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Environmental change and the dynamics of parasitic diseases in the Amazon

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ABSTRACT

The Amazonian environment is changing rapidly, due to deforestation, in the short term, and, climatic change is projected to alter its forest cover, in the next few decades. These modifications to the, environment have been altering the dynamics of infectious diseases which have natural foci in the, Amazonian biome, especially in its forest. Current land use practices which are changing the, epidemiological profile of the parasitic diseases in the region are road building; logging; mining; expansion of agriculture and cattle ranching and the building of large dams. Malaria and the cutaneous, leishmaniasis are the diseases best known for their rapid changes in response to environmental, modifications. Others such as soil-transmitted helminthiases, filarial infections and toxoplasmosis, which have part of their developmental cycles in the biophysical environment, are also expected to, change rapidly. An interdisciplinary approach and an integrated, international surveillance are needed, to manage the environmentally-driven changes in the Amazonian parasitic diseases in the near future.

1. Introduction

The Amazon, the largest drainage basin of the planet, is a vast (7.8 million km^2) and heterogeneous region which contains 20% of the freshwater reserves of the world (Davidson et al., 2012) and around 31% of the remaining tropical forests. This region comprises nine countries in South America and its largest part (around 65%) is included in the northern part of Brazil; Peru has about 10.1% of the region and Colombia 6.2%. The total population of the Amazon region is around 33 million and a significant part of its territory – 1,641,117 km^2 – is recognized as traditional aboriginal land (ISA, 2012). Twelve major river basins form the regional river network and, up to the year 2000, around 68.8% of Amazonia was covered by native forests; from that year until 2010 a decrease in 4.5% of the forest cover was reported (about 240,000 km^2).

It has been acknowledged that the combined effects of environmental detrimental changes, in local land use and alterations in global climate disrupt the natural ecosystems and can increase the risk of transmission of parasitic disease to humans (Patz et al., 2000). Different mechanisms operate in this process (Patz and Confalonieri, 2005; Confalonieri and Aparicio, 2011) and an important one is the expansion of human populations into forest areas, resulting in the exposure of immunologically naïve human and domestic animal populations to pathogens occurring naturally in wildlife (Mandal, 2011).

In the past few decades the occupation of the poorly inhabited Amazon region has intensified, following the expansion of the economic frontier of its countries. Pressures on the natural environment of the region have been increasing steadily due to the opening of new roads, industrial mining, oil extraction; the building of dams for hydroelectricity generation; logging and urban expansion (Ricardo, 2012). These environmental changes, and their associated social-demographic changes, have greatly influenced the dynamics of tropical infectious diseases in the region (Confalonieri, 2000). In this paper we will provide a general overview of the mechanisms involved in the dynamics of the transmission of tropical parasitic diseases in the Amazon and how social interventions in the environment have changed the patterns of parasitic diseases in the region. A special emphasis will be given to malaria, due do its regional importance.

2. The Amazon and parasitic diseases of humans

One of the most outstanding characteristics of the Amazonian environment is the large territory covered by the rain forest,

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Table 1
The parasitic infections common in the Amazon region and the estimated number of cases in Latin America.

Disease	Number of cases	Period	Reference
A – Malaria	1,000,000	2006–2010	WHO (2011)
B – Cutaneous leishmaniases	66,941	2004–2008	Alvar et al. (2012)
C – Visceral leishmaniases	3,668	2004–2008	Alvar et al. (2012)
D – Onchocerciasis	461,000 (at risk)	2010	Gustavsen (2011)
E – Schistosomiasis	1.8 million	2002	Hotez et al. (2008)
F – Soil-transmitted helminthiasis	234 million	2002	Hotez et al. (2008)
G – Chagas disease	8–9 million	2002–2007	Hotez et al. (2008)

associated to a vast network of wetlands: rivers, floodplains and lakes. In this environment a vast diversity of biological species is found and many of them are either arthropod vectors of pathogens or microbial species and parasites associated with diseases in humans. As an example, the Brazilian Amazon alone, accounts for at least 190 species of arbovirus, 35 of them causing human diseases (Vasconcelos, 2009).

The most important parasitic diseases found in the Amazon are listed in Table 1.

Table 1 Most of these parasitic infections of humans are transmitted by arthropod vectors (in the list above only schistosomiasis is not vector-borne) and mosquitoes and sandflies are the most important groups of vectors; kissing bugs (Triatominae) are transmitters of *Trypanosoma cruzi*, the agent of Chagas disease. Although not an agent of a parasitic "disease", blood-sucking bats are increasingly being reported attacking humans in the Amazon region (Caraballo, 1996; Schneider et al., 2009). In a general perspective, the discussion of the impacts of environmental change upon the dynamics of infections disease in the Amazon must take into consideration the diversity of environments – which range from the pristine forest to the built environments of cities – and also the social diversity, which includes semi-isolated aboriginal communities, riverine traditional populations (e.g. rubber tappers; fisherman), peasants in large farms, industrial works and a urbanized high income class. In this review our focus will be mainly on non-urban populations that are more closely associated to the natural ecosystems and are, therefore, more exposed to the increased risks posed by the conversion of the natural environment by anthropic activities.

The most important environmental changes that alter the cycles of the parasitic diseases that affect the populations mentioned above are those that result in forest conversion (deforestation), those that change the water cycle, or both. Global climate change is due to the emission of greenhouse gases (notably CO_2) to the atmosphere due to the burning of fossil fuels and deforestation/forest fires (IPCC, 2007). Scenarios of climatic change for the Amazon region were developed and there is a consensus that a decrease in precipitation and an increase in temperature will occur in the next few decades (Betts et al., 2004; Salazar et al., 2007; Marengo et al., 2012). Scenarios for land use and deforestation in the Amazon were also produced (Soares-Filho et al., 2006) and there is a concern about the impacts of future interactions and feedbacks between forest conversion and climatic change (Laurance and Williamson, 2001; Laurance, 2004; Lapola et al., 2011).

In Fig. 1 we can see the main land use practices, associated with economic activities in the Amazon, that result in the loss of forest cover (deforestation).

A general schedule of the current complexities of environmental changes in the Amazon that may be associated to the incidence of infectious and parasitic diseases is depicted in the Fig. 2.

In Fig. 2, it is indicated that the main general drivers of environmental change in the Amazon are economic activities and the associated demographic process. These frequently occur in the form of large industrial/agricultural operations and land use practices associated with the building of infrastructure (the most

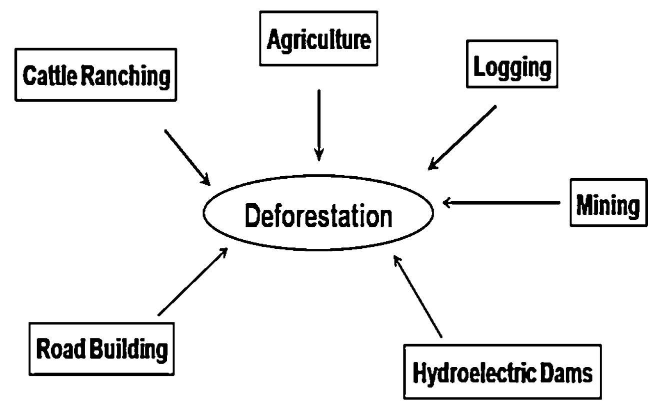

Fig. 1. Land use practices and environmental change in the Amazon.

important were depicted in Fig. 1). As far as the cycles of parasitic diseases are concerned, changes to the natural vegetation and those changes linked to water availability and cycling are the most important. Deforestation and other changes to the land cover (e.g. selective logging, causing partial forest conversion) change the population dynamics of the fauna, both of invertebrates (e.g. vectors) and vertebrates (reservoirs of infections) that maintain parasites and other pathogens in their natural foci. As important as the changes in vegetation cover are changes associated to the water cycle: many arthropod vectors of parasites (*Plasmodium* sp.; *Leishmania* sp.), as well as intermediate hosts (e.g. snails vectors of *Schistosoma* sp.), depend on water collections, on the flow of streams and rivers and on the humidity of the soil and atmosphere. (Olson et al., 2009; Basurko et al., 2011; Barros et al., 2011) An important climatic phenomenon that is known to affect riverine communities in the Amazon, including their health profile, is drought, which reduce the availability of clean drinking water as well as of food (Sena et al., 2012), facilitating human infections.

3. The environmental changes and dynamics of parasitic infections

3.1. Leishmaniasis

The Amazon region is a well-known major focus of cutaneous leishmaniases: it contains a large diversity of both species and strains of *Leishmania* spp. and of species of phebotomine sandlies (Castellón et al., 2000; Lima et al., 2002; Ishikawa et al., 2002; Silva et al., 2010; Alves et al., 2012). The complexities of the natural cycle of mucocutaneous leishmaniasis in the Amazonian environment have been elucidated decades ago (Lainson et al., 1981, 1994) and it was long ago recognized that, in specific localities of the Amazon, most human infections by *Leishmania braziliensis* were acquired during the clearing of primary climax forests and that some vector species, like *Lutzomyia flaviscutellata*, were adapted to non-climax forests, either primary or secondary, natural or man-made (Ready et al., 1983). The foci of leishmaniases are frequently disturbed

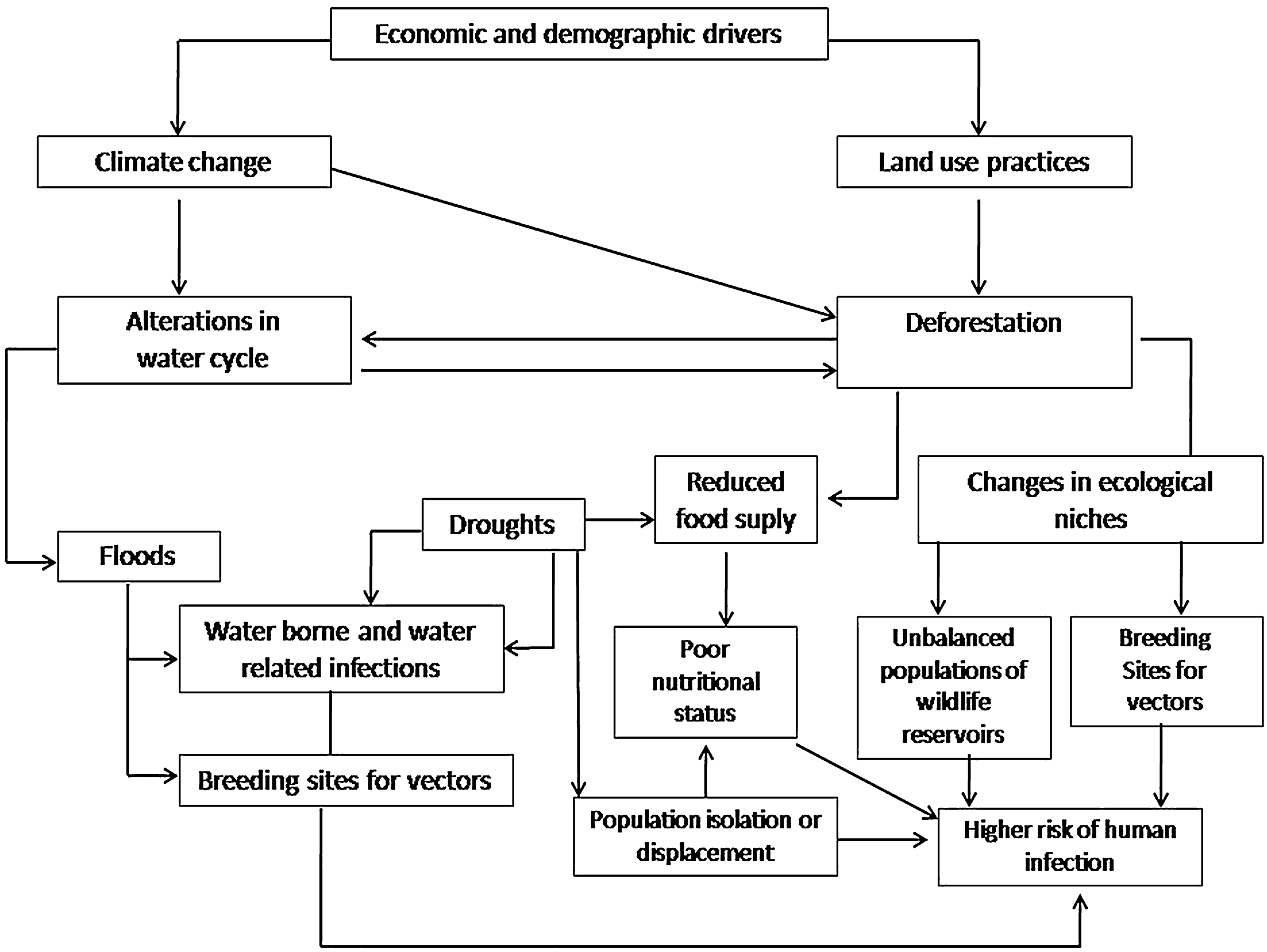

Fig. 2. Environmental changes and infections with natural foci in the Amazon.

by human interventions to the environment. The construction of the Trans-Amazon highway, in the 1970s, was associated to a local increase in cases of the disease and also to a change in the behavior of the vector species, which were observed biting humans during daytime, an unusual aspect for this group of vectors (Pinheiro et al., 1974; Ward and Killick-Kendrick, 1974; Fraiha et al., 1978). Recent changes in phlebotomine populations were observed associated to the building of oil and gas infrastructure in the Amazon (Gomes et al., 2009). On the other hand, Pessoa et al. (2007) have observed both a decrease in infection rates and in population densities of sandfiles in deforested areas of this region. The explanatory hypothesis was a reduction on the ecological niches for the vectors and the local depletion of population of small mammals reservoirs of infection. In general, it is acknowledged that increases in sandfly diffusion and density occur in the context of human migration, deforestation, urbanization and conflict (Maroli et al., 2012). Brazil et al. (2011) have found that the abundance of phlebotomine sandfly species was higher in undisturbed forests in the Amazon; however, in the disturbed areas a few species became dominant, including important vectors of *Leismania* spp. They also mention that drought in the Amazon has contributed to the dispersion of leishmaniasis endemicity. Gunkel et al. (2003) reported that deforestation associated to the building of the Curuá-Una dam, in the Brazilian Amazon, led to the introduction of leishmaniasis locally, due to an increase in the size of forest edge areas. In a recent review of infectious diseases at the Brazilian Amazon, Penna et al. (2009) state that the degree of exposure to the transmission of leishmaniasis is largely associated with disorganized occupation of new areas and cases tended to occur among populations in recent land settlements and former rainforest areas.

Kala-azar (visceral leishmaniasis) is found in the Amazon in discrete foci of its eastern part (Brazil) and also at the northernmost part of the Brazilian Amazon. There has been a debate whether this is an enzootic disease autochtonous to this region or has been introduced by infected human migrants and if the transmission cycle is maintained by domestic dogs. The recent finding of a wild canid species infected by *Leishmania* (L.) *chagasi*, in a protected area of eastern Amazonia of Brazil (where no humans or dogs are found), is a strong evidence on the existence of an indigenous enzootic cycle of this parasite in the Amazonian wilderness (Silveira and Corbettet, 2010). This parasitic disease is becoming increasingly urbanized in Brazil (Rangel and Villela, 2008) and elsewhere, due to the adaptation of the vector *Lutzomyia longipalpis* to the urban environment; this seems to be happening already in the Amazon since cases at the periphery of the city of Santarém, Brazil, are being reported since the 1980s (Silveira et al., 1997).

3.2. *Chagas disease*

Chagas disease is an enzootic infection of wild animals (an anthropozoonosis), caused by the protozoan species *T cruzi*, which affect humans accidentally. The presence of the wild cycle of this parasite in the Amazon was recognized almost a century ago and up to now, at least 27 species of the triatomine vectors were found infected with this parasite in the region (Junqueira et al., 2005). Human infections with *T. cruzi* in the Amazon were reported initially in French Guiana and then at the northeastern part of the Brazilian Amazonia, in the late 1960s (Shaw et al., 1969); nearly all Amazonian countries have reported acute cases of the disease (Coura and Junqueira, 2012). The Brazilian Amazon concentrates the largest number of cases and new foci were recently identified in the northwestern part of the region; from 1969 through 2008 the Brazilian Ministry of Health has reported a total of 761 cases in the Amazon, 75% of them between 2002 and 2008 (Brum-Soares et al., 2010). The complexities of the ecological niche of Chagas transmission, associated with palm trees in the Amazon, have been described in detail and the role of marsupial reservoirs and of the vector species, *Rhodnius pictipes*, was well characterized (Teixeira et al., 2001). The transmission of Chagas disease to humans in the Amazon through the bites of infected bugs seem to be rare and the oral route of infection – usually by ingesting the contaminated juice of the açai fruit from palm tress – is being increasingly reported from the Brazilian portion of the basin (Nóbrega et al., 2009). Coura and Junqueira (2012) indicate that the risk of Chagas disease becoming widespread in the Amazon is associated to the following phenomena: (a) extensive deforestation, resulting in the displacement of wild mammals reservoirs of infection, which are the common sources of blood for the vectors; (b) adaptation of wild species of triatomines to human dwellings and (c) migration of humans and domestic animals from other endemic regions to the Amazon.

3.3. Schistosomiasis

This is a helminth infection, caused by *Schistosoma mansoni*, and its cycle involves an aquatic snail (*Biomphalaria* spp.) as intermediate host that seem to have been introduced to the eastern Amazonian area in Brazil by human migrants from the endemic northeastern region of this country. The role of human migration in the geographic spread of the disease is well known, and also its association, in Brazil, with water management infrastructure–especially small dams–at the semi-arid part of the country. Streams in the Amazon were found to harbor at least eight species of snail hosts susceptible to *S. mansoni* infection (Valadão and Milward-de-R, 1991). The reporting of the first autochthonous human case of schistosomiasis (eastern Amazon) dates back to the late 1940s but the disease has remained restricted to discrete foci at the periphery of urban areas. This is the case of the city of Belém, Brazil, with its favorable topography and hydrography, where up to 22% of the snails from districts endemic for the infection were found to contain *S. mansoni*. The cycle of infection is directly related to poor sanitation infrastructure (no water supply or waste disposal facilities), causing the contamination of water bodies where the susceptible snails colonize.

It has been speculated that the *Biomphalaria* snails could spread to non-flooded areas, after deforestation (Aragão, 1987) but this has not been observed so far in this region. Although already observed colonizing spillways of dams in Africa (Grosse, 1993), snail hosts of *S. mansoni* have not been found in these structures in dams built in Amazonia.

3.4. Soil-transmitted helminthiases and filarial infections

Soil-transmitted helminthiases (STHs) collectively cause the highest global burden of parasitic disease, after malaria (Weaver et al., 2010). The parasites involved in STHs are nematodes of the species *Ascaris lumbricoides, Trichuris trichiura*, *Necator americanus* and *Ancylostoma duodenale*. There are complex interactions between the physical environment (either natural or man-modified) and the human behavior involved in the maintenance of the endemic status of STHs globally. Of special importance are low income communities who live in degraded and high risk environments lacking adequate housing, water supply and sanitation, resulting in close contact with immature forms of these worms in the environment (Gazzinelli et al., 2012). Several surveys have shown high rates of infection of human communities all over the Amazon, both rural and urban, with species causing STHs, as well as protozoan intestinal parasites (Coura et al., 1994; Eve et al., 1998; San Sebástian and Santi, 2000; Egido et al., 2001; Araújo and Fernandez, 2005; Rios et al., 2007; Souza et al., 2007; Carvalho-Costa et al., 2007; Hinke, 2009; Santos et al., 2010; IDB/PAHO, 2012). Besides the poverty and sanitation aspects mentioned above, in the Amazon, environmental conditions such as soil type and humidity as well as climatic conditions (e.g. temperature; rainfall) are essential for the development of these parasites, which spend part of their cycles in the physical environment. There has been recently a discussion on the possible role of the projected changes in global climate on the incidence of STHs since climatic factors can directly influence STHs through its effects on the free-living stages of the parasites. However, it was hypothesized that climate-driven changes in epidemiology could be circumvented by effective intervention for control (e.g. sanitation) and it would override the influence of environmental factors (Weaver et al., 2010).

Filarial infections in the Amazon are transmitted by blackfly vectors (*Simulium* spp.) and are caused by two species: *Onchocerca volvulus* and *Mansonella ozzardi*. The latter has its distribution restricted to the southwestern and northern part of the Amazon, in Brazil, Venezuela and Guyana (Medeiros et al., 2007). Its prevalence seems to be higher in rural areas (Martins et al., 2010). It is considered of less importance in public health due to its low pathogenicity for the human hosts. In regard to Onchocerciasis, its distribution in the Amazon is restricted to the Yanomami Indian tribe, in southern Venezuela and in the northernmost part of the Brazilian Amazon (Shelley, 2002; Gustavsen, 2011). This species, introduced from Africa to the Americas more than a century ago, is pathogenic for humans and the most serious effect of parasitism are eye lesions that can result in blindness. The disease occur essentially in wild habitats since the vector species needs substrates in fast flowing, clean water (such as in rapids in streams and waterfalls), with high levels of oxygen, in order to breed. Botto et al. (2005) reported that, in Venezuela, there were significant correlations between onchocerciasis and temperature, geological substrate, river courses and types of landscapes and vegetation. Environmental changes that could affect the cycle of blackflies – and the incidence of onchocerciasis in the Amazonian foci – are those that would affect the water flow and water quality of streams and rivers, either locally (e.g. soil erosion due to land use) or regionally, such as changes in climate and hydrology.

3.5. Toxoplasmosis

Toxoplasmosis, caused by the protozoan parasite *Toxoplasma gondii* has been reported from Amazonian countries, both in a domestic cycle (with cats taking a central role) and also as a forest cycle, involving wild felids (Thoisy et al., 2003; Borges, 2006; Demar et al., 2007; Carme et al., 2009; Gilot-Fromont et al., 2012). In French Guiana, an emerging severe form of the disease in immunocompetent patients was reported as a major public health problem and most people affected reported forest-related activities such as ingestion of surface water, consumption of undercooked meat and hunting. Although not yet reported outside French Guiana, this form of the disease, designated as “wild rain forest toxoplasmosis” or “Amazonian toxoplasmosis”, is expected to be found in other areas of the region populated by wild felids (Carme et al., 2009).

Besides this wild strain, authors have found, also in French Guiana, a genetically distinct population of *T. gondii*, in the anthropized environment. It was hypothesized that the ongoing anthropization of tropical forest areas in the Americas would facilitate the gene flow between wild and domestic strains of *T. gondii*, and the adaptation of the more aggressive strain to domestic hosts, in the disturbed environment (Mercier et al., 2011; Gilot-Fromont et al., 2012).

3.6. Malaria

Malaria is the most common parasitic disease of humans in the Amazon region and its transmission is associated mostly to the vector species *Anopheles darlingi* (Hivat and Bretas, 2011). The majority of malaria cases in this region are caused by the species *Plasmodium vivax* (77%), followed by cases due to *Plasmodium falciparum*; around 500,000 malaria cases were reported in the Amazon in 2008 (Silva-Nunes et al., 2012). In the past decade, the natural history of malaria in the Amazon has undergone significant changes. In Brazil, strains of *P. vivax* resistant to chloroquine have emerged; a pattern of unusual clinical complications with fatal cases due to *P. vivax* infection were reported, and asymptomatic infections caused by both *P. vivax* and *P. falciparum* were frequently detected in southwestern Amazonia (Oliveira-Ferreira et al., 2010). Environmental changes can result in changes in the availability of breeding sites for mosquitoes and may also affect their survival rate and reproduction (Takken et al., 2005). Most malaria transmission typically occurs in mining and logging camps and in new farming settlements. These settlements not only induce massive environmental changes, such as deforestation, that alter vector biology, but also cluster large numbers of non-immune migrants close to natural and man-made vector breeding sites (Silva-Nunes et al., 2012). Throughout Amazonia, malaria transmission hotspot areas are intermingled with areas of moderate or low transmission risks.

A particular situation is the case of the city of Manaus, in Brazil, where "urban" malaria has been endemic for several years, at squatter settlements in the periphery of the city. Vector species come from the nearby forest and bite human hosts inside and around their houses; in 2005 around 64,000 cases of the disease were reported (Saraiva et al., 2009). It is, actually, an endemic form of "wild" malaria, which is maintained due to the urban sprawl encroaching into the forest, associated to infected people migrating from the countryside as well as poor health care.

Tadei et al. (1998) have found that anopheline abundance was estimated to be five times greater in disturbed compared to undisturbed areas. Besides changes in abundance, deforestation often result in changes in mosquito species composition (Conn et al., 2002; Vittor et al., 2006; Vittor, 2009; Moutinho et al., 2011). Vittor et al. (2006) studying a recently deforested area in the Peruvian Amazon, have observed that deforested sites had an *A darlingi* biting rate 278 times higher than the rate observed in areas predominantly forested. In this same area sites with *A. darlingi* larvae had an average of 24.1% of forest cover, compared with 41.0% for sites without *A. darlingi* (Vittor, 2009). Parente et al. (2012) have analyzed both malaria incidence and deforestation rates (as measured by satellite imagery), in four different regions at the state of Pará, eastern Amazon, Brazil. Using time series of data from 1998 to 2005, they found that, after periods of intense deforestation, malaria incidence rates were high or very high. Castro et al. (2006) observed that, as human settlements in deforested areas of the Amazon became stable, a plateau of malaria cases was observed; in areas completely deforested and replaced by pasture, malaria cases become rare. Besides deforestation, other environmental changes affecting river flow or regional climate can have a significant impact in the dynamics of malaria. The role of dams in enhancing malaria transmission was reviewed by Queiroz and Motta-Veiga (2012), Kaiser et al. (2005) have compared malaria data before and after the construction of three dams in the Amazon and found that, in all, the incidence of the disease has increased in association with environmental modifications: deforestation and the creation of large collections of surface water.

The association between climatic and hydrological factors and the monthly incidence of *P. vivax* malaria was investigated in a locality in French Guiana (Basurko et al., 2011). These authors found positive associations between malaria incidence and different physical parameters–especially river level and precipitation–with varying lag times. The only factor detrimental to the development of malaria cases were particularly high temperatures. In Venezuela, Metzger et al. (2009) have found positive significant correlation between rainfall and *P. vivax* and *P. falciparum* malaria, with lag times of about four months. Gil et al. (2007) found high anopheline densities accompanying the peak of rainfall, in a rural locality of southwestern Brazilian Amazon, as well as minor peaks of vectors between the end of the dry season and the beginning of the next rainy season; these secondary peaks were related to permanent anopheline breeding sites resulting from human activities.

Positive associations between river level and both anopheline densities and/or malaria incidence have been also found in other Amazonian countries (Rozendaal, 1992; Bautista et al., 2006; Magris et al., 2007; Wolfarth, 2011). Barros et al. (2011) observed that *A. darlingi* larval densities were associated to small obstructions of river flow, such as those caused by fallen tree trunks in river channels, which caused the pooling of water during the dry season and, thus, extended the breeding season for this vector species.

The maintenance of malaria as a year-round parasitic disease endemic in the Amazon depend on these variations and changes in the environment but also depend, to a great extent, on the frequent mobility of humans, both infected and susceptible, as well as on the difficult logistics for the provision of health care services to remote communities in the region. These complex interactions can be illustrated by the example of the informal gold mining sites. These places, with small-scale alluvial gold mining activities, are considered as hotspots for malaria transmission (Vosti, 1990; Silbergeld et al., 2002; Duarte and Fonters, 2002; Barbieri et al., 2005; Barbieri and Sawyer, 2007; Moreno et al., 2009; Schutz, 2011).

4. Human exposure to parasitic diseases in gold mining sites

The informal gold mining places are linked to a multitude of acute environmental problems such as mercury pollution; river siltation and turbidity; soil erosion; deforestation and landscape degradation (Eisler, 2003). They are also characterized by the extreme mobility of people since mining involves, essentially, a temporary work. Incoming miners often originate in areas non-endemic for malaria outside the Amazon and, therefore, they are biologically susceptible to malaria due to the lack of immunity. On the other hand, infected people frequently move from one mining site to the other, in the wake of a new "gold rush", and thus disperse strains of *Plasmodium* sp. throughout the region. Local environmental changes, as described in the preceding paragraphs, create many adequate breeding sites for mosquitoes, building up dense populations of vectors. Outbreaks of malaria in these usually remote areas are also facilitated by the absence of medical care and of early detection and adequate treatment of cases. Even when anti-malarial medicines reach these communities, there is no adequate follow-up of treatment and this enhances the occurrence of relapses of the disease as well as the development of resistant strains, due to incomplete or improper treatment. Miners usually rest in temporary tents without walls, in the camps, which make insecticide spraying difficult for the control of vector populations.

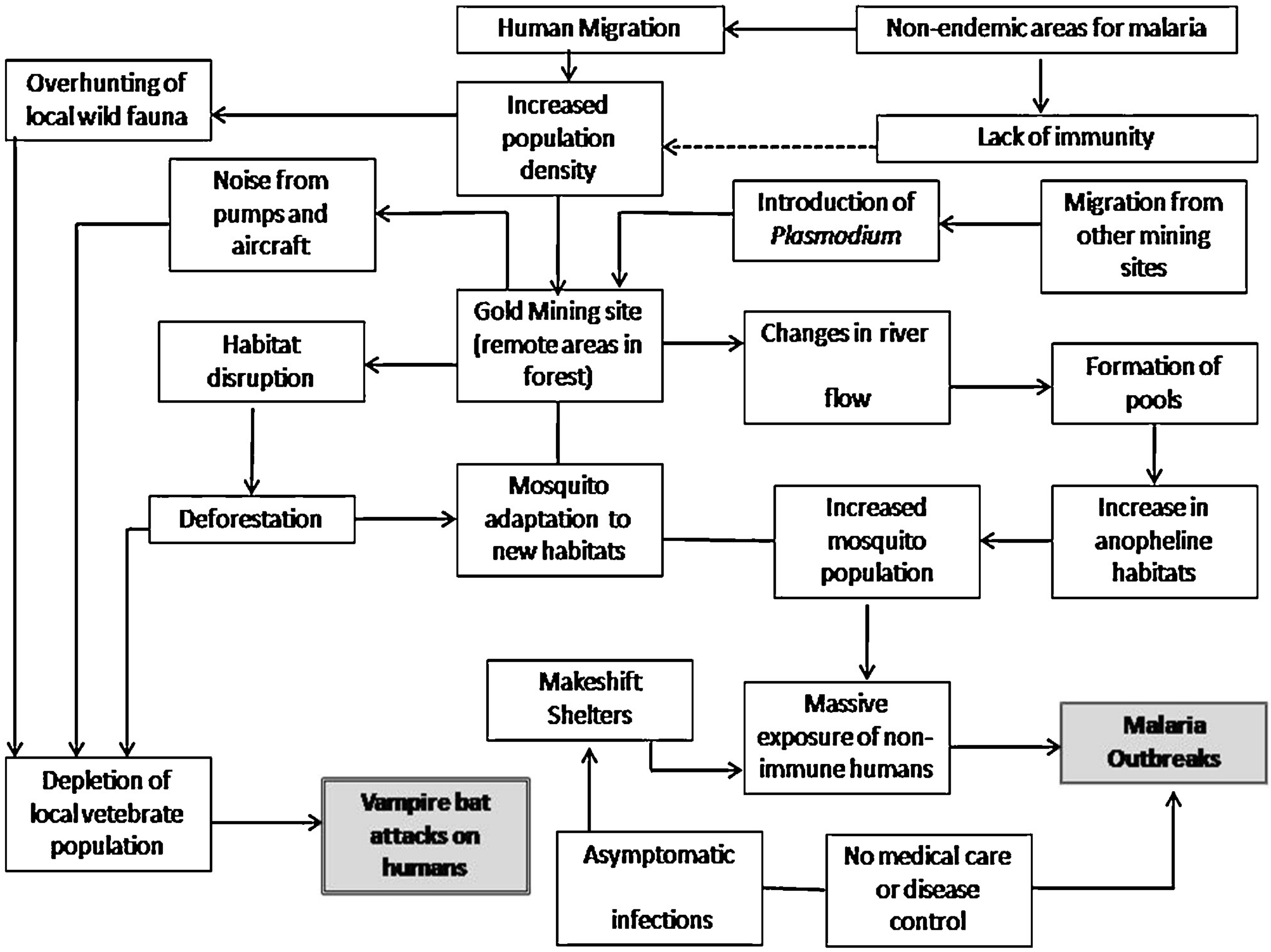

Fig. 3. Causal diagram for malaria transmission and vampire bat attacks in gold mining sites in the Amazon.

The role of blood sucking bats in the transmission of viral infections is well known and at least 60 different types of these diseases were reported (Streicker et al., 2012; Wong et al., 2007). In Latin America human rabies has reemerged due to bat-associated transmission (Carvalho-Costa et al., 2012). In the Amazon region, the adaptation of vampire bats to anthropic environments has been recognized long ago (Mok and Lacey, 1980) and, in recent years, several outbreaks of vampire bat attacks in the region were reported, either followed by human rabies outbreaks (Schneider et al., 1996; Rosa et al., 2006; Lopez et al., 1992; Mendes et al., 2009; Gilbert et al., 2012) or not resulting in virus transmission (Schneider et al., 2001; Carvalho-Costa et al., 2012).

In relation to the vampire bat attacks that occur in mining places, these are basically due to the replacement of local population of wild vertebrates – on which bats usually take their blood meal – by large numbers of human hosts, which are massively exposed to the bites. Attacks on humans are also facilitated by the precarious shelters where gold diggers live.

Lee et al. (2012) have used the ecological niche modeling approach to project future potential distribution of the bat species *Desmodus rotundus*, the most commonly associated to human attacks in the L. America. The projections were made according to scenarios of climatic change and some scenarios indicated an expansion of the range of this species to western Amazonia.

We have summarized in a causal diagram (Fig. 3) the main environmental and social processes that take place in mining sites of this type and which facilitates the occurrence of outbreaks of both malaria and vampire bat attacks, a common occurrence.

5. Discussion and conclusions

The processes of ecological change, especially those on a larger scale, involve complex interactions and feedbacks, making their association with disease emergence difficult to demonstrate scientifically (Plowright et al., 2008). These authors have suggested the association of different techniques for the study of the ecological drivers of infectious disease emergence, including strong inference, causal diagrams and model selection.

However, on a local scale, and for infectious/parasitic diseases with well know cycles, the identification of the environmental drivers of the variations in the observed incidence rates is easier. Accurate and continuous empirical observations in the field can produce enough factual information to be represented in a causal diagram; this will point to possible social and environmental pathways and their interactions, involved in disease outbreaks.

Specifically for the Amazon, a typology for the analysis of the linkages between environmental change and human health was proposed (Confalonieri, 2005). In this approach, several types of “disease landscapes” were described for endemic infections, these landscapes being differentiated by the dominant land use practice, the dependence of communities on forest products and the degree of degradation of ecosystem services. Coupled to these were also considered the mobility of the population and the capacity of the health care systems to perform effectively the disease control activities, required for specific landscapes (Confalonieri, 2005).

The Amazon basin is undergoing rapid changes, both in the natural environment and in human society. Large cities in the region, such as Manaus, have their particular urban environmental health problems, just like other large cities elsewhere. Part of these problems are linked to tropical parasitic diseases, which persist, despite changes associated to the epidemiological transition, when chronic diseases become the main determinants of mortality, a fact more clearly seen in urbanized populations. However, most of the regional changes–already observed and expected to occur–in the epidemiology of parasitic diseases, are projected for those infectious disease cycles with natural foci in the biomes. This is the case of several "neglected" diseases, such as the leishmaniases, soil-transmitted helminthiases, schistosomiasis and onchocerciasis, which are endemic throughout the basin, or in parts of it. Many tropical parasitic diseases are changing, in different parts of the world (Mandal, 2011), including the Amazon, in aspects related to their ecological niches (e.g. urbanization of kala-azar); modes of transmission (e.g. oral transmission of Chagas disease); host and geographical range; pathogenicity; vector species involved and susceptibility to drugs (McMichael and Confalonieri, 2012). The determinant of these changes are mainly social-environmental in nature and, in the Amazon, the conversion of native forests to other forms of land use, is especially important for the region, in regard to focal parasitic diseases. Some of these, with direct linkages to the natural environment, which provides ecological niches for vectors, such as malaria and the cutaneous leishmaniases, are responding rapidly to environmental changes, especially deforestation and climatic shifts, or a combination of both. Others, such as the soil-transmitted helminthiases, are more likely to change in response to environmental interventions, such as the building of sanitation infrastructure, in urban and peri-urban areas. Of special concern are the large scale impacts projected to occur in Amazonia, as a consequence of global climate change. Although climatic scenarios have projected a drastic reduction in forest cover in eastern Amazon, as a result of changes in the global climate system, no models have so far been developed in order to estimate future risks of malaria and other tropical diseases, as a consequence of these scenarios of environmental change.

New knowledge is needed, both on a regional and in more localized scales, of the specific impacts of environmental changes on the dynamics of infectious and parasitic diseases of Amazonia. For this, integrated, multidisciplinary approaches to research, with exchanges between disciplines such as parasitology, epidemiology, ecology, climatology, geography, land use science and social sciences will be required, for the achievement of practical results.

Regional health systems must also be prepared for these changes to the epidemiological profile of the Amazon region, as a consequence of accelerated changes to its environment and society. One important strategy would be to enhance regional epidemiological surveillance in general, but especially to target its activities to sub-regions or areas where social-environmental modifications are occurring, or are expected to occur, in the near future. This is the case of the projected pavement of highway BR-163, in Brazil; the large dams being built at the Xingu and Madeira river, also in Brazil (the latter with upstream impacts in Bolivia) and the construction of the Transoceanic highway (Brazil – Peru), which will allow Amazonian export products to gain access to port cities at the Pacific Ocean (Ricardo, 2012). An integrated, international system of surveillance for infectious diseases linked to environmental changes, especially those that could cross borders, would be an important strategy for health protection in the Amazon. Some useful disease-focused systems have been operating recently, as is the case "Amazon Malaria Initiative" (USAID/PAHO, 2010) and the "Intergovernmental Initiative of Chagas Disease Surveillance and Prevention in Amazonia" (IICDSPA, 2005).

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