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Working Group7

LAND-USE DYNAMICS AND IMPACTS ON ECOLOGICAL PROCESSES, ECOSYSTEM SERVICES, AND HUMAN WELLBEING

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CHAPRTER 21 - HUMAN WELL-BEING AND HEALTH IMPACTS OF THE DEGRADATION OF TERRESTRIAL AND AQUATIC ECOSYSTEMS

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Chapter 21

HUMAN WELL-BEING AND HEALTH IMPACTS OF THE DEGRADATION OF TERRESTRIAL AND AQUATIC ECOSYSTEMS

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Chapter 21

ACRONYMS AND ABBREVIATIONS INCLUDING CHEMICAL SYMBOLS, COMPOUNDS

As - arsenic

ASGM - artisanal and small-scale gold miners

Cd – cadmium

CH_4 - methane

Co - cobalt

CO - carbon monoxide

CO2 - carbon dioxide

COVID-19 - Coronavirus Disease

Cu - Copper

Hg- mercury

IQ - Intelligence quotient

Me-Hg - methyl-mercury

MERS - Middle East Respiratory Syndrome

Mn – manganese

N - nitrogen

N2O - nitrous oxide

Ni - nickel

NOx - nitrogen oxides

Chapter 21

Pb- lead

PM – particulate matter

SO_2 - sulfur dioxide

WHO - World Health Organization

Zn - zinc

Chapter 21

INDEX

KEY MESSAGES

- Substantial evidence exists that environmental degradation can have acute and chronic impacts on human health.

- Outbreaks and increased incidence of different emerging, re-emerging, and endemic infectious diseases in the Amazon are associated with environmental changes, driven by a range of factors such as rapid human population growth, urbanization, and/or economic development activities. Deforestation and associated degradation of forest and aquatic ecosystems may facilitate the spread of infectious diseases and increase the likelihood of emergence of new zoonotic diseases. The short- and long-term health impacts of fire-related air pollution and mercury contamination from deforestation, dams, and mining activities are also well-described.

- Although we don’t know all of the detailed mechanisms and synergistic impacts, the evidence to date suggests an urgent need for action to avoid severe and persistent declines in human health and wellbeing due to environmental degradation throughout the Amazon.

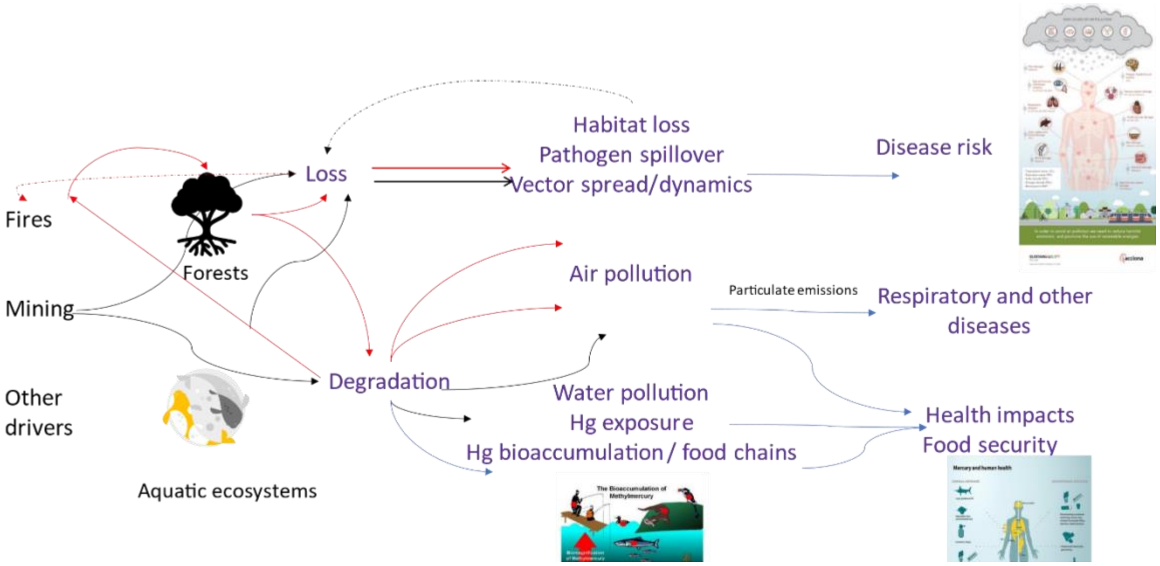
Chapter 21

ABSTRACT

Forests and aquatic ecosystems are the basis for 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 current health problems are associated with deforestation and degradation of terrestrial and aquatic ecosystems, including the risk of contracting infectious diseases, respiratory problems caused by exposure to smoke from forest fires, and mercury (Hg) contamination due to mining and other deforestation practices. Emergent, re-emergent, and endemic infectious diseases in the Amazon have all been associated with environmental changes driven by rapid human population growth and/or socioeconomic transition. Yet the relationship between forest conversion and fragmentation and the incidence of infectious disease is complex, scale-dependent, and heavily modulated by socio-ecological feedbacks. Amazonia is also a region of exceptionally high (yet poorly known) diversity of viruses and viral hosts, exacerbating the risks of potential zoonotic spillovers. Another major environmental and public health concern in the Amazon basin is mercury contamination resulting from gold mining, hydropower dams, deforestation, and petroleum extraction. Not only are Amazon basin communities exposed to high Hg concentrations at risk of toxicological contamination, but environmental effects on water resources, fisheries and wildlife are seen throughout Amazonian ecosystems. As a result, communities with high levels of fish consumption present some of the world’s highest recorded Hg levels. Forest fires are also a big concern, since they emit large quantities of particulate matter and other pollutants that degrade air quality and affect human health, especially among vulnerable groups in the Amazon. Here we demonstrate that environmental degradation is also a socio-economic issue, affecting the health of millions of Amazonians.

Keywords: human well-being, human health, environmental degradation, pollution, tropical disease.

GRAPHICAL ABSTRACT [draft, to be developed]



Chapter 21

1. INTRODUCTION

According to the World Health Organization, health is “a state of complete physical, mental and social well-being”, going beyond the absence of disease or illness (World Health Organization 1947). Enjoying a clean and sustainable environment is critical for human health and well-being (European Environment Agency 2020) and preserving crucial regions such as the Amazon Basin is central to achieving that goal. However, quantifying the risks and impacts of environmental degradation to 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 of Indigenous populations and traditional communities undoubtedly have a profound long-term impact on the well-being of already vulnerable populations (Athayde and Silva-Lugo 2018; Damiani *et al.* 2020), but these impacts are hard to measure. On the other hand, there is a substantial body of literature that specifically addresses the impacts of deforestation and environmental degradation on physical health (Ellwanger *et al.* 2020; White and Razgour 2020), which will be the focus of this chapter. Here, we address physical health problems in the Amazon resulting from deforestation and the degradation of terrestrial and aquatic ecosystems, focusing on the risks of contracting infectious diseases, respiratory problems caused by forest fires, and mercury contamination due to pollution.

There are multiple drivers of deforestation and overall environmental degradation in the Amazon, including agricultural and cattle ranching land-use changes, logging, fires, mining, urban expansion, and hydropower dams, among others (Kalamandeen *et al.* 2018; Piotrowski 2019). The type and level of degradation associated with each activity can have specific impacts on infectious disease transmission, particularly zoonotic or vector-borne diseases (Ellwanger *et al.* 2020). They may also contribute to other health problems such as respiratory syndromes, food security, and contamination invulnerable populations. Processes related to these activities can have additional, often compounding impacts on well-being, many of which are beyond the scope of this chapter. For example, illegal logging and mining can introduce forced labor and human trade, drug use, and an increase in HIV and sexually transmitted diseases (Wagner and Hoang 2020). Increased population density in urban settings facilitates the transmission of respiratory infections, as seen with

COVID-19 (Rader *et al.* 2020) – which can be further exacerbated by poor air quality and exposure to smoke from biomass burning. Uncontrolled urbanization and the lack of sanitation and urban planning can also increase the incidence of arboviruses and diarrheal diseases in growing Amazonian cities (Viana *et al.* 2016; Lowe *et al.* 2020). Finally, environmental degradation and urbanization can lead to food insecurity by undermining diverse, sustainable diets and increasing reliance on mass-produced foods from crops and livestock, which can be vulnerable to extreme climate events such as droughts, floods, and fires (Sundström *et al.* 2014).

2. 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. Emerging diseases are those that have recently been discovered, while re-emerging diseases are those that were controlled in the past but have emerged as a problem once again. The incidence of emerging and re-emerging infectious diseases in the Amazon is expected to rise with deforestation and anthropogenic climate change, but there are important differences depending on the dynamics of each infectious agent. For example, vector-borne diseases such as Malaria have received much attention because of their incidence, events of re-emergence, and important socio-ecological determinants of transmission and control. In contrast, the potential for emerging zoonotic diseases, particularly of viral origin, has received far less attention (Box 1). Surveillance for wildlife viruses has revealed the Amazon to be a hotspot of coronavirus diversity (Anthony *et al.* 2017), for example, with essentially unknown risks for spillover to human populations. Rabies is perhaps the best documented viral zoonotic disease in the region (Gilbert *et al.* 2012). Finally, while the risk of zoonotic acquisition of infectious diseases such as Yellow fever is well-documented, less is known about the risk of environmental change generating human-to-wildlife spillbacks, establishing wildlife reservoirs for other arboviruses (e.g., the causal agents of dengue fever, Chikungunya, and Zika) (Valentine *et al.* 2019), or even the SARS-CoV-2 coronavirus itself (Botto *et al.* 2020). Here, we summarize the literature on the association between environmental change and risks from emerging and re-emerging infectious diseases in the Amazon.

2.1. Malaria

Decades of work on deforestation and malaria in the Amazon have yielded evidence for non-linear, scale-dependent relationships with disease incidence (Laporta 2019), and important feedbacks from disease incidence to deforestation (MacDonald and Mordecai 2019). Analyses of the density of *Anopheles darlingi*, the main Malaria vector in South America, show a positive relationship with recent deforestation (Vittor *et al.* 2006, 2009; Burkett-Cadena and Vittor 2018), suggesting that forest clearing could increase the risk of Malaria near forest edges. In regions with consolidated human settlements, however, the incidence of Malaria is positively correlated with forest cover (Valle and Clark 2013; Valle and Tucker Lima 2014) . 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 (Barros and Honório 2015; Terrazas *et al.* 2015) and forest patches in urban areas.

Socioeconomic factors, including the hours of human activity and migration patterns, may also play important roles in modulating risk and disease outcomes. For example, crepuscular activities before dawn or at sunset were associated with higher risk of Malaria in the Peruvian Amazon (Andersen *et al.* 2000), highlighting strong interactions between vector ecology and human activities. Likewise, at a different spatial scale, the presence of both gold mining and higher rural incomes were linked to higher Malaria incidence in Brazil (Valle and Tucker Lima 2014), demonstrating how rapid environmental change coupled with economic development 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 (MacDonald and

Mordecai 2019). Such complex socioecological feedbacks are still poorly understood, but they underscore the intimate relationship between environmental change and human health.

2.2. Chagas

Although less studied than anophelines that transmit Malaria, the vectors for Chagas disease (i.e., the triatomine bugs *Rhodnius* and *Triatoma*) and leishmaniasis (i.e., the phlebotomine sandflies in the genus *Lutzomya*) also respond 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 (Brito *et al.* 2017). 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. It is still unclear whether these juices become contaminated due to the presence of bug faeces or because infected bugs themselves are mixed in with the fruit during food preparation (Valente *et al.* 2009; de Barros Moreira Beltrão *et al.* 2009; Sousa Júnior *et al.* 2017). 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 (Brito *et al.* 2017)— experience outbreaks from a different epidemiological mechanism (Ellwanger *et al.* 2020).

2.3. American cutaneous leishmaniasis

Socioecological interactions are also evident for leishmaniasis, another important and neglected vector-borne disease in the Amazon. Like Malaria, environmental factors such as deforestation may correlate positively with the incidence of cutaneous leishmaniasis (Olalla *et al.* 2015; Gonçalves-Oliveira *et al.* 2019), but at least one study has found decreasing incidence as a function of forest loss (Rodrigues et al. 2019). Socioeconomic factors, and a strong dependence on longer-term landscape trajectories might explain these conflicting results. For example, across Amazonian municipalities, cutaneous leishmaniasis decreases with health system effectiveness (Rodrigues et al. 2019). 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 (Rosário *et al.*

2016). Thus, nonlinear relationships between forest loss and disease risk are mediated by their interactions with a diverse vector fauna and local health systems.

2.4. 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 (Figure 1, Anthony *et al.* 2017). Increased human population densities also increase the potential for zoonotic spillovers (Figure 1, Olival *et al.* 2017) . Risk predictions were originally based on bat species richness, after finding both alpha- and beta-coronaviruses in a few bat species, notably the virus subfamily including the human pathogens that cause SARS, MERS and SARS-CoV-2 (Anthony *et al.* 2017). Other viruses also circulate in the Amazon region and present serious risks of widespread outbreaks, including the Rocio, Oropouche, Mayaro and Saint Louis arboviruses (Vasconcelos *et al.* 2001; Araújo *et al.* 2019) as well as hantaviruses (Guterres *et al.* 2015) and arenaviruses (Bausch and Mills 2014). Given the scant record, our understanding of the potential for land-use change to increase spillover risk remains limited.

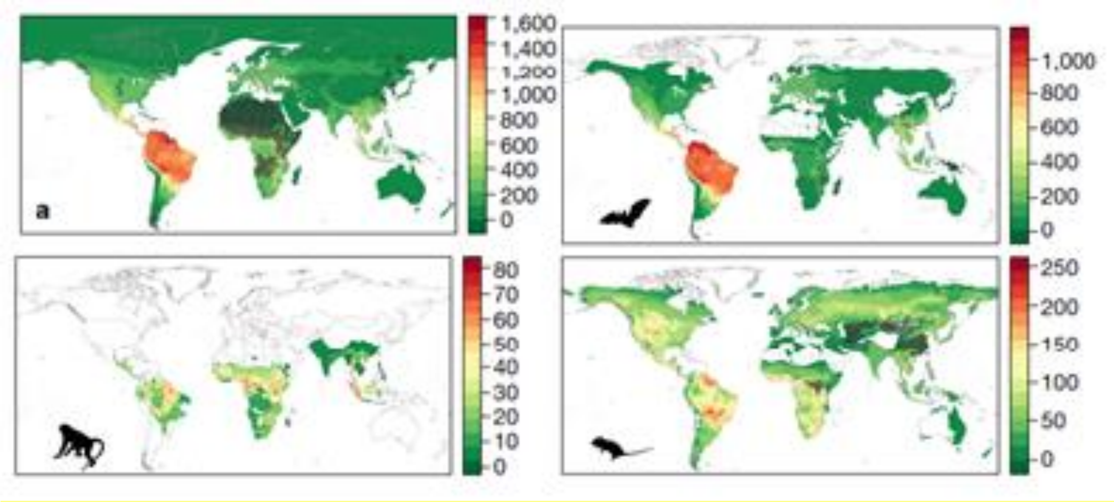


Figure 1. Predicted number of missing zoonoses by order in the Amazon basin. a. All wild mammals, b, bats, c, primates and e, rodents. Adapted from Olival et al 2017 and Anthony et al 2017.

Nevertheless, global surveillance for viruses of zoonotic potential offers key lessons for preventing future zoonotic spillovers. Because 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 (Holmes *et al.* 2018; Carlson 2020). 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 hyperdiverse 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.

One global coronavirus pandemic, COVID-19 has reminded the world about the risks of zoonotic spillovers. However, the potential for spillback from humans to wildlife is just as important for biodiversity (Nuñez et al. 2020). 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 killing dozens of non-human primates prompted an early public health response to vaccinate people (Fernandes *et al.* 2017). 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 (Valentine *et al.* 2019). 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 (Valentine *et al.* 2019). As with the risk of zoonotic emergence, averting the establishment of zoonotic reservoirs for arboviruses requires sustained investments in public health, including the necessary tools to diagnose the diversity of viruses circulating in the human population. As the COVID-19 crisis has revealed, public health infrastructure is woefully inadequate throughout the Amazon (de Castro *et al.* 2020; Navarro *et al.* 2020), emphasizing the need to consider socioecological risks arising from human migration, contact with wildlife and disease vectors, and deforestation.

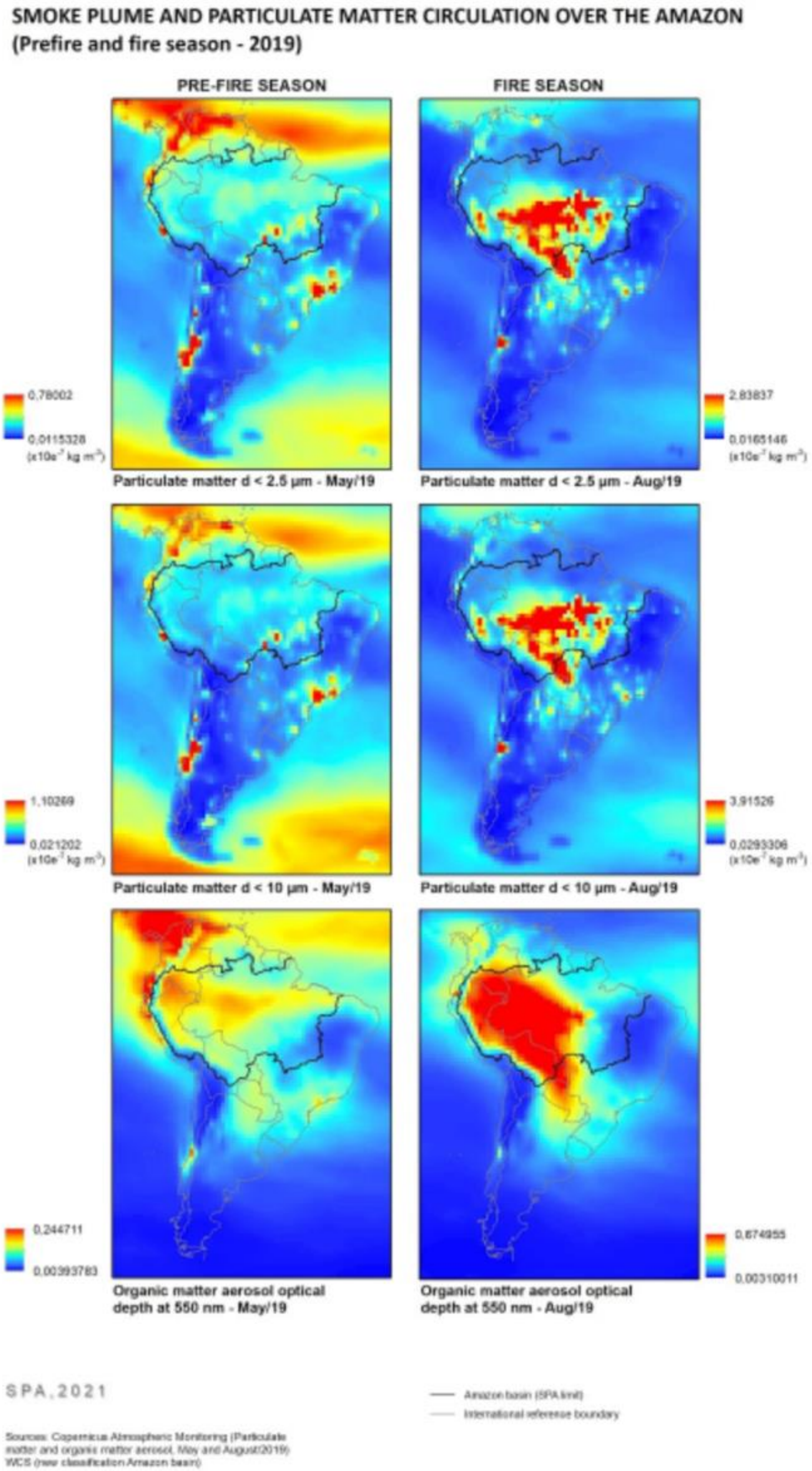
3. IMPACTS OF MERCURY CONTAMINATION FROM MINING ON HUMAN HEALTH

Between 2000 and 2010, the price of gold quadrupled, stimulating gold mining activities in Amazonia (Swenson *et al.* 2011; Alvarez-Berríos and Mitchell Aide 2015), with severe environmental consequences for terrestrial and aquatic ecosystems in the region (See Chapter 19 and Chapter 20, respectively). 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) (Filho and Maddock 1997; Pereira *et al.* 2020). These elements are associated with a variety of adverse health effects elsewhere, including childhood mortality. However, the impacts of these substances on human health in Amazonia are still largely unknown. The main impact of gold mines on human health is mercury (Hg) contamination – a result of both legal and illegal mining. Communities living near gold mining operations are exposed to harmful Hg concentrations released during gold extraction and discharged into waterways, soils, and the atmosphere (Gibb and O'Leary 2014). Once the inorganic metallic mercury (Hg) is released by anthropogenic activities, it is transformed into its more toxic organic form (methyl-mercury, MeHg) by specific bacteria, usually in anoxic conditions. This process of mercury methylation allows MeHg to enter aquatic food webs, where it may accumulate in individual organisms (bioaccumulation) or be magnified as it moves into higher trophic levels (e.g., biomagnification in predatory fish) (Morel *et al.* 1998; Ullrich *et al.* 2001) and can affect fish that are of great importance for food security of local communities (Diringer *et al.* 2015), (Box 2).

Despite the lack of systematic analyses, studies from Colombia, Peru, and Bolivia over the course of the last 20 years have documented mercury poisoning even in remote Indigenous populations. The median Hg concentration in the adult group reached 16.0 µg/g (The internationally recommended limit of hair mercury concentration is 1µg/g as proposed by the WHO). Indigenous Kayabi, from Teles Pires, presented average Hg in hair of 12.8 µg/g. Similar studies conducted by the Yaigojé Apaporis National Natural Park and the University of Cartagena reported high Hg levels in Indigenous populations in the Caquetá River, basin in the Colombian Amazon for Bocas de Taraira, Ñumi, Vista Hermosa, and Bocas de Uga communities. Further, mercury 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 (Rice *et al.* 2014). 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 (Gibb and O'Leary 2014). Studies investigating associations between Hg levels in hair and neuropsychological performance found strong links between mercury and cognitive deficiencies in children and adolescents across the Amazon, including the Madeira (Santos-Lima *et al.* 2020) and Tapajós rivers in Brazil (Grandjean *et al.* 1999) and the Madre de Dios region in Peru (Reuben *et al.* 2020). Hg can also impact the health of adults, as it affects the nervous, digestive, renal, and cardiovascular systems. Central nervous system effects include depression and extreme irritability; hallucinations and memory loss; tremors affecting the hands, head, lips, and tongue; blindness, retinopathy, and optic neuropathy; hearing loss; and a reduced sense of smell (IPCS, 2008). Minamata Disease was recently confirmed in Amazonian communities -- a result of exposure to high levels of MeHg, with symptoms including tremors, insomnia, anxiety, altered tactile and vibration sensations, and visual perimeter deficit.

4. IMPACTS OF FOREST FIRES ON AIR QUALITY AND HUMAN HEALTH

Both 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 (Smith *et al.* 2015). The dry season is the most critical period for population exposure to smoke from fires - particulate matter levels during these months (Figure 2) are usually well above the World Health Organisation's (WHO) recommended safe levels (0.5 mg.kg- 1). Emergency room visits increase during the dry season, especially among children under the age of 10. They are positively correlated with PM2.5 concentrations (i.e., particulate matter <2.5 micrometers in diameter), which correspond to fine particles present in smoke (Mascarenhas *et al.* 2008). Fine particles can remain in the atmosphere for up to one week, and may be transported far downwind to urban areas, where they may impact the health of populations far from the fire origin (Freitas *et al.* 2005; Liana Anderson and Marchezini 2020).



Sources: Copernicus Atmospheric Monitoring (Particulate matter and organic matter aerosol, May and August/2019) WCS (new classification Amazon basin)

Figure 2 . Smoke plume and particulate matter circulation over the Amazon in May 2019 and August 2019.

Other components of smoke are PM10 (i.e., particulate matter <10 micrometers in diameter) and soot and Black Carbon – both of which are also very toxic to humans. PM10, for example, has the potential to cause DNA damage and cell death (Alves 2020), leading to the development of PM10-mediated lung cancer (ALVES, ET AL 2017). These inhalable particles were classified as class 1 carcinogens in 2016 (IARC Working Group On The Evaluation Of Carcinogenic Risks To Humans; International Agency For Research On Cancer, 2016). They can penetrate the alveolar regions of the lung, pass through the cell membrane, reach the bloodstream, and accumulate in other organs. PM2.5 and Black Carbon are associated with reduced lung function in children 6 to 15 years old (Jacobson *et al.* 2012, 2014; Jacobson 2013). School children from municipalities with high levels of deforestation, and therefore exposed to deforestation fires and smoke, have a high asthma prevalence (ROSA et al 2009 and FARIAS et al 2010). Smoke can also affect children's well-being indirectly, for example, by reducing outdoor time and, thus, compromising cognitive development.

Pregnant women are also highly vulnerable to smoke pollution. Silva et al. (2014) showed that exposure to particulate matter (PM2.5) and carbon monoxide (CO) from biomass burning during the second and third trimesters increased the incidence of low birth weight (LBW) by 50%. This is consistent with previous studies demonstrating that the exposure of pregnant women to deforestation and forest fires during pregnancy may increase the risk of premature birth and jeopardize the child's development.

5. INTERACTIONS BETWEEN IMPACTS

The drivers of forest and aquatic ecosystem degradation in the Amazon can have synergistic impacts on human wellbeing. Interactions among drivers and impacts of degradation are complex phenomena 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 (Galardo *et al.* 2013; Adhin *et al.* 2014; Sanchez *et al.* 2017), Leishmaniasis (Rotureau *et al.* 2006; Loiseau *et al.* 2019), Hantaviruses (Terças-Trettel *et al.* 2019) and even Chagas disease (Almeida *et al.* 2009). Historically, such activities also attract large numbers of immigrants from non-endemic regions (Godfrey 1992), many of whom are susceptible and immunologically naïve (Bury 2007). If large outbreaks and epidemics take place, insecticide and antimicrobial resistance can follow if drug use is not controlled (Adhin *et al.* 2014). Insecticide resistance arising from excessive use of pesticides in croplands (Schiesari and Grillitsch 2011) can spill over to other vector populations as well (Schiesari *et al.* 2013). 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 (Vittor *et al.* 2006, 2009). Heavy metal poisoning, alcohol and drug use and abuse, prostitution, and human trafficking can further exacerbate these conditions, decreasing human wellbeing (Terrazas *et al.* 2015). Local Indigenous populations are affected, and many are displaced and forced to leave or clash with illegal settlers (Terrazas *et al.* 2015). Variations of these scenarios have been observed clearly in Madre de Dios, Peru, the Guiana Shield, and the garimpos of Pará, Brazil (Terrazas *et al.* 2015). Countless areas of the Amazon replicate similar conditions at a smaller scale.

Land transformation for agriculture creates a similar setting for the encroaching of "frontier" Malaria (Bourke *et al.*, 2018) and possibly Leishmaniasis. Several studies have shown that populations close to forest edges, such as those engaged in artisanal small-scale gold mining (Hacon *et al.* 2020) are at higher risk of contracting infectious diseases due to their increased contact with vectors and hosts (Ellwanger *et al.* 2020). Over time, large-scale industrial agriculture exacerbates climate change, increases contamination by pesticides (Schiesari and Grillitsch 2011; Schiesari *et al.* 2013), and reduces the diversity of the food supply. These factors contribute to the double burden of malnutrition and increased risk of obesity and cardiovascular disease later in life (Oresund 2008).

Roads and even rivers eventually facilitate the transit of *Aedes* mosquitoes to colonize small and previously difficult to reach towns and settlements (Guagliardo *et al.* 2014; Sinti-Hesse *et al.* 2019). Forest fire exposure introduces acute respiratory conditions and can also induce long-term vulnerabilities such as asthma (D'Amato *et al.* 2015; Rappold *et al.* 2017). Among cases of Covid-19 (Box 3), many of these comorbidities have severely increased the risk of adverse outcomes and may have contributed to the devastating impact of the pandemic in the Amazon basin (Filho 2017).

Many of the synergies described above have been in place for decades. For example, the gold rush in Madre de Dios dates back to the 1930s. Such synergies have often magnified the inequities that historically plagued the Amazon basin within each country, and the colonial history of the Amazon basin seems to correlate with this hypothesis (Dávalos *et al.* 2020). What is different today is the magnitude and scale of degradation already inflicted, their cumulative effects, and the declining potential to reverse these processes. Decades of degradation have led the Amazon to a critical point today, generating an urgent need to implement integrated strategies for addressing these challenges. The recent growth in the number and extent of drivers of deforestation has further contributed to this critical scenario.

6. UNCERTAINTIES AND KNOWLEDGE GAPS

Complex relationships prevent broad generalizations about the comprehensive impact of environmental degradation on human wellbeing and health. While extensive evidence exists, it is often limited to specific settings using a "case study" research approach (Magliocca 2018). Characterizing these complex relationships requires both more detailed studies and studies that cover broader temporal and spatial scales, as illustrated by research on the relationships between Malaria incidence and deforestation. Furthermore, there is a great need to expand research beyond physical health to broaden our understanding of how environmental degradation affects the mental health of rural and urban Amazonians.

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.

Because the Amazon is highly heterogeneous, studies of the impacts of environmental degradation on human health and wellbeing are needed at different levels of geographic granularity. These range from Amazon-wide and country-level models to estimates for specific locations and issues of individual health and wellbeing. Similarly, models at different timescales will improve our perspectives on these complex issues. Such information is crucial for effectively guiding decision-making at all levels.

7. CONCLUSIONS

- Degradation of terrestrial and aquatic ecosystems generates complex chain reactions with a range of impacts on human health and well-being.

- Disease outbreaks and the increased incidence of emerging, re-emerging, and endemic infectious diseases in the Amazon are associated with a range of environmental changes. 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 (e.g., Malaria vector *Anopheles darlingi*, Chagas vector *Rhodnius*, and Leishmania vector *Lutzomya*), can increase along deforestation frontiers. However, the spatial matrix, abundance of domestic animals and specific human activities, modulate the disease burden in complex ways.

- Although the burden of Malaria and cutaneous leishmaniasis may decrease in structured urban areas , heavily urbanized settings in the Amazon can provide niches that facilitate the spread of other arboviruses transmitted by vectors such as *Aedes aegypti* and *Aedes albopictus*.

- Emerging diseases associated with the zoonotic spillover of hantaviruses and arenaviruses have been linked to specific deforestation activities.

- Mercury contamination from mining activities has been shown to produce neurological, motor, sensory, and cognitive declines in exposed Amazonian populations. Unless addressed now, mercury toxicity will have lasting effects on future generations, given the scale and growth of mining activities; the processes of bioaccumulation and biomagnification; and specific health impacts on developing embryos and youth.

- The complex interactions and negative synergies between the different impacts and their pathways are not clearly understood yet. Moreover, there is a need to understand the relationship between the individual and cumulative impacts of different environmental disturbances.

8. RECOMMENDATIONS

- Given the important influence of socioecological factors on disease burden, improving human health in the Amazon will require uncovering all environmental risks, managing landscapes, and promoting equitable solutions.
- To reduce the risk of viral emergence from wild populations, region-wide improvements to public health services (including access, environmental sanitation, and health facilities) and close surveillance of infectious diseases in human population are necessary.
- Prevention of infectious diseases also 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.
- 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.
- Tailored public health strategies are needed to target each specific problem, but these measures require better integration of actions across different sectors and spheres of society.
- Innovative methods and approaches are needed to address the challenge of the broader, cumulative impacts of forest and aquatic ecosystem degradation on human health.

Chapter 21

- It is necessary to recognize that the Amazon Basin is crucial for human subsistence, especially for traditional communities and Indigenous peoples who depend on the Amazon's natural resources for their survival.

- Efforts are necessary to formulate legitimate participatory management policies, developed in an intercultural framework (e.g., Indigenous, academic, and institutional) to enhance strategies for climate resilience, sustainability, 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.

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10. CORE GLOSSARY

Sources: Global Environmental Outlook 6 (GEO6), Millennium Ecosystem Assessment (MA), European Centre for disease Prevention and Control

Arboviruses. Viruses that are transmitted by arthropod vectors, such as mosquitoes and ticks. A number of diseases found in the Amazon are caused by arboviruses, including chikungunya, dengue, yellow fever, and zika.

Bioaccumulation. The increase in concentration of a chemical in organisms. Also used to describe the progressive increase in the amount of a chemical in an organism resulting from rates of absorption of a substance or element in excess of its metabolism and excretion. [GEO6]

Biohazard. Infectious agents or hazardous biological materials that present a risk or potential risk to the health of humans, animals, or the environment. The risk can be direct through infection or indirect through damage to the environment. Biohazards include certain types of recombinant DNA, organisms and viruses infectious to humans, animals, or plants (e.g., parasites, viruses, bacteria, fungi, prions, and rickettsia), and biologically active agents (e.g., toxins, allergens, and venoms) that can cause disease in other living organisms or cause significant impact to the environment or community. [CDC]

Biomagnification. The build-up of certain substances in the bodies of organisms at higher trophic levels of food webs. Organisms at lower trophic levels accumulate small amounts. Organisms at the next higher level of the food chain eat many of these lower-level organisms and hence accumulate larger amounts. The tissue concentration increases at each trophic level in the food web when there is efficient uptake and slow elimination. [GEO6]

Black carbon. Operationally defined aerosol based on measurement of light absorption and chemical reactivity and/or thermal stability. Black carbon is formed through the incomplete combustion of fossil fuels, biofuel and biomass, and is emitted as part of anthropogenic and naturally occurring soot. It consists of pure carbon in several linked forms. Black carbon warms the Earth by absorbing sunlight and re-emitting heat to the atmosphere and by reducing albedo (the ability to reflect sunlight) when deposited on snow and ice. [GEO6]

Coronavirus. A family of RNA viruses, some of which can cause illnesses such as the common cold, severe acute respiratory syndrome (SARS) and the Middle East respiratory syndrome (MERS). A newly identified coronavirus, SARS-CoV-2, has caused a worldwide pandemic of respiratory illness, called COVID-19 (i.e., coronavirus disease 2019). [Mayo Clinic, John Hopkins].

Deforestation. Conversion of forested land to non-forest areas (Putz and Redford 2010).

Dengue. An infectious disease caused by any one of four related viruses transmitted by mosquitoes. The dengue virus is a leading cause of illness and death in the tropic and subtropics. [GEO6]

Disease. A condition that affects the functioning of the whole body, or parts of the body, of living animals or plants. It is typically manifested by distinguishing signs and symptoms. [Merriam-Webster]

Disease risk. The risk of acquiring a disease. Many different metrics of disease risk are used in epidemiological and ecological studies of disease systems, including the density of infected reservoir hosts, the prevalence of infection in reservoir hosts, the rate of change in the density of infected hosts, the density of infected vectors, and the infection prevalence in vectors, among many others [Keesing et al. 2006].

Emerging diseases. Diseases that have recently increased in incidence, impact, or geographic or host range; that are caused by pathogens that have recently evolved; that are newly discovered; or that have recently changed their clinical presentation. []

Endemic diseases. The constant presence of an agent or health condition within a given geographic area or population; can also refer to the usual prevalence of an agent or condition. [CDC]

Chapter 21

Environmental degradation. Environmental degradation is the deterioration in environmental quality from ambient concentrations of pollutants and other activities and processes such as improper land use and natural disasters.[GEO6]

Epidemiology. The branch of medicine which deals with the incidence, distribution, and possible control of diseases and other factors relating to health.[GEO6]

Equity. Fairness of rights, distribution and access. Depending on context, this can refer to access to resources, services or power. [GEO6]

Feedback. Where nonlinear change is driven by reactions that either dampen change (negative feedbacks) or reinforce change (positive feedbacks). [GEO6]

Food security. Physical and economic access to food that meets people's dietary needs as well as their food preferences.

Governance. The act, process, or power of governing for the organization of society/ies. For example, there is governance through the state, the market, or through civil society groups and local organizations. Governance is exercised through institutions: laws, property-rights systems and forms of social organization.[GEO6]

Hantaviruses. A genus of RNA viruses that are transmitted by rodents.

Heavy metals. A subset of elements that exhibit metallic properties, including transitional metals and semi-metals (metalloids), such as arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc, that have been associated with contamination and potential toxic.

Human health. Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. [GEO6]

Human well-being. The extent to which individuals have the ability to live the kinds of lives they have reason to value; the opportunities people have to pursue their aspirations. Basic components of human well-being include security, meeting material needs, health and social relations. [GEO6]

Chapter 21

Infectious disease. A disease caused by an exogenous agent (e.g. bacteria, virus) and that can be transmitted to other individuals.

Livelihood. A livelihood is a means of making a living. It encompasses people's capabilities, assets, income and activities required to secure the necessities of life. A livelihood is sustainable when it enables people to cope with and recover from shocks and stresses (such as natural disasters and economic or social upheavals) and enhance their well-being and that of future generations without undermining the natural environment or resource base. [IFRC]

Mental health. A state of well-being in which an individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively and is able to make a contribution to his or her community. [WHO]

Mercury methylation. The process of forming methylmercury (MeHg), an environmental contaminant that biomagnifies in aquatic food webs and poses a health hazard to aquatic biota, piscivorous wildlife, and humans. The primary source of MeHg to freshwater systems is methylation of inorganic Hg by anaerobic microorganisms, although methylation can occur via both biotic and abiotic pathways.

Minamata Disease. A neurological syndrome caused by severe methylmercury poisoning. It was first described in the inhabitants of Minamata Bay, Japan and resulted from their eating fish contaminated with mercury industrial waste. Symptoms include ataxia, numbness in the hands and feet, general muscle weakness, narrowing of the field of vision and damage to hearing and speech. In extreme cases, insanity, paralysis, coma and death follow within weeks of the onset of symptoms. A congenital form of the disease can also affect fetuses.

Neglected virus. Neglected diseases are the most common chronic and/or debilitating diseases among the world's poorest people. A neglected virus causes a neglected disease transmitted by a virus.

Neurotoxin. A poison that acts on the nervous system. [GEO6]

Chapter 21

Nutrient pollution. Contamination of water resources by excessive inputs of nutrients. [GEO6]

Nutrients. The approximately 20 chemical elements known to be essential for the growth of living organisms, including nitrogen, sulphur, phosphorus and carbon.[GEO6]

Overexploitation. The excessive extraction of raw materials without considering the long-term ecological impacts of such use.[GEO6]

Physical health. One of the health dimensions that refers to the state of the physical body and the proper functioning of the organism of individuals. [WHO]

Pollutant. Any substance that causes harm to the environment when it mixes with soil, water or air. [GEO6]

Pollution. The presence of minerals, chemicals or physical properties at levels that exceed the values deemed to define a boundary between good or acceptable and poor or unacceptable quality, which is a function of the specific pollutant. [GEO6]

Re-emerging diseases. Diseases that used to be a major global, regional or national problem, declined significantly, and now are becoming a major health issue again.

Social well-being. An end state in which basic human needs are met and people are able to coexist peacefully in communities with opportunities for advancement. It is characterized by equal access to and delivery of basic needs services (water, food, shelter, and health services); the provision of primary and secondary education; the return or resettlement of those displaced by violent conflict; and the restoration of social fabric and community life. [UNDP/USAID]

Socioeconomic. Of, relating to, or involving a combination of social and economic factors. [GEO6]

Spillback. Transmission of an infectious agent from an invasive species to a native one. It is usually used in the context of pathogen transmission from humans to animals.

Chapter 21

Spillover. Cross species transmission of an infectious agent. It is usually used in the context of animal to human spillovers (i.e. zoonotic spillovers)

Sustainable agriculture. Sustainable Agriculture puts the emphasis on methods and processes that improve soil productivity while minimizing harmful effects on the climate, soil, water, air, biodiversity and human health. It aims to minimise the use of inputs from nonrenewable sources and petroleum-based products and replace them with those from renewable resources. It Focuses on local people and their needs, knowledge, skills, socio-cultural values and institutional structures. It ensures that the basic nutritional requirements of current and future generations are met in both quantity and quality terms. It provides long-term employment, an adequate income and dignified and equal working and living conditions for everybody involved in agricultural value chains. It reduces the agricultural sector's vulnerability to adverse natural conditions (e.g. climate), socioeconomic factors (e.g. strong price fluctuations) and other risks. [GEO6]

Vector. A living organism (e.g. mosquitoes, beetles, rats) that transfer an infectious agent (e.g. bacteria, virus) from one host to another.

Vector-borne diseases. Diseases that, in order to be transmitted from one host to another, require a vector.

Vulnerability. An intrinsic feature of people at risk. It is a function of exposure, sensitivity to impacts of the specific unit exposed (such as a watershed, island, household, village, city or country), and the ability or inability to cope or adapt. It is multidimensional, multi-disciplinary, multi-sectoral and dynamic. The exposure is to hazards such as drought, conflict or extreme price fluctuations, and also to underlying socioeconomic, institutional, and environmental conditions.

Water quality. The chemical, physical and biological characteristics of water, usually in respect to its suitability for a particular purpose. [GEO6]

Water scarcity. The point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements such that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity is a relative concept and may refer both to physical shortages or to lack of access due to the failure of institutions to ensure a regular supply or adequate infrastructure. It occurs when annual water supplies drop below 1000 m^3 per person, or when more than 40 percent of available water is used. [UN-Water]

Water security. A term that broadly refers to the sustainable use and protection of water systems, the protection against water related hazards (floods and droughts), the sustainable development of water resources, and the safeguarding of (access to) water functions and services for humans and the environment.[GEO6]

Zoonotic disease (Also known as zoonosis). An infection or disease that is transmissible from animals to humans under natural conditions. [GEO6]

Chapter 21

11. BOXES

Box 1. Neglected Viruses in the Amazon

Authors: Cecilia S. Andreazzi

Outbreaks of febrile disease and hemorrhagic fevers have fostered virology research in the Amazon region and provided opportunities to find new viruses in humans and animals. Arthropod-borne viruse (arboviruses) research in the Amazon region started in the beginning of the 20th century, led by the Rockefeller Foundation research program to understand and control Yellow fever (Downs 1982). Over the past seven decades, studies conducted in the Brazilian Amazon have already isolated and characterized around 220 different arboviruses species, which is remarkable considering that there are around 500 species registered in the International Catalog of Arboviruses (Medeiros et al. 2019). Several species of hantaviruses and arenaviruses causing human illness have also been identified in the Amazon region (Gimaque et al. 2012; Fernandes et al. 2020; Delgado et al. 2008; Terças-Trettel et al. 2019). Such large numbers of viruses can be explained by the large biodiversity of both arthropod vectors and vertebrate hosts, as well as by the huge variety of ecological conditions that maintain and promote virus biodiversity (Rosa 2016; Medeiros et al. 2019). Despite the enthusiastic efforts of Latin American scientists (Rosa 2016), such viruses are underdiagnosed and neglected by health systems, despite being the most common infections among the world's poorest people (Hotez et al. 2008). Here, we describe some of these viruses found in Amazonia in more detail, and evaluate the possibility of disease emergence in the region.

Arboviruses are generally transmitted by arthropod vectors to their vertebrate host and circulate among wild animals, serving as reservoirs in the sylvatic life cycle. The most frequent hematophagous arthropods that may serve as arbovirus vectors include mosquitoes, ticks, sandflies, midges, and possibly mites (Medeiros et al. 2019). Through spillover transmission from enzootic amplification cycles, humans can be infected as incidental and dead-end hosts (P. F. da C. Vasconcelos et al. 1991). By contrast, some arboviruses undergo an urban cycle involving humans as amplifying hosts and have causedd several epidemics in urban areas (Medeiros et al. 2019). Most of the arboviruses that cause human/animal diseases belong to the *Togaviridae, Flaviviridae, Bunyaviridae, Reoviridae and Rhabdoviridae* virus families (Figueiredo 2007). Infections in humans and animals could range from subclinical or mild to encephalic or hemorrhagic, with a significant proportion of fatalities. In contrast, arthropods infected by arboviruses do not show detectable signs of infection, even though the virus may remain in the arthropod for life (Figueiredo 2007). Thirty-six arboviruses have been associated with human disease in the Amazonian region; seven of them are important in public health and are involved in epidemics. They are: Dengue, Chikungunya, Zika, Mayaro, Oropouche, Rocio, and Yellow fever viruses (Rosa 2016). Other important arboviruses are those associated with encephalitis, which in the Amazon are represented by the equine encephalitis viruses (Eastern, Western, and Venezuelan) and the Saint Louis encephalitis virus. Aside from these, several other arboviruses have been isolated from cases of acute febrile illness, including the viruses of the super group Bunyamwera: arboviruses of groups C and Guamá, and the viruses Tacaiuma, Guaroa, Tucunduba and Xingu, among others (P. F. C. Vasconcelos et al. 2001).

Viral hemorrhagic fevers are highly lethal diseases that produce hemorrhagic disorders and fluid leakage syndromes, with or without capillary damage, that affect the liver, kidneys and central nervous system (Bausch e Ksiazek 2002). Viral transmission to humans occurs through the bite of an infected arthropod (which includes some arboviruses), or inhalation of particles from the excreta of infected rodents (Figueiredo 2006). More than 25 different viruses from six families are related to hemorrhagic fevers worldwide. In the Amazon region, *Flaviviridae* (hemorrhagic dengue / dengue shock syndrome and yellow fever), , *Hantaviridae* (hemorrhagic fever with hantavirus renal syndrome and hantavirus pulmonary and cardiovascular syndrome), and *Arenaviridae* (Junin, Machupo, Guanarito and Sabiá hemorrhagic fevers deserves special attention (Figueiredo 2006).

As unsustainable economic activities increasingly expand over the Amazon, so does the risk of contact between humans and vectors/transmitters of zoonotic disease agents including arboviruses, hantaviruses, arenaviruses, rabies. There is evidence showing that construction of the Tucuruí hydroelectric dam in the Tocantins River led to the emergence of almost 40 arboviruses, 30 of them described for the first time after the dam construction

(P. F. C. Vasconcelos et al. 2001). Experts list at least 10 types of virus as most likely to emerge in the Amazon due to increased human interference in the region: *Flaviviridae* (yellow fever, dengue, and hepatitis C viruses), *Bunyaviridae* (hantavirus, and Oropouche, Rift Valley fever, and Crimean-Congo hemorrhagic fever viruses), *Rhabdoviridae* (rabies virus), *Filoviridae* (Ebola virus), *Togaviridae* (chikungunya and Mayaro viruses), *Papillomaviridae* (human papillomavirus), *Hepadnaviridae* (hepatitis B virus), *Orthomyxoviridae* (influenza virus), *Coronaviridae* (severe acute respiratory syndrome coronavirus), and *Retroviridae* (human T-cell lymphotropic virus) (do Vale Gomes et al. 2009). One of the main challenges involved in early detection, prevention, and mitigation of emerging viruses in the Pan-Amazonian region is the lack of molecular diagnosis in the syndromic surveillance of febrile diseases. Many infections result in similar symptoms and because there is a high diversity of prevalent viruses such as Dengue, it is crucial to improve local health units, implementing sentinel areas and systematic monitoring of viral circulation in humans, vectors, and reservoirs. An integrated surveillance, monitoring and networking system with strong intersectoral collaboration and coordination between animal, human health and environmental sectors is necessary to prevent, control, and mitigate emerging zoonoses (Andreazzi et al. 2020).

Chapter 21

Box 2 Food security and fisheries.

Authors Marcia Macedo, Fabrice Duponchelle, Sebastian Heilpern, David McGrath

Fish historically have great societal importance as one of the main sources of protein and other essential animal- derived nutrients (e.g., fatty acids, iron, zinc) for people of the Amazon (Veríssimo 1895). They accounted for up to 75% of the vertebrate species consumed in early human settlements (750 to 1020 A.D.) in Brazil, for example (Prestes-Carneiro et al. 2015). The long cultural and socioeconomic dependence on fish is also illustrated by the fact that fishing was one of the first subsistence and economic activities in the Amazon (Furtado 1981; Erickson 2000; Blatrix et al. 2018). Today, even outside professional fisher communities, most Amazonians living in riverbank cities and riverine communities have some members of the family engaged in this activity (Cerdeira et al. 2000; Agudelo et al. 2006; Doria et al. 2016). Fishing is not always a core activity, but can be complementary to other productive activities sustaining livelihoods, such as farming, animal husbandry, and harvesting of natural products (Agudelo et al. 2000; Ruffino & Isaac 2000). Floodplain fisheries often act as safety nets for many Indigenous and poor rural communities who turn to fish more than to forest products when faced with adversity (Coomes et al. 2010).

The importance of fish to Amazonians is also emphasized by some of the world's highest consumption rates, although they can vary substantially across river basins (Isaac & Almeida 2011); with conservation status and isolation of the region (Isaac et al. 2015; Van Vliet et al. 2015); or with cultural and regional preferences (Begossi et al. 2019). The average per capita rate ranges from 30-40 kg.year-1 for urban populations and from 70-200 kg.year-1 for rural population (Batista et al. 1998; Isaac & Almeida 2011; Doria et al. 2016; Doria et al. 2018; Isaac et al. 2015). These per capita rates are well above the world average of ~ 20 kg.year-1 (Tacon & Metian, 2013) and the recommendation by the World Health Organization of 12 kg year-1 (WHO, 2007).

Estimates indicate that ~ 600,000 tons.year-1 of fish are consumed in the Brazilian Amazon (Isaac & Almeida, 2011) and 29,000 tons year-1 in the Colombian Amazon (Agudelo, 2015). This represents three times the total commercial landings reported for the Amazon basin as a whole (173,000 to 199,000 tons.year-1, Bayley & Petrere 1989; Barthem & Goulding, 2007). Although part of this consumption could be accounted for by marine fisheries and aquaculture in the large Amazonian cities, these figures clearly indicate that in the Amazon basin (as in other tropical freshwater fisheries), unreported subsistence catches are strongly underestimated (Fluet-Chouinard et al. 2018) and may be of the same order of magnitude as commercial fish landings (Tello & Bayley 2001; Crampton et al. 2004). Another figure illustrates the importance of fish for the food security of Amazonian people: in the Brazilian Amazon alone, the fisheries sector directly employs 168,000 people and generates a total yearly incomes of up to US $200 million (Petrere 1992; Barthem et al. 1997).

Although declines in total fish biomass have yet to be documented conclusively, signs of overexploitation are evident in changes to fish biodiversity. In Brazil, for example, large tambaqui are virtually absent near urban centres (Tregidgo et al. 2017). These ongoing changes in biodiversity have two implications for food security. First, changes in species composition reflect a sequential replacement of large and high-biomass species such as catfish and boquichico with smaller, faster growing species. This pattern of "fishing down a size" could result in declining long-term resilience, and eventual biomass collapses (Heilpern et al. in review). The second implication for food security is that fish provide people with a variety of nutrients beyond protein, but they vary in nutritional quality (Tacon & Metian 2013; Tilami & Stampels 2018; Hick et al. 2019). By changing biodiversity, anthropogenic threats to freshwater ecosystems may affect both the amount of nutrients available to people and the probability of meeting nutritional adequacy (Heilpern et al. in review).

Increased urbanization in the Amazon basin is also shifting food habits. While riverine communities still consume high amounts of wild-caught fish and some bushmeat, urban and peri-urban communities are consuming higher proportions of aquaculture-fish, chicken and other derivative products (Nardoto et al. 2011; Van Vliet et al. 2015, Pettigrew et al. 2019, Oestreicher et al 2020). Such changes in the food habits of Amazonian people, together with reduced diversity in the fish species consumed, could exacerbate existing nutritional deficiencies since farmed animal foods can have lower nutritional value, particularly omega-3 fatty acids and minerals (e.g., iron, selenium; Heilpern et al. in review, Pettigrew et al. 2019).

The shift to domesticated sources of animal foods has another profound implication for food security – a shift from subsistence, wild-caught foods to foods that are more capital intensive and depend on access to cash. Because they are less affordable, this shift can ultimately affect livelihoods and access to healthy diets. Compounding these issues, the nutritional transition to a more Westernized diet is also associated with higher fat and sugar intake, which can exacerbate the dual burden of malnutrition and obesity playing out through the Amazon.

Chapter 21

Box 3: The impact of Covid-19 in the Amazon region

Cecilia S. Andreazzi, Tatiana C. Neves and Cláudia T. Codeço

In December 2019, it was discovered a new emergent respiratory viral disease caused by a previously unknown coronavirus, the severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2), after investigations on a sudden increase in the number of pneumonia cases in the city of Wuhan, Hubei province, China. The new coronavirus disease-2019 (COVID-19) epidemic rapidly evolved to a Public Health Emergency of International Importance. On March 11, 2020, due to its geographical spread across different continents with sustained human transmission, the World Health Organization (WHO) declared the COVID-19 pandemics. SARS-CoV-2 reached the Amazon region in Ecuador on March 7 and by the end of March, almost all the Pan Amazonian countries were already affected (Ramírez et al. 2020). In all those countries, the Amazon region accounted for most of the cases and deaths, led by Brazil, Ecuador, and Colombia (Ramírez et al. 2020). The first case in the Brazilian Amazon region was confirmed in Manaus, on 13 March 2020. The COVID-19 epidemic severely impacted the Amazon, highlighting the region's social and environmental vulnerabilities (Codeço et al. 2020). Although the Amazon region encompasses many countries which adopted distinct policies to control COVID-19 pandemics, the social and economic vulnerabilities of the populations living in this region share great similarities. Brazil corresponds to the largest territorial area and the dynamics of COVID-19 spreading in the Brazilian Amazon is a good proxy of its dynamics in this region. In only four months since its arrival, this region reached a total of 32.259 confirmed cases and 1.957 deaths (Buss et al. 2020; Hallal et al. 2020).

The disproportionate impact of the COVID-19 epidemic in the Amazon region is strongly related to access to health assistance(Codeço et al. 2020, Bezerra et al. 2020). Most of the population, including indigenous, quilombolas and riverine communities (Codeço et al. 2020), need to travel long distances, and even cross borders, to access health services and consumption goods (Canalez et al. 2020). The Amazon region shows one of the lowest per capita numbers of Intensive Care Unit (ICU) beds. In Ecuador, for example, the departments in the Amazon region had only 10 ICU /100,000 inhabitants (Navarro et al.

2020). In Brazil, the number of per capita ICU beds exclusively for patients with COVID-19 (Figure 1) were lower in the Amazon region (M = 2.20 ICU/100,000 inhabitants, SD = 1.94), in comparison with the non-Amazonian regions (M = 3.06 ICU/100,000 inhabitants, SD = 1.64). This number remained lower, even after actions to increase the number of beds in response to the ongoing COVID-19 epidemics (Figure 1). The precarious health system and the high dependence on the large cities for health services played a major role in the COVID-19 Amazonian epidemics, with high numbers of incidence and mortality, and overburdened health and funeral systems.

COVID-19 infection rapidly spread from Amazonian cities to the rural and forest communities (Codeço et al. 2020), marking the rapid interiorization of COVID-19 in the Amazon region when compared to other regions in Brazil (Figure 2). The disease spread occurred hierarchically, jumping over geographic scales because of the high connection among ports and airports, from larger cities (e.g. Manaus) to smaller towns. The transportation in Amazonia is mainly by river. There is a dense network of waterways with overcrowded boats and intense flow to the larger cities for services, provisioning of goods, and business. These boats, with restricted natural ventilation, favor viral transmission and the contagious diffusion spread of COVID-19 (Aleixo et al. 2020). The consequences of these mobility and behavioral patterns on COVID-19 spreading and evolution remains unclear, but studies suggest they might have played a role in the emergence of new variants (Naveco et al. 2020).

The COVID-19 epidemics showed a time-lagged spatial dynamic among the urban and rural Amazonian municipalities and two waves in early and late 2020. Increased transmission periods correlate to varying levels of adoption of nonpharmaceutical interventions, such as social distancing measures and the use of face masks. A genomic epidemiology study (Naveca et al. 2020) investigated the successive lineage replacements of Sars-Cov-2 in the Amazonas state and the emergence of new variants of concern, in special the P.1 virus, a more transmissible variant coincident with the second wave of COVID-19. The authors suggest that the adopted levels of social distancing were able to reduce Sars-Cov-2 effective reproductive number (Re), but were insufficient to control the COVID-19 epidemics. Uncontrolled transmission and high prevalence provides the conditions for the diversification of viral lineages, especially when mitigation measures were relaxed (Naveca et al. 2020).

COVID-19 propagation patterns in Brazil clearly evidentiate the large disparities in quantity and quality of health resources and income among regions. Despite the evident severe public health emergence, we witnessed a failure in the coordination of control actions in part due to the governamental denial of the seriousness of the pandemic. The politicization of the pandemic had a role in the negation or low adherence to control actions in the Brazilian Amazon (Castro et al. 2021). The absence of mobility restrictions and total disregard to social distancing and lockdown policies contributed to the successive collapses in the health system, mortuaries and cemeteries (Ferrante et al. 2020). The excess of deaths included not only COVID-19 cases, but also a large fraction of patients affected by prevalent diseases that are endemic and epidemic in the Amazon region, such as malaria and dengue (Navarro et al. 2020, Torres et al. 2020), and those affected by chronic diseases such as hypertension, obesity, diabetes, cardiovascular and chronic respiratory diseases, which are also prevalent in the region and require prompt health assistance (Horton 2020).

Impacts of COVID-19 in the Amazon goes far beyond the sanitary crisis and are interconnected with the several crises we have been currently facing, including the climatic, the biodiversity, the cultural and the socio-environmental crises creating syndemics (make a reference to the SPA Chapters). Indigenous populations are in a more vulnerable social context, and the pandemic impacts not only on their health, but also on their cultural heritage, as deaths prevent knowledge to be transferred between generations (Nicoleti et al. 2021). The impacts are not only direct to indigenous, riverside and quilombola populations, but also indirect, causing damage to the environment, through the non-inspection of illegal activities such as deforestation, mining, and land invasion (Monteiro 2020).

Interconnections among crises were clearly described when evaluating COVID-19 pandemics consequences on the weakening of environmental regulation and enforcement (Vale et al. 2020). A great increase in the number of legislative acts weakening the environmental legislation have been observed during the pandemics, including a massive reduction of environmental fines and the exoneration of technical staff. On the other side, violence against indiginous people and traditional communities increased, fostered by conflicts over the use of land and resources in the Amazon. This dismantling of environmental protection has the potential to intensify ongoing loss of biodiversity, greenhouse gas emissions, and inflict substantial harm to traditional and indigenous peoples (Vale et al. 2020). Deforestation, degradation of natural habitats, and intensification of agriculture and livestock production increase the likelihood of other zoonotic disease outbreaks and opens new fronts for zoonotic disease emergence (Jones et al. 2008). Therefore, a systemic approach for dealing with COVID-19 syndemy may also integrate biodiversity conservation, economic resilience and socio-environmental justice as mechanisms for promoting health and well-being.

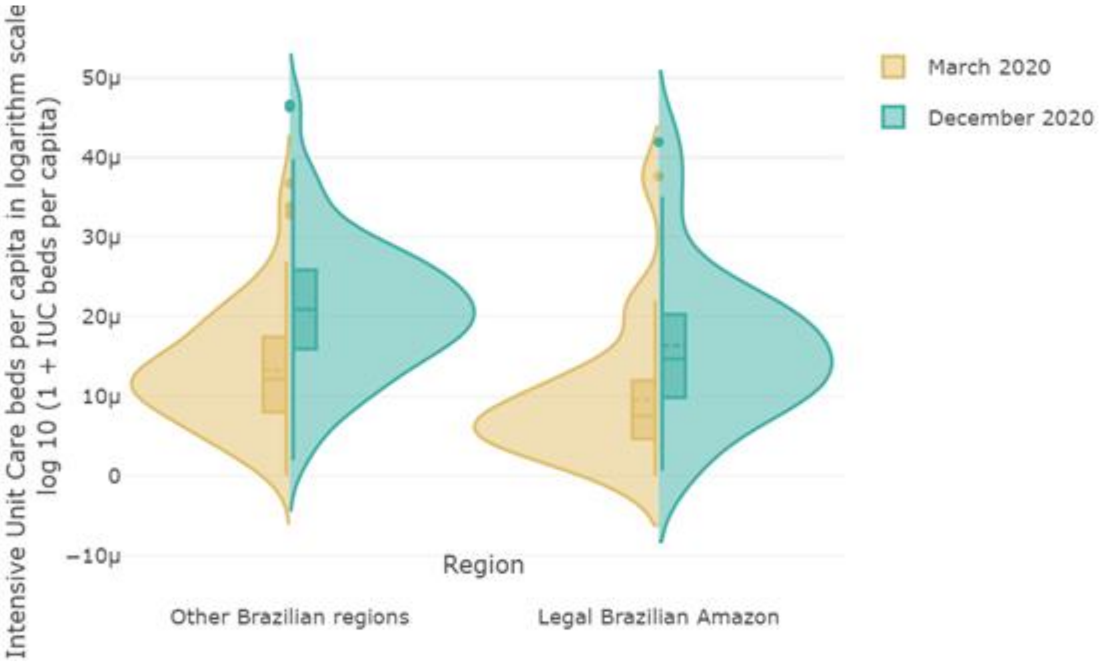

Figure 1. Boxplot showing lower Intensive Unit Care for COVID-19 per capita in health macro regions in the Legal Brazilian Amazon compared to other other Brazilian regions, both in early and late 2020. Data Source: Brazilian National Register of Health Establishments (CNES), Ministry of Health.

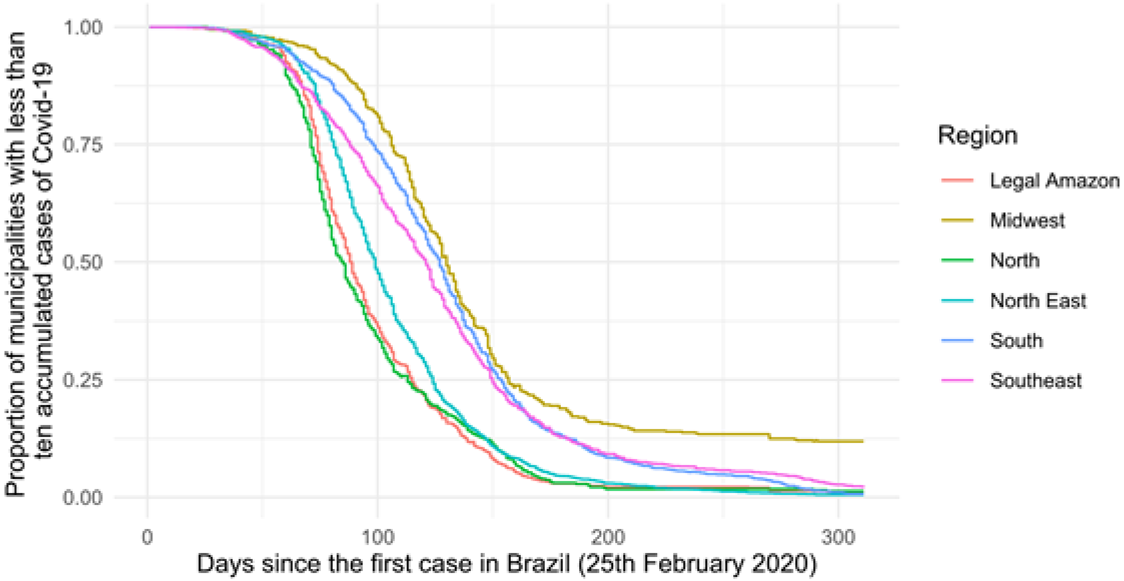

Figure 2. Proportion of municipalities with less than ten accumulated cases of COVID-19 among the Legal Brazilian Amazon and geographic regions. The North region (in green) had the fastest rate of spread of covid, with 50% of municipalities being reached in 90 days since the start of the epidemic; followed by the Legal Brazilian Amazon (in orange), which is composed mainly by Northern municipalities; and the North East region (in light blue). The Southeast (in pink), South (in dark blue) and Midwest (in light brown) regions, respectively, spent more than 100 days (after the first case in Brazil) to have half the municipalities with ten or more accumulated COVID-19 cases. Even in late 2020, after more than 300 days, the Midwest region still has more than 10% of its municipalities with less than ten accumulated COVID-19 cases. Data source: Brasil.IO.

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