Chapter 21 In Brief

Human well-being and health impacts of the degradation of terrestrial and aquatic ecosystems

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THE AMAZON WE WANT
Science Panel for the Amazon

Human well-being and health impacts of the degradation of terrestrial and aquatic ecosystems

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Key Messages & Recommendations

1) Substantial evidence exists that environmental degradation can have acute and chronic impacts on human health.
2) Degradation of terrestrial and aquatic ecosystems generates complex chain reactions with a range of impacts on human health and well-being.
3) Outbreaks and increased incidence of different emerging, re-emerging, and endemic infectious diseases in the Amazon can be associated with environmental changes, including deforestation.
4) Pollution, including air pollution from deforestation and forest fires, and mercury contamination of aquatic systems due to mining, impact human health in the short and long term.
5) Region-wide improvements to public health services, including increased access and environmental sanitation, and close surveillance of infectious diseases in human populations are necessary to reduce the risk of viral emergence from wild populations.
6) Prevention of infectious diseases requires a robust monitoring system focused on the circulation of pathogens in the environment (water, soil, and sediments), as well as populations of disease vectors and animal reservoirs.
7) Complex interactions between drivers of deforestation and ecosystem degradation and the resulting disease burden in the Amazon region need to be further investigated. It is particularly important to emphasize the role of deforestation and climate change in the modelling of vector-borne diseases.
8) Reduction in deforestation and, as a consequence, deforestation fires is imperative to decrease respiratory syndromes in the region.
9) Effective curbing of illegal mining operations is crucial for halting mercury contamination of water and fish.
10) Innovative methods and approaches are needed to address broader, cumulative impacts of forest and aquatic ecosystem degradation on human health.
11) Legitimate participatory management policies, developed in an intercultural framework (e.g., Indigenous, academic, and institutional) are needed to enhance strategies for food security and human health. Promoting socially-just and culturally-sensitive practices can be achieved through action-oriented research where academia and community actors jointly develop practical solutions.

Abstract Amazonian forests and aquatic ecosystems are the basis for several ecosystem services, all of which play a crucial role in people's livelihoods, human well-being, and health. Some of the most relevant and challenging health problems in the Amazon are associated with deforestation and degradation of terrestrial and aquatic ecosystems,

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including the risk of contracting infectious diseases, respiratory problems caused by exposure to smoke from deforestation and forest fires, and mercury contamination caused by gold mining. Here we demonstrate that environmental degradation affects the health of millions of Amazonians.

Introduction According to the World Health Organization (WHO), health is "a state of complete physical, mental, and social well-being", going beyond the absence of disease or illness[1]. Enjoying a clean and sustainable environment is critical for human health and well-being[2], and preserving crucial regions such as the Amazon Basin is central to achieving that goal. However, quantifying the risks and impacts of environmental degradation on human health poses several methodological challenges, particularly when considering complex issues such as mental health or social well-being. For example, the loss of culture, language, and traditions undoubtedly have a profound long-term impact on the well-being of already vulnerable Indigenous peoples and local communities[3,4].

There are multiple drivers of deforestation and overall environmental degradation in the Amazon, including agricultural expansion, logging, fires, mining, urban expansion, and hydroelectric dams[5,6]. The type and level of degradation associated with each activity can have specific impacts on infectious disease transmission, particularly zoonotic or vector-borne diseases[7]. They may also contribute to other health problems such as respiratory syndromes, mercury contamination, and food insecurity. Processes related to these activities can have additional, often compounding impacts on well-being.

Impacts of deforestation on the diversity and spread of diseases Environmental changes in the Amazon; particularly shifts in climate, microclimates, and land use; have been repeatedly linked to the increased risk (and incidence) of emerging and re-emerging infectious diseases, which are expected to rise with deforestation and anthropogenic climate change. There are important differences depending on the dynamics of each infectious agent. A few cases are discussed below.

Malaria Decades of work on Amazonian deforestation and the *Plasmodium* parasites that cause malaria in humans have yielded evidence for non-linear, scale-dependent relationships with disease incidence[8], and important feedbacks from disease incidence to deforestation[9]. Analyses of the density of the mosquito *Anopheles darlingi*, the main malaria vector in South America, show a positive relationship with recent deforestation[10–12], implying that forest clearing increases the risk of malaria near forest edges. In regions with consolidated human settlements, however, the incidence of malaria is positively correlated with forest cover[13,14]. This apparent nonlinearity can be explained in part by *A. darlingi's* ecology, which favors forest edges, translating into increased malaria risk in both newly deforested areas[15,16] and forest patches in urban areas.

Socioeconomic factors, including the timing of human activity and migration patterns, may also play important roles in modulating malaria risk and disease outcomes, reflecting a strong relationship between vector ecology and human activities. Likewise, at a different spatial scale, the presence of gold mining was linked to higher malaria incidence in Brazil[14], demonstrating how rapid environmental change can increase exposure. Finally, at the scale of the Brazilian Amazon as a whole, recent work suggests a complex, bidirectional relationship between malaria risk and deforestation. Although deforestation significantly increased malaria transmission (a 10% increase in deforestation led to a 3.3% increase in malaria incidence), a high malaria burden simultaneously reduced forest clearing (a 1% increase in malaria incidence led to a 1.4% decrease in deforestation). The latter was presumably associated with changes in human behavior, economic activity, migration, and settlement, and the strength of the interaction attenuated as land use intensified[9].

Chagas Chagas disease, transmitted by the triatomine bugs *Rhodnius* and *Triatoma*, also responds to environmental changes. At the interface between human settlements and forest habitats, Chagas vectors appear to have quickly adapted to makeshift settlements, leading to a positive correlation between forest fragmentation and disease incidence[17]. Urbanized environments, however, are not completely exempt from transmission despite the lack of forest cover. This is because Chagas may be acquired orally via ingestion of contaminated fruit juices such as açaí and bacaba[18–20]. Thus, new forest settlements experience sylvatic Chagas cycles, but more urbanized settlements, which would be expected to have lower vector abundances due to higher temperatures and low forest cover[17], experience outbreaks through a different epidemiological mechanism[7].

American cutaneous leishmaniasis Environmental factors such as deforestation may correlate positively with the incidence of cutaneous leishmaniasis[21,22], however across Amazonian municipalities, cutaneous leishmaniasis decreases with increased health system effectiveness[23]. In addition, the introduction of domestic animals into recently settled areas may also contribute to the acclimation of vectors to human landscapes, increasing disease risks from deforestation[24]. Thus, nonlinear relationships between forest loss and disease risk are mediated by their interactions with a diverse vector fauna and local health systems.

Emergence of new diseases Surveillance efforts to identify hotspots of zoonotic coronaviruses with spillover potential have flagged the Amazon as a region with an exceptionally high, yet poorly known, diversity of viral hosts and viruses[25]. Increased contact between humans and wildlife also increases the potential for zoonotic spillovers[26]. Risk predictions were originally based on findings of both alpha- and beta-coronaviruses in a few bat species, the latter is notably the coronavirus subfamily that includes the human pathogens that cause SARS, MERS, and COVID–19[25] (though no close relatives of these human pathogens have been found in the fauna of the Americas). Other viruses also circulate in the Amazon region and present serious risks of widespread outbreaks, including the Rocio, Oropouche, Mayaro, and Saint Louis arboviruses,[27,28] hantaviruses[29], and arenaviruses[30]. From the 500 arboviruses species registered in the International Catalog of Arboviruses, 220 occur in the Brazilian Amazon alone[31]. Given the scant record, our understanding of the potential for land-use change to increase spillover risk remains limited.

Since the diversity of viruses in wild animal populations is vast, but spillover potential for most viruses is limited, close surveillance of infectious diseases in the human population is an effective way to avert future pandemics[32,33]. Region-wide improvements to public health services would also reduce the burden of well-known pathogens such as *Plasmodium* or *Leishmania*, and are necessary to reduce the risk of viral emergence from wild populations. While the Amazon harbors a hyper-diverse range of hosts and diverse communities of viruses of unknown human pathogenic potential, preventing a catastrophic pandemic requires implementing strategies that will improve human health more broadly.

The COVID-19 pandemic has reminded the world about the risks of zoonotic spillovers. However, the potential for spillback or pathogen pollution from humans to wildlife is just as important for biodiversity[34]. Decades of research on vector-borne arboviruses have already revealed the consequences of spillback. Outside the Amazon, in Espírito Santo (Brazil), a yellow fever outbreak killed dozens of non-human primates and prompted an early public health response to vaccinate people[35]. Although a chain of transmission has not been established among wild primates, sylvatic mosquitoes harboring the recently introduced Chikungunya and Zika viruses have been documented, indicating a plausible risk to wildlife[36]. The finding that endemic *Aotus* night monkeys do not contract dengue after exposure to infected mosquitoes in Iquitos suggests that dengue transmission remains confined to humans and insect vectors rather than generating a sylvatic cycle[36]. As with the risk of zoonotic emergence, averting the establishment of zoonotic reservoirs for arboviruses requires sustained investments in monitoring the diversity of viruses circulating in the human population.

Impacts of mercury contamination from mining on human health and food security Gold mining sites are commonly associated with contamination by a number of elements, including arsenic (As), cobalt (Co), lead (Pb), manganese (Mn), and zinc (Zn)[37,38]. These elements are associated with a variety of adverse health effects elsewhere, including child mortality. However, the impacts of these substances on human health in the Amazon are still largely unknown. The main impact of gold mines on human health in the region is mercury (Hg) contamination. Communities living near gold mining operations are exposed to harmful Hg concentrations released during gold extraction and discharged into waterways, soils, and the atmosphere[39]. Once the inorganic metallic Hg is released by anthropogenic activities, it is transformed by certain bacteria into its more toxic organic form, methyl-mercury (MeHg). This process allows MeHg to enter aquatic food webs, where it may accumulate in individual organisms (bioaccumulation), a process which is magnified as it moves into higher trophic levels (e.g., biomagnification in predatory fish)[40,41]. This can affect fish that are of great importance for the food security of local communities[42].

Despite the lack of systematic analyses, studies from Colombia, Peru, and Bolivia over the course of the last 20 years have documented Hg poisoning even in remote Indigenous populations. Further, Hg exposure can be toxic even at very low doses, and the toxicological effects of MeHg are of special public health concern, given its capacity to cross the placenta and the blood-brain barrier[43]. MeHg reaches high levels in both maternal and fetal circulation, with the potential to cause irreversible damage to child development, including decreased intellectual and motor capacity[39]. Studies investigating associations between Hg levels in hair and neuropsychological performance found strong links between Hg and cognitive deficiencies in children and adolescents across the Amazon[44–46]. Mercury can also impact the health of adults, affecting the digestive, renal, nervous, and cardiovascular systems; it can cause depression, extreme irritability, hallucinations, and memory loss[47]. Minamata Disease was recently confirmed in Amazonian communities as a result of exposure to high levels of MeHg, with symptoms including tremors, insomnia, anxiety, altered tactile and vibration sensations, visual perimeter deficit, and ultimately death.

Impacts of fires on air quality and human health Deforestation and forest fires emit large quantities of particulate matter and other pollutants to the atmosphere. This degrades air quality, affecting human health, especially among vulnerable groups, such as young children[48]. The dry season is the most critical period for population exposure to smoke from fires; particulate matter levels during these months are usually well above the WHO's recommended safe levels. Emergency room visits increase during the dry season, especially among children under the age of 10. They are positively correlated with $PM_{2.5}$ concentrations (i.e., particulate matter less than 2.5 micrometers in diameter), which correspond to fine particles present in smoke[49]. Fine particles can remain in the atmosphere for up to one week, and may be transported downwind to urban areas, where they may impact the health of populations far from the fire origin[50,51].

Other components of smoke are PM_{10} (i.e., particulate matter less than 10 micrometers in diameter but more than 2.5 micrometers) and black carbon, both of which are acutely toxic to humans. PM_{10} has the potential to cause DNA damage and cell death[52], leading to the development of PM_{10}-mediated lung cancer[53]. They can penetrate the alveolar regions of the lung, pass through the cell membrane, reach the bloodstream, and accumulate in other organs. $PM_{2.5}$ and black carbon are associated with reduced lung function in children 6 to 15 years old[54–56]. School children from municipalities with high levels of deforestation, and therefore fires and smoke, have high asthma prevalence[20,57]. Pregnant women are also highly vulnerable to smoke pollution. Exposure to particulate matter ($PM_{2.5}$) and carbon monoxide (CO) from biomass burning during the second and third trimesters increased the incidence of low birth weight by 50%[58].

Interactions between drivers and impacts Interactions between drivers and impacts of degradation are complex, affecting people and biodiversity via multiple, context-specific pathways. For example, gold mining and logging introduce environmental degradation that facilitates the transmission of vector-borne diseases such as malaria[59–61], leishmaniasis[62,63], hantaviruses[64], and Chagas disease[65]. New ecological niches are created that pave the way for the introduction of disease vectors that are well-adapted and can sustain diseases over the long term[10,11]. Land transformation for agriculture creates a similar setting for the encroaching of "frontier" malaria[66] and possibly leishmaniasis. Over time, large-scale industrial agriculture exacerbates climate change[67,68], and reduces the diversity and quality of the food supply. These factors contribute to the double burden of malnutrition and increased risk of obesity and cardiovascular disease later in life.

Many of the synergies described above have been in place for decades and have often magnified the inequities that historically plagued the Amazon basin[69]. What is different today is the magnitude and scale of degradation already inflicted, their cumulative effects, and the declining potential to reverse these processes.

Uncertainties and knowledge gaps Complex relationships prevent broad generalizations about the comprehensive impact of environmental degradation on human well-being and health. Characterizing these complex relationships requires more detailed studies, covering broader temporal and spatial scales. Furthermore, there is a great need to expand research beyond physical health to broaden our understanding of how environmental degradation affects mental health. Analyzing and predicting diverse impacts interacting at various scales requires broad, flexible conceptual frameworks. Ecosystem approaches can be valuable to better understand the interactions, synergies, and overall complexities inherent in the relationships among forest loss, water resource degradation, and human health. Similarly, multidisciplinary research combining fields such as earth observation, data science, mathematical modelling, economics, social sciences, and anthropology will be critical to quantify these knowledge gaps and address uncertainties.

Conclusions The relationship between forest conversion and fragmentation and the incidence of infectious disease is complex, scale-dependent, and often modulated by socioecological feedbacks. Certain disease vectors can increase along deforestation frontiers, while emerging diseases associated with zoonotic spillover of hantaviruses and arenaviruses have been linked to deforestation activities. In addition, the spatial matrix, abundance of domestic animals and specific human activities modulate disease burden in complex ways. There is an urgent need to better clarify the relationship between the individual and cumulative impacts of different environmental disturbances to better target policies to minimize their impacts. Environmental degradation is not only an ecological problem, it is a socioeconomic and health issue, affecting millions of Amazonians.

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