[138].
- Reduce deforestation to decrease the creation of new vector breeding sites, such as for mosquitoes, and reduce the exposure of human populations and domestic animals to wildlife with potential pathogens.
- Establish a coordinated transnational response by unifying surveillance systems, reporting platforms, and predictive models to address the rising incidence of malaria, dengue, and chikungunya, as well as emerging threats like Mayaro fever and Oropouche. This integrated approach will enhance early detection, improve response efforts, and mitigate the spread of these diseases across borders[139].
- Prevent the reemergence of viral diseases through early identification, monitoring, and surveying of viruses in sentinel populations (indigenous and quilombolas) who live near habitats of key viral reservoirs (rodents, bats, pigs, monkeys); live or work near animal breeding or slaughtering areas; and reside in regions affected by viral vectors, particularly mosquitoes[140].
- Utilize transdisciplinary science teams, including insights from indigenous peoples and local communities, to understand the connections between wildlife trafficking, zoonotic pathogens, and health and ecosystem impacts.
- Develop tools and approaches to support local livelihoods and tackle challenges in monitoring, detection, prevention, interdiction, and remediation[118,141].
- Focus on prevention by enhancing surveillance, biosafety, and security efforts. Strengthen national and local response capacities through global governance structures like the One Health Tripartite Agreement and the One Health High-Level Expert Panel[118,141].
- Implement education and policy changes to restore ecosystem functions and prevent future pandemics[118]
- Develop decision support models to boost local capacity for pathogen risk prevention, detection, and response, and ensure compliance with existing regulations and crime prevention[141].
- Harmonize a "network of networks" to promote joint surveillance, biosafety and security efforts for better human and animal health, disease detection, and IWT reporting[141].

Financial support to avoid zoonotic diseases:

- Amazon countries should engage with international initiatives like Finance for Biodiversity (FfB), Global Canopy's Forest 500, and the Investors Policy Dialogue on Deforestation (IPDD) to address ZDs risks in the Amazon region.
- National and multilateral development banks, such as the Inter-American Development Bank, should support financial disclosure of not only climate risks but also zoonotic risks stemming from anthropogenic land-use changes in specific regions and sectors associated with increased ZDs risks.
- Companies should mitigate zoonotic risks by protecting or restoring ecological conditions that reduce pathogen spillover, applying land use interventions to reduce "edge effects," and co-

investing with the public sector to improve pathogen surveillance systems and the health and economic security of communities in ZDs hotspots.

- Responsible investors in high-risk sectors in the Amazon should use their oversight and voting power at annual general meetings to pressure corporate management to adopt zoonotic-risk policies and complement existing sustainability and climate reporting with financial disclosure of ZDs risks.

Capacity building:

- Implement effective local and regional capacity-building for all health professionals in the Amazon, beyond just physicians and nurses. This includes updating health curricula to address climate-related challenges, continuous training for primary care teams, expanding internship opportunities, and promoting exchange programs and fellowships to enhance skills and preparedness[142].
- Equip and train healthcare professionals to handle the health consequences[143].

Remote Communities:

- Remote locations and limited healthcare access in these communities hinder regular monitoring of health issues, including NCDs. There is an urgent need to establish dedicated health professional careers focused on serving remote areas, like *Mais Médicos* or other comprehensive national approaches[144].
- To improve disease tracking and response, it is essential to develop new surveillance techniques that encompass both endemic and emerging infectious agents.

Indigenous Medicines:

- Climate change causes cultural losses for indigenous peoples, including healthcare technologies. Disappearing plants and fish due to droughts, floods, and fires affect indigenous medicine and festivities. Actions to strengthen indigenous care technologies include guaranteeing indigenous peoples' isolation, strengthening traditional education, and integrating healthcare based on indigenous culturalities.

Indigenous Health Policies:

- Indigenous health policies often are the only public policies reaching many Amazon territories. These policies must consider climate change, involve all government levels and sectors, include contingency plans, address logistical issues, structure HCFs in safe locations, and develop policies together with indigenous peoples.

Climate Emergencies in indigenous context:

- Local peoples face pressure to adapt to climate change, dealing with issues like water scarcity, malnutrition, flu syndromes, and diarrhea. Multidisciplinary teams reinforcing Primary care teams in the territory are essential, with more professionals needed during climate emergencies. Plans must consider terrestrial and air logistics, as air transport involves higher costs.

Land Rights:

- Protecting Amazon Indigenous territories could prevent over 15 million respiratory and cardiovascular cases annually, saving approximately $2 billion USD in health costs[134]. Advance the demarcation of traditional territories, recognize self-determination, respect traditional peoples' consultation protocols, and support local governance based on ancestral knowledge and autonomy[145].

Protecting Mother Nature:

- Prohibit the export and import of goods causing deforestation, create an Amazonian seal for agroecological and agroforestry products, reject extractive pressures damaging the water cycle, promote a just and decentralized energy transition, and declare the rights of the Amazon based on ancestral knowledge[146].

Extractivism and alternatives:

- Declare the Amazon a no-go area for any kind of extractivism (e.g. both legal and illegal mining in the Amazon) and fossil fuels, oppose inequitable energy transitions proposed by the global north, support traditional and family-scale pesticide-off agriculture, and encourage community-based tourism as an alternative to extractivism[147].

Gender based approach:

- Ensure indigenous peoples, especially women, participate in forest protection initiatives, create violent-free zones around megaprojects, focus on women's integrative health and sexual and reproductive health, value ancestral wisdom, and establish networks among women's organizations of original peoples[148].

Health Context and Social Justice:

- Implementing the One Health approach necessitates developing infrastructure and institutional capacity to promote health support for all Amazonian populations, with a focus on indigenous peoples and vulnerable individuals. This includes equitable access to health resources and dignified living conditions.

Restoration and conservation:

- Disease prevention depends on a healthy environment, including clean air, a stable climate, and quality natural resources like potable water and food.
- Forest restoration is crucial for biodiversity conservation, climate regulation, and human health protection. Restoring deforested and degraded forests in the Amazon can maintain water

bodies, regulate disease vector populations, and reduce human-animal contact, lowering the risk of ZDs like yellow fever, leptospirosis, and rabies.

- Urgent forest restoration is needed in areas with intense deforestation, such as the Arc of Deforestation, to prevent ecological imbalance and climate adaptability issues that could affect human health.

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FIGURES (UNDER CONSTRUCTION)

Figure 1. Ecological calendar of illnesses from the Pamiwa cosmovision and climate change disturbances

Figure 2. Key food systems threats to the amazonian biome

Figure 3. The One Health Framework

Figure 4. Projected mean number of spillover events per capita and change in cover between 2020 and 2050

Figure 5. Health Expenditure in Amazonian Countries vs. Latin America and the Caribbean vs. World (2000 – 2021)

Figure 6. Governmental Health Expenditure in Brazil by State in 2023