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Article

The Impact of Global Environmental Changes on Infectious Disease Emergence with a Focus on Risks for Brazil

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Abstract

Environmental changes have a huge impact on the emergence and reemergence of certain infectious diseases, mostly in countries with high biodiversity and serious unresolved environmental, social, and economic issues. This article summarizes the most important findings with special attention to Brazil and diseases of present public health importance in the country such as Chikungunya, dengue fever, yellow fever, Zika, hantavirus pulmonary syndrome, leptospirosis, leishmaniasis, and Chagas disease. An extensive literature review revealed a relationship between infectious diseases outbreaks and climate change events (El Niño, La Niña, heatwaves, droughts, floods, increased temperature, higher rainfall, and others) or environmental changes (habitat fragmentation, deforestation, urbanization, bushmeat consumption, and others). To avoid or control outbreaks, integrated surveillance systems and effective outreach programs are essential. Due to strong global and local influence on emergence of infectious diseases, a more holistic approach is necessary to mitigate or control them in low-income nations.

Key words: climate change; disease emergence; EIDs; environmental drivers; landscape change; vector-borne diseases; weather; zoonoses

Introduction

It is widely accepted that human modifications to the environment are the main causes or drivers for global environmental changes (Hautier et al. 2015; Lewis and Maslin 2015; Pimm et al. 1995; Vitousek et al. 1997). Turner et al. (1990) state that global environmental change is both systemic and cumulative. Diverse scientific fields have generated much data about the complex environmental systems on our planet with conclusive evidence of anthropogenic environmental change (Oreskes 2004). Some authors have proposed that due to human-induced global environmental changes, planet Earth has entered a new geological epoch termed the Anthropocene (Crutzen and Stoermer 2000). Building on the Millennium Ecosystem Assessment definition of drivers of ecosystem change (Millennium Ecosystem Assessment 2003), Nelson et al. (2006) define drivers of ecosystem change as "a complex web of interactions between humans and their surroundings as humans seek to satisfy their basic needs and improve their wellbeing." There are many anthropogenic drivers of environmental changes and they are the result of development and economic pressures (Geist and Lambin 2002).

According to the World Health Organization, environmental threats to human health at global and regional levels include: "climate change, stratospheric ozone depletion, changes in ecosystems due to loss of biodiversity, changes in hydrological systems and supplies of freshwater, land degradation, urbanization, and stresses on food-producing systems" (WHO 2017). Rapid social and environmental changes are occurring globally, affecting both low-income countries and the largest advanced economies. Travel and transportation are the greatest increase to the risks of rapid spread of infectious diseases (Jaffry et al. 2009). Particularly in the tropics where there is high biodiversity, ecological change is greatest, making these regions potential hotspots for the emergence of new pathogens affecting human, wildlife, and domestic animal health (Jones et al. 2008; Wilcox and Gubler 2005).

Emerging infectious diseases (EIDs) are increasingly recognized as a global threat, with major concerns on their rapid global spread (Daszak et al. 2000; Johnson et al. 2015). To effectively design EID prevention and control programs, the complex and fluid relationships among multi-host and multi-pathogen systems, environmental change, and human populations must be thoroughly understood (Morse et al. 2012). Improved and targeted surveillance systems will provide better knowledge for analysis of the specific risks of disease emergence (Loh et al. 2016). The interactions among wildlife, domestic animals, and humans can be present in different landscapes and are implicated as potential causes of important outbreaks globally (Murray and Daszak 2013). Host–pathogen interactions can be strongly affected by species diversity and community composition (Keesing et al. 2006; Ostfeld and Keesing 2012). Therefore, it is urgently necessary to understand the effects of habitat fragmentation and other environmental changes on host–pathogen interactions (Huang et al. 2016). Establishing local policies that require integrated assessments prior to development projects can help predict risks and emphasize practices to mitigate the disease transmission between humans and other species (Machalaba et al. 2015).

This review presents within a global context the public health threats that may arise as the drivers of environmental change lead to emergence of infectious diseases in Brazil, but that are broadly applicable to populous tropical regions throughout the world experiencing similar drivers. As the sixth largest country by land mass and with the fifth largest population primarily clustered (80%) in urban centers, Brazil is uniquely positioned to be affected by many of the drivers of environmental change and disease emergence as frequency of contact with wildlife and other disease reservoirs increases (CIA 2017). Even though the Brazilian government signed the United Nations Framework Convention on Climate Change in 2016, in many instances the potentially catastrophic environmental impact of new development projects has been neglected for the sake of political and economic interests (Eduardo and Franchini 2017). Despite active projects of infectious and vector-borne disease surveillance in Brazil, there has been a failure to detect and predict recently emerged diseases such as Zika virus (Vasconcelos 2015; Zanluca et al. 2015). Extensive land use change, large-scale deforestation, and disruption of important ecosystems and ecosystem services driven by these projects in Brazil may result in the emergence of infectious diseases in wildlife, domestic animals, and humans in the surrounding communities. To develop effective control or mitigation measures, it is necessary to understand the impact these environmental drivers have in the modification of ecological processes associated with emerging infectious disease outbreaks, as well as to analyze the impact of specific drivers on factors including the ecosystems, country policies, and the interaction of pathogens and their reservoirs.

Drivers of Emerging Infectious Diseases

The drivers of environmental changes are detailed along with their associated emerging infectious diseases (Table 1). Significant changes in land use occur particularly in many low-income countries that contain tropical forests (Lambin and Meyfroidt 2011). Anthropogenic drivers of global environmental change can have different impacts: population growth, for instance, may have both a systemic and cumulative impact (Rosa et al. 2004). Affluence is also considered a driver in countries with slow population growth like Brazil (0.7%) and others and at least as great a threat to the environment as rapid population growth elsewhere (CIA 2017; Rosa et al. 2004). Long-lasting impacts are also caused by agriculture as it replaces natural vegetation, increasing species extinction rates, and altering biogeochemical cycles (Lewis and Maslin 2015).

Recently, most EID events have been linked to anthropogenic drivers (Table 2) such as land use change (deforestation, mining, oil extraction, etc.), food production changes (extreme livestock intensification without proper biosecurity measures), and global trade and travel (Daszak et al. 2001; Karesh et al. 2012; Machalaba et al. 2015). The simultaneous expansion of agriculture and urbanization has significantly modified the structure and functioning of ecosystems and patterns of species distribution and biodiversity (Gibbs et al. 2009; Kerbiriou et al. 2009). Urbanization has been responsible for a decline of biodiversity due to the fact that many wildlife species are unable to adapt and many generalist species are highly adaptable (Mackenstedt et al. 2015). Fragmentation and habitat loss can change the community structure of species and may result in areas with greater risk of zoonotic disease outbreaks (Gay et al. 2014; Kamiya et al. 2014; Rubio et al. 2014). Anthropogenic-driven land use change is highly correlated with the presence of zoonotic diseases (Murray and Daszak 2013; Patz et al. 2004).

Brazil: A Hot Spot of Emerging Infectious Diseases

Particularly in Brazil, there is an irrevocable advance of the agriculture frontier into the rainforest, resulting in increasing rates of species contact and subsequent spillover or transmission of infectious diseases (Confalonieri 2000; Costa and Silva 2016; Jones et al. 2013; Prodes 2016; Tyukavina et al. 2017). In Mato Grosso do Sul state, vector-borne Mayaro and Oroupouche viruses have been detected in nonhuman primates (Batista et al. 2012). In the states of Tocantins and Maranhão, mimivirus has been discovered to have spilled over from nonhuman primates to domestic cattle (Dornas et al. 2014).

As a clear example of a socio-environmental driver of infectious disease emergence in a low-income nation, Bausch and Schwarz (2014) explain how poverty in Guinea drives people to expand their range of activities and use areas including species ranges of hunted game that increase the risk of exposure to

Table 1 Key drivers of environmental changes affecting the emergence and spillover of infectious diseases between wild animals, domestic animals, and humans globally

Driver	Transmission Route	Author(s) and Year	Disease Emergence/Spillover Event
El Niño	Vector-borne	Epstein (1999)[a]	Increasing outbreaks of emerging diseases were linked to El Niño.
		Haines and Patz (2004)[a]	Outbreaks and epidemic of malaria positively connected with El Niño.
		Lindsay et al. (2000)[a]	Strikingly less malaria found in El Niño years in Tanzania.
		Hjelle and Glass (2000)[a]	Hantavirus cardiopulmonary syndrome found to be related to El Niño in the Colorado Plateau.
	Water-borne	Dwight et al. (2004)[a]	Risk of diarrheal symptoms doubled when exposed to southern California coastal waters during an El Niño winter.
El Niño Modoki, El Niño Southern Oscillation, Indian Ocean Dipole	Vector-borne	Imai et al. (2016)	Decreased malaria incidence in Papua New Guinea associated with global climate indices.
La Niña	Vector-borne	Chretien et al. (2007)[a]	Chikungunya fever epidemic connected with the La Niña drought.
		Nicholls (1993)[a]	La Niña epidemic of West Nile fever and Japanese encephalitis.
	Water-borne	Bunyavanich et al. (2003)[a]	Risk of diarrheal symptoms increased during La Niña winter.
Quasi-Biennial Oscillation (QBO)	Vector-borne	Dwight et al. (2004)[a]	QBO linked to incidence of Ross River virus in Australia.
Heatwaves	Vector-borne	Paz (2006)[a]	Heatwave associated outbreak of West Nile fever in Israel in 2000.
	Air-borne	Kan (2011)[a]	Heatwave increased morbidity and mortality from infectious respiratory diseases.
Drought	Water-borne	Epstein (2001a)[a]	Diarrheal diseases increase during drought especially in refugee camps.
	Vector-borne	Khasnis and Nettleman (2005)[a]	Drought associated with hantavirus pulmonary syndrome.
		Wang et al. (2010)[a]; Lima-Camara (2016)	Increased West Nile virus risk following drought
		Shaman et al. (2002)[a]	Increased St. Louis Encephalitis virus risk during droughts
		Chretien et al. (2007)[a]	Chikungunya fever epidemic associated with droughts
		Lima-Camara (2016)	Chikungunya virus outbreaks increase after droughts due to water stored in barrels providing vector breeding sites in Brazil.
		Paull et al. (2017)	Drought increased West Nile virus epidemics through mosquito infection prevalence.
Flood	Water-borne	MacKenzie et al. (1994)[a]	Flood favors water-borne disease transmission such as Cryptosporidium infection
		Reacher et al. (2004)[a]	Significant increase in risk of gastroenteritis associated with depth of flooding in Southern England
	Vector-borne	Epstein (1999)[a]	Floods in Mozambique led to spread of malaria, typhoid and cholera
		Mackenzie et al. (2000)[a]	Strong rain or flood can lead to outbreak of Ross River fever
		Ahern et al. (2005)[a]	Post flood, diarrheal cases (such as cholera) may grow
		Woodruff et al. (1990)[a]	Diarrheal and malaria incidences were observed to increase after floods in 1988 in Sudan
		Nielsen et al. (2002)[a]	Increased lymphatic filariasis after flooding
		Cordova et al. (2000)[a]	Increased arboviral disease after flooding
		Chen (1999)[a]	Hemorrhagic Fever with Renal Syndrome diseases increase during flooding
		CDC (2000)[a]	HPS diseases may increase during flooding
		Leal-Castellanos et al. (2003)[a]	Leptospirosis diseases may increase during flooding
	Contact with Rodent Urine	Gracie et al. (2014)	Leptospirosis incidence higher in flooded areas (local scale) in Brazil
Hurricane, Typhoons, and Cyclones	Vector-borne	Epstein (2000)[a]; Sanders et al. (1999)[a]	Following a hurricane, malaria and dengue fever outbreaks occurred in Honduras and Venezuela. A cyclone tends to increase the incidence of leptospirosis.
	Water/food-borne	Shultz et al. (2005)[a]	A cyclone tends to increase the incidence of cholera
Temperature	Vector-borne	Salomón et al. (2012)	Leishmaniasis vectors activity increased with increased local temperature and humidity Seasonality of breeding season (global and local scale) Vectors geographical expansion due to increased temperature (global scale)
		Teurlai et al. (2015)	Increase in mean temperature associated with higher incidence of dengue fever in New Caledonia due to stimulation of vectors' gonotrophic cycle and female biting behavior

Continued

Table 1 Continued

Driver	Transmission Route	Author(s) and Year	Disease Emergence/Spillover Event
		Vianna and Ignotti (2013)	Hottest months present the highest incidence of dengue in Brazil
		Imai et al. (2016)	Increased minimum temperature associated with increase in malaria incidence in Papua New Guinea with differing lag times according to different regions (local scale)
		Barcellos and Lowe (2014)	Increase in mean temperature associated with higher incidence of dengue fever in Brazil
	Water and food-borne disease	Yan et al. (2016)	Toxoplasmosis infection increases in higher temperatures due to higher sporulation of oocysts and also larger geographical distribution of reservoir hosts
Humidity	Contact with blood or other contaminated secretion	Bausch and Schwarz (2014); Alexander et al. (2015)	Ebola outbreaks suggested to emerge after sharply dry end of rainy season leading to higher infection of bat reservoir or higher contact with reservoir species
Rainfall	Water and food-borne	Yan et al. (2016)	Heavier rainfall is associated with enhanced *Toxoplasma gondii* oocyst dynamics and distribution
	Vector-borne	Lima-Camara (2016)	Higher rainfall associated with more breeding sites for Chikungunya, West Nile and Zika virus vectors
		Vianna and Ignotti (2013)	Highest rainfall months present the highest dengue incidence in Brazil
		Monath and Vasconcelos (2015)	Heavy rainy season associated with periodic expansion of yellow fever in endemic areas
Deforestation	Vector-borne	Karesh et al. (2012)	Lyme disease outbreaks caused by a history of deforestation, reforestation and habitat fragmentation that caused increase in preferred reservoir population infection and higher contact with infected vectors
	Contact with blood or other contaminated secretion	Fahr et al. (2006)	Deforestation-caused increase in contact rates between Ebolavirus infected or reservoir species and humans
Land Use Conversion	Contact with contaminated excretion	Suzan et al. (2008)	Increased hantavirus infection in Panama
Bushmeat Consumption	Contact with blood or other contaminated secretion	Alexander et al. (2015); Bausch and Schwarz (2014)	Ebola virus outbreaks occur in locations with direct contact between infected animals, meat, or contaminated fruits

Modified from Wu et al. (2016). Highlighted cells detail incidence of disease emergence or spillover in Brazil.
[a]References cited in Wu et al. (2016).

Ebola virus and other zoonotic pathogens. Multiple anthropogenic factors can be involved in the emergence of an Ebola virus outbreak through bushmeat consumption (Alexander et al. 2015), deforestation (Fahr et al. 2006), and land use change (Wallace et al. 2014). Bushmeat consumption is also a driver for emerging infectious disease in Brazil (Gonçalves et al. 2012; Sangenis et al. 2016). The wildlife trade and especially the pet trade have been heavily implicated as a driver of disease emergence (Chomel et al. 2007; Gomez and Aguirre 2008; Matias et al. 2016; Ripple et al. 2016).

The construction of hydroelectric dams has direct and indirect ecological impacts due to massive deforestation, biodiversity loss, and socioeconomic changes brought upon local communities and surrounding ecosystems (Lees et al. 2016). Dams and other water control projects have been shown to drive disease emergence by providing favorable habitats increasing vector and host species ranges (Patz et al. 2004). Global evidence of markedly increased incidence of emerging or reemerging pathogens such as Rift Valley fever (Dzingirai et al. 2017), schistosomiasis (N'Goran et al. 1997), and malaria (Tadei et al. 1998) has been correlated with dam construction and the consequent environmental changes.

Trypanosoma spp., the causative agent for trypanosomiasis, has been isolated in bats captured near a hydroelectric dam in the Brazilian Amazon (Costa et al. 2016). This discovery indicates the potential risk of zoonotic spillover to the growing cities in the vicinity of hydroelectric dams. Building dams requires a large workforce, many of whom remain in the region post construction, which not only dramatically increases the impact of humans upon the environment but also increases opportunity for disease spillover (Fearnside 1999; Patz et al. 2004; Randell 2015; Vaz et al. 2007). The lack of epidemiological surveillance and risk assessment prior to the construction of hydroelectric plants increases the exposure of neighboring human populations to zoonotic diseases.

The higher incidence of leptospirosis in Brazil has been associated with densely populated urban and flooded areas (Gracie et al. 2014). Similarly, Zika virus outbreaks in Brazil have been associated with urbanization or deforestation, which likely favor the habitat of the mosquito vector (Ali et al. 2017). Hantavirus outbreaks in Brazil also have been linked to increased contact rates between rodent reservoirs and humans in rapidly urbanizing and deforested rural areas (Pinto Junior et al. 2014). Yellow fever outbreaks occurred in both Congo and Brazil in 2016 and 2017, respectively, and in both instances the virus shifted from forested areas to urban populations, raising concerns about effective public health response and sufficient vaccine reserves (Dyer 2017; Ortiz-Martínez et al. 2017). The outbreak in Congo was associated with high population mobility and low vaccination coverage (Otshudiema et al. 2017). In Brazil, the outbreak was likely driven by anthropogenic deforestation and forest fragmentation that isolated and stressed the

Table 2 Key anthropogenic drivers of environmental changes affecting the emergence and spillover of infectious diseases between wild animals, domestic animals, and humans in Brazil

Drivers	Transmission Route	Author(s) and Year	Disease Emergence/Spillover Event
Urbanization and Deforestation	Contact with rodents or urine	Pinto Junior et al. (2014)	Increased urbanization and deforestation correlated with exposure to Hantavirus rodent reservoirs
		Gracie et al. (2014)	Increased urbanization associated outbreaks of leptospirosis.
	Vector-borne	Ali et al. (2017)	Urbanization and deforestation associated with higher incidences of Zika virus.
		Ribeiro and Antunes (2009)	Urbanization and deforestation associated with Yellow Fever outbreak.
Bushmeat Consumption	Contact with wildlife meat or blood	Sangenis et al. (2016)	Chagas disease transmission due to wild animal meat or blood consumption
		Gonçalves et al. (2012)	Hepatic calodiasis disease transmission due to wild animal meat or blood consumption
Land Use Conversion	Contact with contaminated excretions	Oliveira and Morraye (2014); Santos et al. (2016)	Increased incidence of hantavirus due to agricultural activities
	Contact with rodents	Prist et al. (2016)	Hantavirus Pulmonary Syndrome associated with Atlantic forest areas converted to sugarcane plantations and lower HDI in São Paulo State.

reservoir monkey species most likely altered the vector geographic range (Ortiz-Martínez et al. 2017; Ribeiro and Antunes 2009; Rosseto et al. 2017).

Climate Change and Emerging Infectious Diseases

Climate change includes variations in temperature, precipitation, wind, and sunshine that may affect the survival, reproduction, or distribution of disease pathogens and their hosts (Wu et al. 2016). According to Patz et al. (2005), correlating the emergence or increased range of infectious diseases with climate change is still not possible due to a dearth of longitudinal, quality data sets and sociodemographic factors. Still ample evidence has shown that climate change results in long-term shifts in weather conditions as well as patterns of extreme weather events, both of which may threaten human health and well-being (Aguirre and Tabor 2008; Wu et al. 2016).

By providing higher landscape suitability for rodent host reservoirs and increasing human-to-host contact rates, climate change and human population growth are predicted to be the most important drivers of Lassa virus in western Africa by 2070 (Redding et al. 2016). West Nile virus (WNV) epidemics have increased globally as a result of droughts. In periods with low rainfall, the rate of infection of the WNV mosquito vector increases (Paz 2015). Predictive models have shown a potential tripling of WNV cases over the next three decades in areas of increased drought and with low human host immunity (Paull et al. 2017). Climate change has also been associated with increased intensity of droughts and flooding in the Amazon region (Marengo and Espinoza 2015). Higher incidence of cases of Chikungunya, WNV, and Zika virus infection in Brazil is associated with areas with more frequent rainfall and severe droughts, since both increase breeding sites for the vectors *Aedes* spp. and *Culex* spp.

Temperature change alone, or together with other variable changes such as rainfall, may alter the transmission of diseases. Temperature affects the spatial–temporal distribution of disease vectors on both global and regional scales, and as temperature continues to rise due climate change and greenhouse gas emissions, insect vectors in low-latitude regions may expand into novel habitats in mid- or high-latitude regions and in higher altitudes, leading to geographical expansions or shifts of disease ranges. An example of this scenario is the association between inter-annual variability in temperature and malaria transmission in the African highlands (Bouma 2003). Temperature and rainfall are the most important abiotic factors affecting dengue prevalence in Brazil as well as the breeding sites for the mosquito vector (Vianna and Ignotti 2013). In other regions, increased temperatures result in increased sporulation of oocysts and geographic distribution of reservoir hosts for *Toxoplasma gondii*, yielding higher infection rates (Yan et al. 2016). Increased rainfall also enhances infection rate due to enhanced oocyst survival.

Some vector-borne diseases including malaria, African trypanosomiasis, Lyme disease, tick-borne encephalitis, yellow fever, plague, and dengue fever all have expanded ranges following increased temperatures (Harvell et al. 2002).

Imai et al. (2016) studied both local weather and global climate associations with malaria incidence in Papua, New Guinea and determined that there was an association between minimum temperature and increase in malaria incidence with different time lags, according to the region studied. For climate indices, the authors described a negative association between modoki El Niño, El Niño Southern Oscillation and Indian Ocean Dipole indices and malaria incidence with a larger time lag, suggesting it could have happened due to lower precipitation and malaria transmission or vice versa.

Strong correlations between increased temperature and dengue fever incidence have been recorded in New Caledonia (Teurlai et al. 2015), Thailand (Watts et al. 1987), and Brazil (Barcellos and Lowe 2014). The regional and global increases in humidity and temperature lead to increased leishmaniasis vector (*Lutzomyia* spp.) activity, breeding, and the geographic expansion in Argentina and other regions of the Americas (Salomón et al. 2012).

Modelling efforts have supported future increasing trends in disease emergence driven by climate change. Predictive models for Brazilian Atlantic forest and the Cerrado describe a strong association between increased risk of Hantavirus pulmonary syndrome and changes in socioeconomic, landscape, and weather factors: low Human Development Index, increase in sugarcane cultivation, decreased forest cover, and increased annual mean temperature (Prist et al. 2016).

Conclusions

Several studies have described local climate change, disruption of important ecosystems and ecosystem services, large-scale deforestation, and urbanization as drivers of a wide range of life-threatening infectious diseases, including hantavirus pulmonary syndrome, dengue fever, yellow fever, malaria, trypanosomiasis, leishmaniasis, and leptospirosis in Brazil. There is strong evidence that some of these environmental changes will intensify in the near future if key anthropogenic activities are not controlled.

Active surveillance is indispensable in preventing disease emergence by identifying areas of risk before they become a threat to human and animal health. Especially in times of reduced budgeting for research funding it is worth highlighting to policy makers the importance of recognizing anthropogenic drivers, their ecological connections, and the dynamics of specific diseases, reservoirs, and environments. An integrated surveillance system of the health of at-risk human and animal populations should be designed to identify the geographic regions, populations, vectors, and interactions that may result in emerging and reemerging pathogens. This would establish a system of early outbreak warning system and permit the modelling of spread, analyses, and potentially the application of prompt control or mitigation measures.

A key education component should clearly present the anthropogenic drivers of EIDs as not only ephemeral or present concerns, but establish the perception of them as long-term public health threats requiring improved public support for more effective environmental protection or insurance practices at national and even international levels. Global human, domestic animal, and wildlife morbidity and mortality caused by EIDs will only be controlled once a holistic and transdisciplinary approach is designed and effectively implemented.

References

Aguirre AA, Tabor GM. 2008. Global factors driving emerging infectious diseases: Impact on wildlife populations. Ann N Y Acad Sci 1149(1):1–3.

Alexander KA, Sanderson CE, Marathe M, Lewis BL, Rivers CM, Shaman J, Drake JM, Logfren E, Dato VM, Eisenberg MC, Eubank S. 2015. What factors might have led to the emergence of Ebola in west Africa? PLoS Negl Trop Dis 9(6):e0003652.

Ali S, Gugliemini O, Harber S, Harrison A, Houle L, Ivory J, Kersten S, Khan R, Kim J, LeBoa C, Nez-Whitfield E, O'Marr J, Rothenberg E, Segnitz RM, Sila S, Verwillow A, Vogt M, Yang A, Mordecai EA. 2017. Environmental and social changes drive the explosive emergence of Zika virus in the Americas. PLoS Negl Trop Dis 11(2):e0005135.

Barcellos C, Lowe R. 2014. Expansion of the dengue transmission area in Brazil: The role of climate and cities. Trop Med Int Health 19(2):159–168.

Batista PM, Andreotti R, Chiang OJ, Ferreira MS, Vasconcelos PFC. 2012. Seroepidemiological monitoring in sentinel animals and vectors as part of arbovirus surveillance in the state of Mato Grosso do Sul, Brazil. Rev Soc Bras Med Trop 45(2).

Bausch DG, Schwarz L. 2014. Outbreak of Ebola virus disease in Guinea: Where ecology meets economy. PLoS Negl Trop Dis 8(7):e3056.

Bouma MJ. 2003. Methodological problems and amendments to demonstrate effects of temperature on the epidemiology of malaria. A new perspective on the highland epidemics in Madagascar, 1972–1989. Trans R Soc Trop Med Hyg 97:133–139.

Chomel BB, Beloto A, Meslin FX. 2007. Wildlife, exotic pets, and emerging zoonoses. Emerg Infect Dis 13(1):6–11.

Chretien JP, Anyamba A, Bedno SA, Breiman RF, Sang R, Sergon K, Powers AM, Onyango CO, Small J, Tucker CJ, Linthicum KJ. 2007. Drought-associated chikungunya emergence along coastal East Africa. Am J Trop Med Hyg 76(3):405–407.

CIA. 2017. *The World Factbook*. Washington, DC: Central Intelligence Agency. Available online (https://www.cia.gov/library/publications/the-world-factbook/geos/br.html), accessed on December 7, 2017.

Confalonieri U. 2000. Environmental change and human health in the Brazilian Amazon. Glob Chang Hum Health 1(2): 174–183.

Costa AP, Nunes PH, Leite BHS, Ferreira JI, Tonhosolo R, da Rosa AR, da Rocha PA, Aires CC, Gennari SM, Marcili A. 2016. Diversity of bats trypanosomes in hydroeletric area of Belo Monte in Brazilian Amazonia. Acta Trop 164:185–193.

Costa D, Silva C. 2016. Instituições e enforcement na redução do desmatamento na Amazônia. Teoria e Evidência Econômica 47:312–330.

Crutzen PJ, Stoermer EF. 2000. The Anthropocene. International Geosphere-Biosphere Programme 41:17–18.

Daszak P, Cunningham AA, Hyatt AD. 2000. Emerging infectious diseases of wildlife—threats to biodiversity and human health. Science 287(5452):443–449.

Daszak P, Cunningham AA, Hyatt AD. 2001. Anthropogenic environmental change and the emergence of infectious diseases in wildlife. Acta Trop 78(2):103–116.

Dornas FP, Rodrigues FP, Boratto PVM, Silva LCF, Ferreira PCP, Bonjardim CA, Trindade GS, Kroon EG, La Scola B, Abrahão JS. 2014. Mimivirus circulation among wild and domestic mammals, Amazon Region, Brazil. Emerg Infect Dis 20(3):469–472.

Dyer O. 2017. Yellow fever stalks Brazil in Zika's wake. Br Med J 356:j707.

Dzingirai V, Bukachi S, Leach M, Mangwanya L, Scoones I, Wilkinson A. 2017. Structural drivers of vulnerability to zoonotic disease in Africa. Philos Trans R Soc Lond B Biol Sci 372(1725): 20160169.

Eduardo V, Franchini M. 2017. The bases for a true brazilian climate leadership: Democracy, economy, and international insertion. In: Brazil and Climate Change: Beyond the Amazon. London: Routledge. p 193–196.

Fahr J, Djossa BA, Vierhaus H. 2006. Rapid assessment of bats (Chiroptera) in Déré, Diécké and Mt. Béro classified forests, southeastern Guinea; including a review of the distribution of bats in Guinée Forestière. In: Wright EE, McCullough J, Alonso LE, Diallo MS, eds. Rapid Biological Assessment of Three Classified Forests in Southeastern Guinea/Évaluation Biologique Rapide de Trois Forêt Classées du Sud-est de la Guinée. RAP Bulletin of Biological Assessment 40. Washington DC: Conservation International. p 168–247.

Fearnside PM. 1999. Social impacts of Brazil's Tucuruí dam. Environ Manage 24(4):483–495.

Gay N, Olival KJ, Bumrungsri S, Siriaroonrat B, Bourgarel M, Morand S. 2014. Parasite and viral species richness of Southeast Asian bats: Fragmentation of area distribution matters. Int J Parasitol Parasites Wildl 3(2):161–170.

Geist HJ, Lambin EF. 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience 52(2):143–150.

Gibbs KE, MacKey RL, Currie DJ. 2009. Human land use, agriculture, pesticides and losses of imperiled species. Divers Distrib 15(2):242–253.

Gomez A, Aguirre AA. 2008. Infectious diseases and the illegal wildlife trade. Ann N Y Acad Sci 1149(1):16–19.

Gonçalves AQ, Asasco C, Santos I, Serra PT, Julião GR, Orlandi PP. 2012. *Calodium hepaticum*: Household clustering transmission and the finding of a source of human spurious infection in a community of the Amazon region. PLoS Negl Trop Dis 6(12):1349.

Gracie R, Barcellos C, Magalhães M, Souza-Santos R, Barrocas PRG. 2014. Geographical scale effects on the analysis of leptospirosis determinants. Int J Environ Res Public Health 11 (10):10366–10383.

Harvell CD, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS, Samuel MD. 2002. Climate warming and disease risks for terrestrial and marine biota. Environ Int 86:14–23.

Hautier Y, Tilman D, Isbell F, Seabloom EW, Borer ET, Reich PB. 2015. Anthropogenic environmental changes affect ecosystem stability via biodiversity. Science 348(6232):336–340.

Huang ZYX, Van Langevelde F, Estrada-Peña A, Suzán G, De Boer WF. 2016. The diversity–disease relationship: Evidence for and criticisms of the dilution effect. Parasitology 3–12.

Imai C, Cheong HK, Kim H, Honda Y, Eum JH, Kim CT, Kim JS, Kim Y, Behera SK, Hassan MN, Nealon J, Chung H, Hashizume M. 2016. Associations between malaria and local and global climate variability in five regions in Papua New Guinea. Trop Med Health 44:23.

Jaffry KT, Ali S, Rasool A, Raza A, Gill ZJ. 2009. Zoonoses. Int J Agric Biol 11:217–220.

Johnson CK, Hitchens PL, Evans TS, Goldstein T, Thomas K, Clements A, Joly DO, Wolfe ND, Daszak P, Karesh WB, Mazet JK. 2015. Spillover and pandemic properties of zoonotic viruses with high host plasticity. Sci Rep 1–8.

Jones BA, Grace D, Kock R, Alonso S, Rushton J, Said MY, McKeever D, Mutua F, Young J, McDermott J, Pfeiffer DU. 2013. Zoonosis emergence linked to agricultural intensification and environmental change. Proc Natl Acad Sci USA 110: 8399–8404.

Jones KE, Patel NG, Levy MA, Storeygard A, Balk D, Gittleman JL, Daszak P. 2008. Global trends in emerging infectious diseases. Nature 451(21):990–994.

Kamiya T, O'Dwyer K, Nakagawa S, Poulin R. 2014. Host diversity drives parasite diversity: Meta-analytical insights into patterns and causal mechanisms. Ecography 37(7):689–697.

Karesh WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, Aldrich S, Harrington T, Formenty P, Loh EH, Machalaba CC, Thomas MJ, Heymann DL. 2012. Ecology of zoonoses: Natural and unnatural histories. Lancet 380: 1936–1945.

Keesing F, Holt RD, Ostfeld RS. 2006. Effects of species diversity on disease risk. Ecol Lett 9:485–498.

Kerbiriou C, Le Viol I, Jiguet F, Devictor V. 2009. More species, fewer specialists: 100 years of changes in community composition in an island biogeographical study. Divers Distrib 15(4):641–648.

Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. Proc Natl Acad Sci USA 108:3465–3472.

Lees AC, Peres CA, Fearnside PM, Schneider M, Zuanon JAS. 2016. Hydropower and the future of Amazonian biodiversity. Biodivers Conserv 25(3):451–466.

Lewis SL, Maslin MA. 2015. Defining the Anthropocene. Nature 519(7542):171–180.

Lima-Camara TN. 2016. Emerging arboviruses and public health challenges in Brazil. Rev Saude Publica 50(36):1–7.

Lindsay SW, Bødker R, Malima R, Msangani HA, Kisinza W. 2000. Effect of 1997–98 El Niño on highland malaria in Tanzania. Lancet 355:989–990.

Loh E, Murray KA, Nava A, Aguirre A, Daszak P. 2016. Evaluating the links between biodiversity, land-use change, and infectious disease emergence in tropical fragmented landscapes. In: Aguirre A, Sukumar R, eds. Tropical Conservation. New York: Oxford University Press. p 79–88.

Machalaba C, Daszak P, Karesh WB. 2015. Anthropogenic drivers of emerging infectious diseases. *In:* United Nations Global Sustainable Development Report Briefs 2015.

Mackenstedt U, Jenkins D, Romig T. 2015. The role of wildlife in the transmission of parasitic zoonoses in peri-urban and urban areas. Int J Parasitol Parasites Wildl 4(1):71–79.

Marengo JA, Espinoza JC. 2015. Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. Int J Climatol 36(3).

Matias, CAR, Pereira IA, Reis EMFD, Rodrigues DDP, Siciliano S. 2016. Frequency of zoonotic bacteria among illegally traded wild birds in Rio de Janeiro. Braz J Microbiol 47(4):882–888.

Millennium Ecosystem Assessment. 2003. Ecosystems and their services, Ch 2. In: Ecosystems and Human Well-Being: A Framework for Assessment. Washington, DC: Island Press.

Monath TP, Vasconcelos PFC. 2015. Yellow fever. J Clin Virol 64: 160–173.

Morse SS, Mazet JAK, Woolhouse M, Parrish CR, Carroll D, Karesh WB. 2012. Prediction and Prevention of the next pandemic zoonosis. Lancet 380(9857):1956–1965.

Murray KA, Daszak P. 2013. Human ecology in pathogenic landscapes: Two hypotheses on how land use change drives viral emergence. Curr Opin Virol 3(1):79–83.

Nelson GC, Bennett E, Berhe AA, Cassman K, DeFries R, Dietz T, Dobermann A, Dobson A, Janetos A, Levy M, Nakicenovic MN, O'Neill B, Norgaard R, Petschel-Held G, Ojima D, Pingali P, Watson R, Zurek M. 2006. Anthropogenic drivers of ecosystem change: An overview. Ecol Soc 11(2):29.

N'Goran EK, Diabate S, Utzinger J, Sellin B. 1997. Changes in human schistosomiasis levels after the construction of two large hydroelectric dams in central Côte d'Ivoire. Bull World Health Organ 75(6):541–545.

Oliveira BL, Morraye M. 2014. Epidemiological aspects of hantavirus pulmonary syndrome (hps) and the correlation between land use and climatic factors in Minas Gerais (2002–2009), Brazil. Hygeia 10(18).

Oreskes N. 2004. Beyond the ivory tower. The scientific consensus on climate change. Science 306(5702):1686–1686.

Ortiz-Martínez Y, Patiño-Barbosa AM, Rodriguez-Morales AJ. 2017. Yellow fever in the Americas: The growing concern about new epidemics. F1000Res 6(398).

Ostfeld RS, Keesing F. 2012. Effects of host diversity on infectious disease. Annu Rev Ecol Evol Syst 43:157–182

Otshudiema JO, Ndakala NG, Mawanda EK, Tshapenda GP, Kimfuta JM, Nsibu LRN, Gueye AS, Dee J, Philen RM, Giese C, Murrill CS, Arthur RR, Kebela BI. 2017. Yellow fever outbreak—Kongo Central Province, Democratic Republic of the Congo, August 2016. MMWR Morb Mortal Wkly Rep 66(12).

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA. 2005. Impact of regional climate change on human health. Nature 438:310–317.

Patz JA, Daszak P, Tabor GM, Aguirre AA, Pearl M, Epstein J, Wolfe ND, Kilpatrick AM, Foufopoulos J, Molyneux D, Bradley DJ, Amerasinghe FP, Ashford RW, Barthelemy D, Bos R, Bradley DJ, Buck A, Butler C, Chivian ES, Chua KB, Clark G, Colwell R, Confalonieri UE, Corvalan C, Cunningham AA, Dein J, Dobson AP, Else JG, Epstein J, Field H, Furu P, Gascon C, Graham D, Haines A, Hyatt AD, Jamaluddin A, Kleinau EF, Koontz F, Koren HS, LeBlancq S, Lele S, Lindsay S, Maynard

N, McLean RG, McMichael T, Morse SS, Norris DE, Ostfeld RS, Pearl MC, Pimentel D, Rakototiana L, Randriamanajara O, Riach J, Rosenthal JP, Salazar-Sanchez E, Silbergeld E, Thomson M, Vittor AY, Yameogo L, Zakarov V. 2004. Unhealthy landscapes: Policy recommendations on land use change and infectious disease emergence. Environ Health Perspect 112(10):1092–1098.

Paull SH, Horton DE, Ashfaq M, Rastogi D, Kramer LD, Diffenbaugh NS, Kilpatrick AM. 2017. Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. Proc Biol Sci 284:20162078.

Paz S. 2015. Climate change impacts on West Nile Virus transmission in a global context. Philos Trans R Soc Lond B Biol Sci 370(1665):20130561.

Pimm SL, Russell GJ, Gittleman JL, Brooks TM. 1995. The future of biodiversity. Science 269(5222):347–350.

Pinto Junior V, Hamidad A, Albuquerque Filho D, Dos Santos V. 2014. Twenty years of Hantavirus pulmonary syndrome in Brazil: A review of epidemiological and clinical aspects. J Infect Dev Ctries 8(2):137–142.

Prist PR, Uriarte M, Tambosi LR, Prado A, Pardini R, D'Andrea PS. 2016. Landscape, environmental and social predictors of Hantavirus risk in São Paulo, Brazil. PLoS One 11(10):e0163459.

Prodes Project. 2016. Instituto Nacional de Pesquisas Espaciais, Ministério da Ciência e Tecnologia do Brasil. Available online (http://www.obt.inpe.br/prodes/index.php), accessed on November 11, 2017.

Randell H. 2015. Structure and agency in development-induced forced migration: The case of Brazil's Belo Monte Dam. Popul Environ 37(3):265–287.

Redding DW, Moses LM, Cunningham AA, Wood J, Jones KE. 2016. Environmental-mechanistic modelling of the impact of global change on human zoonotic disease emergence: A case study of Lassa fever. Methods Ecol Evol 7:646–655.

Ribeiro M, Antunes CMF. 2009. Febre Amarela: Estudo de um surto. Rev Soc Bras Med Trop 42(5):523–531.

Ripple WJ, Abernethy K, Betts MG, Chapron G, Dirzo R, Galetti M, Levi T, Lindsey PA, Macdonald DW, Machovina B, Newsome TM, Peres CA, Wallach AD, Wolf C, Young H. 2016. Bushmeat hunting and extinction risk to the world's mammals. Royal Society Open Science 3(10):160498–160516.

Rosa EA, York R, Dietz T. 2004. Tracking the anthropogenic drivers of ecological impacts. Ambio 33(8):509–512.

Rosseto VE, Angerami RN, Luna EJA. 2017. What to expect from the 2017 yellow fever outbreak in Brazil? Rev Inst Med Trop Sao Paulo 59:e17.

Rubio AV, Avila-Flores R, Suzán G. 2014. Responses of small mammals to habitat fragmentation: Epidemiological considerations for rodent-borne hantaviruses in the Americas. EcoHealth 11:526–533.

Salomón OD, Quintana MG, Mastrángelo AV, Fernández MS. 2012. Leishmaniasis and climate change—Case study: Argentina. J Trop Med 60(1242):1–11.

Sangenis LHC, Nielebock MAP, Silva Santos C, Carriello da Silva MC, Bento GM. 2016. Chagas disease transmission by consumption of game meat: Systematic review. Rev Bras Epidemiol 19(4):803–811.

Santos JP, Steinke VA, Oliveira SV, Garcia-Zapata MTA. 2016. Environment and disease: Anthropic changes and Hantavirus. Hygeia 12(22):1–12.

Suzan G, Marce E, Giermakowski T, Armien B, Pascale J, Mills J, Ceballos G, Gomez A, Aguirre AA, Salazar-Bravo J, Armien A, Parmenter R, Yates T. 2008. The effect of habitat fragmentation and species diversity loss on hantavirus prevalence in Panama. Animal biodiversity and emerging diseases. Ann N Y Acad Sci 1149:80–83.

Tadei WP, Scarpassa VM, Thatcher BD, Santos JM, Rafael MS, Rodrigues IB. 1998. Ecologic observations on anopheline vectors of malaria in the Brazilian Amazon. Am J Trop Med Hyg 59(2):325–335.

Teurlai M, Menkès CE, Cavarero V, Degallier N, Descloux E, Grangeon JP, Guillaumot L, Libourel T, Lucio PS, Mathieu-Daudé F, Mangeas M. 2015. Socio-economic and climate factors associated with dengue fever spatial heterogeneity: A worked example in New Caledonia. PLoS Negl Trop Dis 9 (12):e000421.

Turner BL, Kasperson RE, Meyer WB, Dow K, Golding, D, Kasperson JX, Mitchell RC, Ratick SJ. 1990. Two types of global environmental change: Definitional and spatial-scale issues in their human dimensions. Glob Environ Change 1(1):14–22.

Tyukavina A, Hansen MC, Potapov PV, Stehman SV, Smith-Rodrigues K, Okpa C, Aguilar R. 2017. Types and rates of forest disturbance in Brazilian legal Amazon, 2000-2013. Sci Adv 3(4):e1601047.

Vasconcelos PFC. 2015. Doença pelo vírus Zika: um novo problema emergente nas Américas? Rev Pan-Amaz Saude 6(2): 9–10.

Vaz VC, D'Andrea PS, Jansen AM. 2007. Effects of habitat fragmentation on wild mammal infection by *Trypanosoma cruzi*. Parasitology 134(12):1785–1793.

van Vliet N, Quiceno-Mesa MP, Cruz-Antia D, Neves de Aquino LJ, Moreno J, Nasi R. 2014. The uncovered volumes of bushmeat commercialized in the Amazonian trifrontier between Colombia, Peru, and Brazil. Ethnobiol Conserv 3(7):1–11.

Vianna DV, Ignotti E. 2013. The occurrence of dengue and weather changes in Brazil: A systematic review. Rev Bras Epidemiol 16(2):240–256.

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM. 1997. Human domination of Earth's ecosystems. Science 277(5325): 494–499.

Wallace RG, Gilbert M, Wallace R, Pittiglio C, Mattioli R, Kock R. 2014. Did Ebola emerge in West Africa by a policy-driven phase change in agroecology? Environ Plan A, 46(11): 2533–2542.

Watts DM, Burke DS, Harrison BA, Whitmire RE, Nisalak A. 1987. Effect of temperature on the vector efficiency of Aedes aegypti for dengue 2 virus. Am J Trop Med Hyg 36(1):143–152.

Wilcox BA, Gubler DJ. 2005. Disease ecology and the global emergence of zoonotic pathogens. Environ Health Prev Med 10(5):263–272.

World Health Organization. 2017. Global environmental change. Available online (http://www.who.int/globalchange/environment/en/), accessedon July 4, 2017.

Wu X, Lu Y, Zhou S, Chen L, Xu B. 2016. Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. Environ Int 86:14–23.

Yan C, Liang LJ, Zheng KY, Zhu XQ. 2016. Impact of environmental factors on the emergence, transmission and distribution of Toxoplasma gondii. Parasit Vectors 9:137.

Zanluca C, Melo VCA, Mosimann ALP, Santos GIVD, Santos CNDD, Luz K. 2015. First report of autochthonous transmission of Zika virus in Brazil. Mem Inst Oswaldo Cruz 110(4): 569–572.