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Population and Land Use Effects on Malaria Prevalence in the Southern Brazilian Amazon

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*Malaria prevalence has been one of the most dramatic outcomes of the occupation of the Brazilian Amazon as exemplified by Northern Mato Grosso, one of the areas of highest malaria prevalence in the Americas in the early 1990s. This paper associates the dynamics of high malaria prevalence in Northern Mato Grosso with three land uses—small-scale gold mining (*garimpos*), agricultural colonization/cattle ranching (rural), and urban activities—and their related population characteristics, which constitute risk profiles. Furthermore, spatial proximity and population mobility between (a)* garimpos *and new rural settlements and (b) older rural settlements or urban areas are key factors explaining malaria diffusion throughout the region. The paper identifies and characterizes populations at high malaria risk and the effects of land use types on malaria diffusion, providing policymakers with information for regional and local policies to control malaria and minimize its effects on Amazonian populations.*

KEY WORDS: Brazilian Amazon; malaria prevalence; *garimpo*; rural and urban land use; population mobility.

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INTRODUCTION

Malaria prevalence has been one of the most dramatic outcomes of the occupation of the Brazilian Amazon. Several studies have analyzed the impacts of land uses and population characteristics on malaria prevalence in this region, relying on household surveys carried out in settlement projects and *garimpo* sites (a *garimpo* is a small-scale, semimechanized, and highly labor-intensive mining of alluvial gold deposits). Six key lessons can be drawn from those studies. First, malaria cases are concentrated in males of labor age, indicating the exophilic activities of the mosquitoes (outdoor feeding behavior)[5] and an occupation-related transmission (Castilla and Sawyer, 1986; Sawyer and Sawyer, 1987, 1992; Singer and Sawyer, 1992; Sawyer, 1995; Barbieri, 1997, 2000; Cedeplar/UFMG, 1997; Sawyer, 1999). This pattern is quite different from Africa and Asia, where high malaria prevalence exists among infants and pregnant women (Kindhouser, 2003). Second, malaria prevalence among *garimpeiros*—the garimpo workers—is considerably higher in comparison with colonists (rural settlers) and those engaged in urban activities. This indicates an association between the nature of the risk and occupational profiles in the Amazon (Sawyer and Sawyer, 1992; Singer and Sawyer, 1992; Sawyer and Castilla, 1993; Sawyer, 1995; Barbieri, 2000). Third, the high mobility of garimpeiros is one of the key factors engendering high malaria prevalence and the diffusion of the disease to areas of lower incidence (Castilla and Sawyer, 1986; Marques, 1987; Singer and Sawyer, 1992; Barbieri, 1997, 2000). Fourth, better housing quality (construction with quality material walls, roofs, doors, and windows) provides protection against the mosquitoes, thus playing an important role in reducing malaria rates (Sawyer and Monte-Mór, 1992). Fifth, the proximity of houses to forest and water sources is a key factor affecting malaria risk (Marchesini *et al.*, 1996; Castro, 2002). Sixth, and last, the time of residence in an endemic area may be a proxy to the acquired immunity, as well as the ability, knowledge, and resources to better avert the disease (Sawyer and Sawyer, 1987; Sawyer and Monte-Mór, 1992; Sawyer, 1995; Barbieri, 1997).

Other studies outside Brazil present similar findings regarding linkages between differential malaria risk and occupational profiles of the population (Kitron, 1987; Sevilla Casas, 1989, 1993; Olokesusi, 1991). The accumulated evidence linking land uses and the risk of malaria transmission allows us to better understand individual risks to the disease and how its transmission is related to human settlements.

[5]The feeding habit of the mosquitoes transmitting malaria, especially the *A. darlingi*, is known to be endophilic, or feeding inside houses. Malaria control services use this knowledge for spraying indoors with residual insecticide. The referenced articles show the exophilic feeding behavior of the mosquito, or feeding outdoors.

This paper focuses on an important issue rarely addressed, in the literature: how the *combination* of three land uses—garimpos, agricultural colonization, and cattle ranching (rural) and urban activities—and population characteristics, which constitute risk profiles associated with each land use, acted as a powerful mechanism underlying the dynamics of malaria prevalence in the Amazon. A broader implication of this study is to understand how patterns of human settlement in frontier areas of the Amazon and changes induced in the environment, especially the disruption of ecological equilibrium between humans and vectors transmitting the disease, engender a high malaria endemism.

In order to understand linkages among human population characteristics, human land use, and malaria prevalence, three hypotheses are raised. First, some key population characteristics are associated with high risk profile of malaria prevalence: poorer housing conditions, higher proportion of young adults, higher sex ratio, and a relatively higher proportion of population having *P. falciparum*. Second, the very nature of garimpos and rural areas at initial stages of settlement or land clearing is associated with high malaria prevalence, while long-settled rural areas and urban areas present lower malaria prevalence. Finally, high spatial proximity and human population mobility between areas presenting high and low malaria prevalence facilitates the mobility of the disease, via infected populations of humans and vectors, and consequently the diffusion of malaria.

We consider Northern Mato Grosso to be a valid area to conduct this study given it is one of the areas of highest malaria prevalence in the Americas in the early 1990s (Sawyer, 1995) and it is a broad area encompassing distinct land uses with a high spectrum of malaria rates. An important methodological issue addressed in this paper is the use of spatial and temporal information reflecting the distribution of malaria prevalence in the region.

BACKGROUND

The Amazon tropical environment, especially the breeding locations of shaded and still waters in the forest, favors the thriving of malaria vectors (i.e., mosquitoes such as the *Anopheles oswaldoi* and *Anopheles darlingi*—the latter is the main malaria vector in the Brazilian Amazon). The mosquitoes, well adapted to the Amazon environment, maintain their endemism even at low densities (Tadei *et al.*, 1998) and transmit malaria year-round. The protozoan *Plasmodium falciparum* (or *P. falciparum*) and the *P. vivax* are together responsible for almost all malaria cases in

Brazil (Sawyer, 1995; Spencer, 1996; Sawyer, 1999). *P. falciparum* is more dangerous to human health than the *P. vivax* since it reproduces at much higher rates in humans. The parasites travel to the liver where they grow and multiply, and after as few as eight days, they leave the liver cells and enter red blood cells, where they continue to grow and multiply. After they mature, the infected red blood cells rupture, freeing the parasites to attack other red blood cells, where they eventually burst and release toxins, causing the typical fever, chills, and flu-like malaria symptoms (Meade and Erickson, 2000).

P. falciparum tends to be more common in garimpos and new rural settlements, mostly due to the precarious institutional programs of malaria control and medical treatment, while the *P. vivax* predominates in areas of better malaria control and easier access to medical treatment, such as older rural settlements and urban areas (Sawyer, 1999). Predominance of *P. vivax* can lead to a reduction in malaria prevalence, since as noted, it is a less dangerous form of malaria than *P. falciparum*, and more susceptible to treatment with traditional drugs such as cloroquine.

There is currently no vaccine to prevent malaria. Containment of the disease consists basically of early diagnosis and treatment and control of vector populations through indoor insecticide spraying and, more recently, outdoor spraying. However, three main causes are behind the high resilience of the disease to control programs: a) *P. falciparum* is increasingly resistant to the conventional treatment with cloroquine; b) the adaptation of the *A. darlingi* to the built-up environment; and c) an increasing number of asymptomatic infected people not detected by the control program, who continue to transmit malaria (WHO, 2000a, 2000b).

High malaria prevalence in the Brazilian Amazon has been historically related to the high influx of migrants to the region. Sawyer (1995) and Spencer (1996) pointed out that 80% of all malaria cases in the Brazilian Amazon after 1980 were concentrated in three states: Mato Grosso, Rondônia, and Pará. Prior to explicit Brazilian government policies for the occupation of the Amazon in the 1970s, the reported number of malaria cases in the country was approximately 8,000 (corresponding to an Annual Parasitological Index [AP][6] of less than 0.16). An explosive and monotonic increase in later years resulted in 169,000, 560,000, and

[6]The Annual Parasitological Index (API) is the number of positive cases diagnosed in the year divided by the population in the midyear. Since one person in the population can have more than one positive diagnosis, it measures the prevalence of malaria spells instead of the prevalence of the diseased. Although there is a conceptual difference between malaria prevalence rate (number of malaria cases per population exposure time) and IPA (the number of malaria spells by population exposure time), we will be referring to both as the malaria prevalence rate.

615,000 cases in 1980, 1990, and 2000, respectively (an API of 2.3 in 2000). The growth in the number of cases is associated with the concentration of cases in the Amazon—from 50% of the cases reported in Brazil in 1960 to 99% after 1990 (Ministério da Saúde/FNS/Gerência Técnica de Malária, 2003). Furthermore, 92% of the cases reported in other Brazilian regions were associated with individuals who had recently been in the Amazon (Marques, 1994). Moreover, malaria in 129 of 529 *municípios* (or municipalities) in the Brazilian Amazon, comprised 90% of malaria cases; 37 of the 129 municípios had an API exceeding 100.

The high malaria endemism in most of these Amazon municipalities was related to new rural settlements and to the widespread alluvial gold mining sites, demonstrating that malaria prevalence is intrinsically associated with frontier expansion. In fact, field research in Northern Mato Grosso by the authors of this paper, between 1992 and 1995, supports evidence of associations between malaria prevalence and the characteristics of land uses, especially the garimpos, which are located along rivers or creeks and near large tracts of forest that constitute adequate habitats for the reproduction of vectors, and rural settlement areas in the early stages of occupation.

Garimpeiros present peculiar characteristics, such as the predominance of young males (20–34 years old), little use of family labor, and a clear gender labor division in which men work in gold production activities and women work in food preparation or are prostituted. The garimpeiros have little protection against infection due to their long working hours (an average of 14 hours per day, six or seven days a week), including the hours of the vector's highest hematophagous action. Moreover, poor quality housing in the garimpos favors the access of mosquitoes, while the high concentration of garimpeiros provides an abundant food source of human blood, allowing them to reproduce at high rates. Garimpeiros also have a high spatial mobility; as soon as they exhaust the superficial alluvial gold deposit, the whole group or part of the group move on to the next available area to start a new garimpo.

Rural settlement areas are susceptible to the outbreak of malaria in their initial stages due to the intense contact between settlers and vectors, especially during land clearance activities. After the initial stage of settlement, malaria prevalence declines due to several factors: (a) less interaction between humans and vectors; (b) the larger extent of cleared land; (c) improvements in housing conditions (with the use of wood from the cleared forest); (d) better access to health care; (e) greater personal resistance to malaria; and (f) greater knowledge about the disease.

There are usually fewer chances of contact with vectors in developed urban areas because of the absence of the vector's habitat, although many cases of urban malaria occur due to both the adaptation of vectors to urban settings and the presence of infected individuals from rural areas or garimpos.

STUDY AREA: NORTHERN MATO GROSSO, BRAZIL

The Brazilian Amazon comprises the states of Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, and portions of Mato Grosso, Maranhão, and Tocantins, totaling approximately 5 million km^2—as large as the entire area of Western Europe. Figure 1 shows the study area, located in the northern part of the State of Mato Grosso which is in the Southern Brazilian Amazon. Northern Mato Grosso had five municípios by 1995: Peixoto de Azevedo, Terra Nova do Norte, Nova Guarita, Matupá, and Guarantã do Norte. Each município is constituted by at least one urban center. The largest urban center in the município (its administrative unit) is the *sede municipal*; other urban areas, known as *distritos urbanos* (if any), and rural areas, are subordinated to the sede municipal.

The first colonization projects in Northern Mato Grosso, in the late 1970s, intended to settle landless families from Southern Brazil. The concept of colonization included, from its outset, a dichotomy between the place of residence (in urban *nuclei*) and the place of work (rural areas), which configured a space of intense population mobility. Each colonist family could acquire a rural plot of 50–100 ha, plus 2 ha in an urban area. However, as observed elsewhere in the Brazilian Amazon, spontaneous colonization involving immigrants from all parts of Brazil, especially from the Northeast, became the predominant form of settlement in Northern Mato Grosso over the following years.

Figure 2a shows a typical farm in a colonization project in Northern Mato Grosso. As in most of the colonization experiences in the Brazilian Amazon, settlers usually occupy plots of land along roads opened by the government. They usually burn their lands during the dry season to facilitate deforestation and clearing agricultural fields.

Northern Mato Grosso faced one of the highest deforestation rates in the Brazilian Amazon during the 1990s (Soares, 1998; Soares *et al.*, 2001; see also data from IBAMA—the Brazilian Environmental Agency—at www.ibama.gov.br). Deforestation rates almost doubled between 1994 and 1999 (Fig. 3) when the region lost about 500 km^2 of forest per year—a 200 km^2 increase over earlier years. The forest loss exceeds, at the present time, 8,000 km^2, about 42% of the original forest. If the recent trend prevails, we can expect a reduction to one-fifth its original area within the next 25 years.

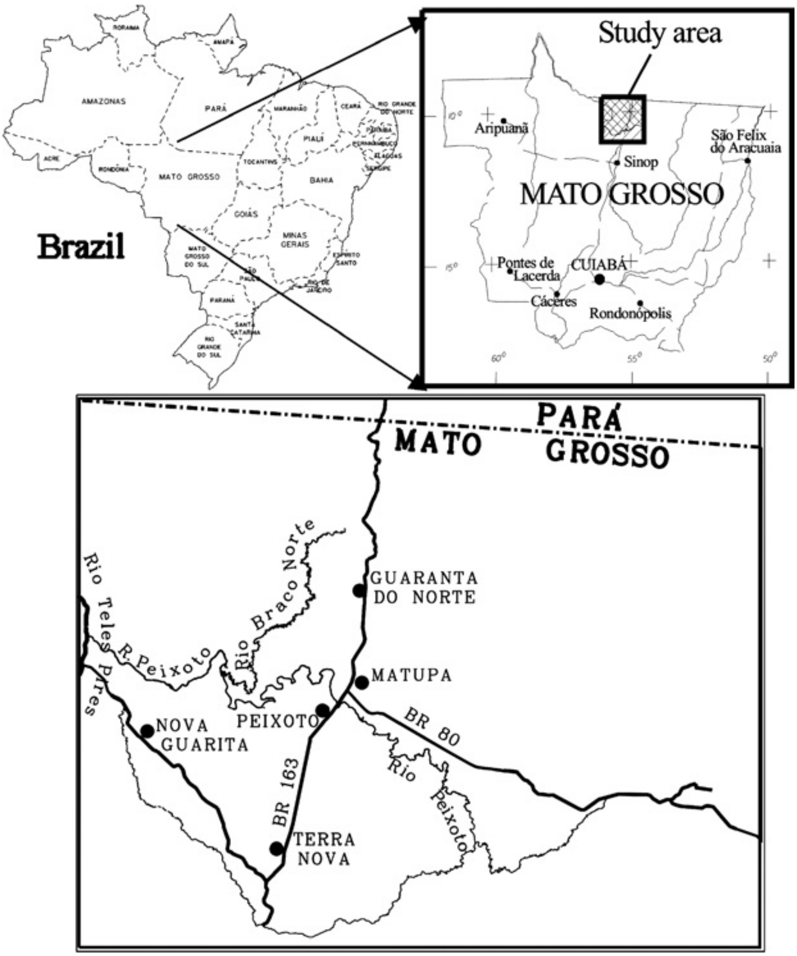

Fig. 1. Map of Brazil with state divisions and location of the study area in Northern Mato Grosso, showing main towns, rivers and roads. Source: Soares-Filho (1998), modified by Barbieri (2000).

Increasing deforestation in Northern Mato Grosso is associated with a remarkable expansion of agriculture and especially cattle ranching. According to the 1996 Brazilian Agriculture Census (www.ibge.gov.br), 32% of the deforested land in Northern Mato Grosso was occupied by pasture by 1995 and only 2.6% was in annuals or food crops. The Municipal Agriculture and Cattle Surveys (www.ibge.gov.br) showed that the area in annuals and food crops (mainly rice and corn) in Northern Mato Grosso doubled from 1991 to 1995, from 28,667 ha to 58,693 ha. The amount of land devoted to

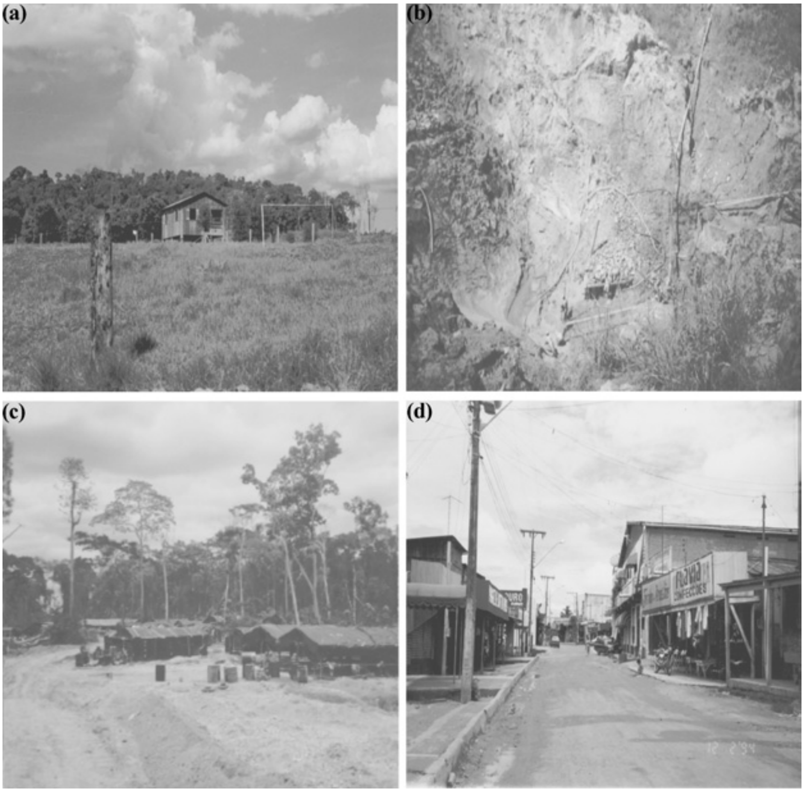

Fig. 2. Typical land uses in Northern Mato Grosso. (a) (Upper left) typical farm in a colonization area in Northern Mato Grosso. Most of the land is cleared and the quality of house (wood) is relatively good, indicating an older settlement. Malaria prevalence is usually smaller in such areas compared to new farms or *garimpos*. (b) (Upper right) typical *garimpo* in Northern Mato Grosso, with an excavated area along a small creek originating a large pit from where sediments containing gold particles are extracted. Machines and ducts extract water and sediments from the bottom of the pit; these sediments will further receive a chemical treatment, using mercury, to separate gold from other substances. (c) (Bottom left) typical *garimpo* housing in Northern Mato Grosso. The improvised building (usually canvas), the large number of *garimpeiros* living in a housing unit and the very proximity to vector's habitat favor intra-housing malaria contamination. (d) (Bottom right) View of the commercial area of Peixoto de Azevedo, the largest town in the study area in Northern Mato Grosso.

growing soy significantly increased over the decade (though from a small base in 1991, and still significantly smaller compared to food/annual crops) from only 10 ha in 1991 to 4,700 ha in 2002. Perhaps more importantly, the number of cattle increased substantially from 272, 570 in 1991 to 880,267 in 2002 (323% increase).

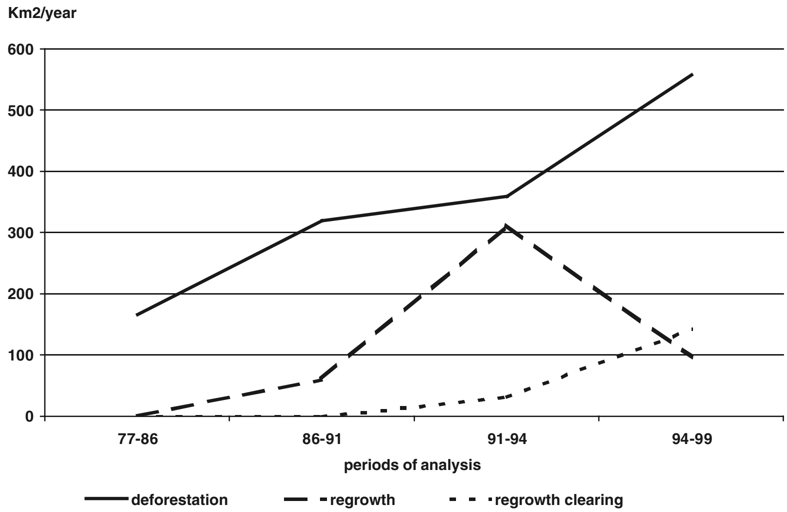

Fig. 3. Annual mean values of landscape changes in Northern Mato Grosso, 1977–1999.

Decreasing agricultural productivity, due to poor soil fertility, inadequate farming skills and lack of adequate infrastructure, caused many colonists to leave their lands—a pattern typical in other parts of the Brazilian Amazon (Bunker, 1984; Hecht and Cockburn, 1989; Fearnside, 1999). Partly because of this garimpos became the most important economic activity in Northern Mato Grosso in the 1980s and early 1990s, attracting many colonists in the region who lived on their farms or in urban houses and worked in the garimpo several days per week.

Figures 2b and 2c show a typical *garimpo* in Northern Mato Grosso. Areas along a river or creek are deforested to accommodate garimpo facilities, and roads are opened to facilitate the movement of workers and supplies. Creeks and rivers are diverted in search of alluvial deposit. Mercury was intensively used to amalgamate gold in the extraction process (Fig. 2b). The garimpeiros usually live in tents covered by canvas or plastic with no walls, each accommodating about ten to twelve hanging hammocks where they rest and sleep (Fig. 2c). Garimpos also attracted large numbers of new immigrants to Northern Mato Grosso and stimulated urban economic activities, especially in Peixoto de Azevedo—the sede municipal with the largest population in the region (Fig. 2d).

By the end of the 1980s, factors such as decreasing gold prices, increasing oil prices, depletion of superficial gold deposits, and establishment of new and more profitable garimpos in other parts of the Brazilian Amazon, engendered a rapid decline of garimpos in Northern Mato Grosso. As a result, agricultural and cattle ranching activities regained their relative economic importance in the 1990s. Colonists who already had a plot of land in the region and had engaged part-time or full-time in garimpos resumed their farming activities, and many former garimpeiros who decided to live permanently in the region acquired, or invaded, land to farm and/or cattle ranch (Barbieri, 2000).

Population dynamics in Northern Mato Grosso are closely linked to the dynamics of land use, especially regarding the decline of garimpo activity and revival of agriculture and cattle ranching. Table I shows the population of four municípios and the percent of population living in urban areas and Table II shows the number of *localidades* by type of land use. A *localidade* is defined by the Brazilian Health Agency (FUNASA) as any grouping of structures that may shelter mosquitoes, and represents an operational unit for the Program of Malaria Control implemented in Northern Mato Grosso between 1992 and 1995. FUNASA classified each localidade as *sítio*, garimpo, and *povoado. Sítio* refers to a cluster of houses in a rural area (on ranches or smallholder farms), while *povoado* (hamlet) refers to a small village or town.

The total population of the study area was 93,974 inhabitants in 1991, declining to 89,711 in 1996 and 84,990 in 2000 (Table I). The population in the município of Peixoto de Azevedo declined from 37,240 in 1991 to 29,085 in 1996 (−4.94%) and 26,156 in 2000 (−2.12%); the percent of the population living in urban areas also declined. Most (73%, Table II) of the localidades in this município between 1992 and 1995 were garimpos. Matupá, with a more balanced proportion of rural and garimpo localidades (and the second highest concentration of garimpos in Northern Mato Grosso), had positive population growth from 1991 to 1996—mostly due to a growing rural population. Terra Nova do Norte and Guarantã do Norte, municípios which corresponded to areas of the original planned settlements in the region (in the late 1970s), had the highest concentration of rural localidades (81% and 75%, respectively). But Terra Nova do Norte had a substantial population decline from 1991, while Guarantã do Norte do Norte had positive population growth in the entire period because the prospect of paving the BR-163 highway towards the southern part of the State of Pará (Soares *et al.*, 2004) attracted farmers, ranchers and speculators, who had expectations of taking advantage of the land that might be available for occupation along the road.

OBJECTIVE, RATIONALE, AND HYPOTHESES

The main objective of this paper is to assess the relationship among land uses, population characteristics that constitute risk profiles, and levels

Table I. Population Size and Growth by *municípios* in the Northern Mato Grosso, Between 1991 and 2000

	1991		1996		2000		Population growth (%)[b]	
Municípios	Total	Urban (%)	Total	Urban (%)	Total	Urban (%)	1991–1996	1996–2000
Terra Nova do Norte[a]	22,448	35.36	21,678	38.90	19,345	40.23	–0.7	–2.28
Peixoto de Azevedo	37,240	87.34	29,085	85.91	26,156	77.15	–4.94	–2.12
Matupá	10,221	69.58	11,339	65.65	11,289	77.83	2.08	–0.09
Guarantã do Norte[a]	23,825	50.50	27,609	50.53	28,200	68.67	2.95	0.42
Total	93,974	63.61	89,711	66.47	84,990	66.02	–0.88	–1.08

Source: IBGE, Censo Demográfico de 1991 and 2000, and IBGE, Contagem Population de 1996. (www.ibge.gov.br).
[a]Terra Nova do Norte includes the population of Nova Guarita, which became a separated *município* in 1993 (after collection of census data in 1991). Guarantã do Norte includes the population of Novo Mundo, which became a separated *município* in 1996. Table I, as well as the remaining of this paper, considers Nova Guarita as part of the *município* of Terra Nova, and Novo Mundo as part of Guarantã do Norte, for analytical purposes.
[b]Exponential annual growth rate: r (%) = [(ln(population, t2/population, t1)/t]*100, in which t = number of years between t2 and t1.

Table II. Distribution of Number (N) and Percentage (%) of *localidades* by Land Use and by Município—Northern Mato Grosso, 1991–1996

Municípios	Urban		Rural		Garimpo		Total
	N	%	N	%	N	%	N
Terra Nova do Norte[a]	6	4.3	113	81.3	20	14.4	139
Peixoto de Azevedo	2	3.3	14	23.3	44	73.3	60
Matupá	3	5.2	25	43.1	30	51.7	58
Guarantã do Norte[a]	2	2.2	68	74.7	21	23.1	91
Total	13	3.7	220	63.2	115	33.0	348

Source: Barbieri, 2000.

[a]Terra Nova do Norte includes the population of Nova Guarita, which became a separated município in 1993 (after collection of census data in 1991). Guarantã do Norte includes the population of Novo Mundo, which became a separated *município* in 1996. Table II, as well as the remaining of this paper, considers Nova Guarita as part of the *município* of Terra Nova do Norte, and Novo Mundo as part of Guarantã do Norte, for analytical purposes.

and trends of malaria occurrence. In order to understand this relationship, a broader area encompassing distinct land uses with a high spectrum of malaria rates, such as Northern Mato Grosso, was selected as an ideal setting. The rationale for this paper comes from previous studies in the literature and evidence from field research in Northern Mato Grosso, which shows that some key individual and household characteristics, in addition to human mobility and spatial proximity between areas with distinct land uses, are associated with a high prevalence of malaria. Even in the absence of household surveys for the study area, it is possible to test the association of several aggregate variables with malaria prevalence. Three hypotheses are raised:

1. Some key population characteristics are associated with malaria prevalence. More specifically, higher sex ratios, higher proportions of poor housing, higher proportions of young adults (at labor ages) and higher population of *P. falciparum* than *P. vivax* are associated with higher malaria rates.
2. The malaria rates in garimpos are higher than in long-settled agricultural and cattle ranching areas and urban areas due to occupational exposure. Malaria prevalence is also higher in agricultural and cattle ranching areas at initial stages of settlement.
3. The third hypothesis is based on the mobility of populations at higher malaria risk: the spatial proximity between areas of high malaria prevalence (garimpos and farms and ranches at initial stages of settlement) and low prevalence areas (long-settled rural and urban areas) favors the diffusion of malaria, due to the high circulation of people (and vectors) among areas of high and low malaria prevalence.

DATA AND METHODS

The analysis of the three hypotheses involves the integration of data sources on population characteristics, land uses, and malaria prevalence in Northern Mato Grosso between 1992 and 1995. Data for census tracts were provided by the Brazilian Census Bureau (IBGE). Road and hydrographic networks and urban areas were visually interpreted from Landsat image composites. The Center of Regional Development and Planning (Cedeplar, Brazil), in collaboration with FUNASA, elaborated a comprehensive epidemiological and land use data set comprising information on the number of malaria cases, type of malaria, and land use by localidade between 1992 and 1995. A field survey collected Global Positioning System (GPS) points for all 348 localidades classified by FUNASA, from which 178 presented at least one case of malaria between 1992 and 1995. Land use for each localidade was determined by Landsat image classification, and three categories were defined: (a) urban (referring to small towns or povoados), (b) garimpo (gold mining), and (c) rural (sítios in areas of agriculture and cattle ranching). Land use data on the 178 localidades were cross-classified with the epidemiological information on the number and type of malaria cases between 1992 and 1995.

Since rural houses were concentrated along or nearby roads, rural localidades assumed a linear form of buffers of 500 meters expanded from these roads. Therefore, buffers representing rural localidades had a rectangular form, following the roads. On the other hand, garimpos were located in areas adjacent to rivers or creeks and had buffers of 500 meters, representing an irregular area that followed the river network. These buffers helped us to visualize land use and epidemiological data for these types of localities; they are *empirical areas* for the purpose of visualization of land uses (garimpo and rural) and epidemiological data and do not represent the *actual area* occupied by a localidade. On the other hand, *urban* localidades are represented by their actual area as depicted in the satellite image.

The FUNASA/Cedeplar dataset does not provide information on population size and characteristics for localidades, and thus does not allow the estimation of malaria rates and the assessment of their associations with population characteristics. In order to overcome this limitation, data on land use and malaria prevalence by localidade were combined with census tract information on population size and characteristics for 1991 and 1996. There are 31 census tracts containing positive cases of malaria (eight census tracts with small populations or mostly unoccupied do not have epidemiological information). A typology of census tracts was established by integrating the types of land uses for localidade at the census tract level. There are three types of census tract: (a) urban (defined by IBGE), (b) rural, if all, or almost all, localidades within the census tract are rural (farms and ranches), and (c) mixed, if there is a mix of rural and garimpo localidades within the census tracts.

An ecological log-linear Poisson model was used to assess the association between population characteristics and malaria prevalence in 1992 and 1995. This model is appropriated to test relationships between aggregated data on population characteristics and malaria prevalence rates. The model fitting was adjusted for overdispersion, a situation that occurs when model fitness is poor because of heterogeneity (unobserved variables and/or associations or other sources of variability). It is very common to observe overdispersion in the analysis of proportions or rates, mostly because the observed variances of the rates are higher than those assumed by the model. If not adjusted, the model will overestimate the degree of associations. In order to implement the model, it was assumed that (a) each reported malaria case corresponded to a person in the population and (b) the prevalence would not be greater than one when the total number of malaria cases was higher than the population (for this case, all—minus one person—in the population had the disease; this assumption assures no zero cases of non-malaria, in order to estimate odds ratios). Those assumptions will lower the prevalence rates in some census tracts but will not affect the degree of their associations with population characteristics, since those with higher malaria prevalence will still rank higher. The model fits malaria rate (the dependent variable) for each census tract and the following population characteristics as independent variables: (a) the sex ratio, or the proportion of male to female population (less than 1.20 and 1.20 or more), (b) the proportion of young adults between 20 and 34 years of age (less than 26% and 26% or more), (c) the type of census tract (urban, rural, and mixed), and (d) the proportion of permanent housing (less than 20% and 20% or more). The formal logistic approach to the model is:

$$\log(n_i) = \log(N_i) + \widetilde{x}_i\widetilde{\beta} \tag{1}$$

where n_i is the number of malaria cases in the census tract $\boldsymbol{i}$; N_i is the population at risk, or alternatively the population in the mid-year; $\widetilde{x}_I$ is the vector of explanatory variables and $\widetilde{\beta}$ is the vector of the model parameters. The model was adjusted separately for 1992 and 1995.

The analysis of the fitted model complements the descriptive analysis of population characteristics and spatial analysis of malaria prevalence trends between 1992 and 1995. The spatial analysis includes thematic maps showing prevalence by localidade and census tracts (both classified by land use), and controls by their spatial proximity, which will be used as a proxy of population mobility among types of land use.

RESULTS

Population Characteristics and Malaria Prevalence

Table III presents population and malaria prevalence characteristics in Northern Mato Grosso in 1992 and 1995 by type of census tract. As shown in Table I, there is a significant population decline in Northern Mato Grosso, especially in mixed census tracts (with garimpo localidades) and urban areas, which are common places of residence for garimpeiros (especially in the sede municipal of Peixoto de Azevedo) (Barbieri, 2000). Urban census tracts, which contained about 66% of the population in 1992 and 1995, reported 26% of the malaria cases in 1992 and 24% in 1995, declining from 346 cases per 1,000 inhabitants in 1992 to 88 per 1,000 in 1995.[7] Mixed census tracts, with about 73% of malaria cases in 1992 and 1995, accounted for 3,098 malaria cases per 1,000 persons in 1992 and 924 cases per 1,000 in 1995. Rural census tracts, with less than 3% of malaria cases in 1992 and 1995, had malaria rates decreasing from 98 to 42 cases per 1,000 between 1992 and 1995. Overall, there was a 74% reduction in the total number of malaria cases between 1992 and 1995, with malaria rates decreasing from 868 cases per 1,000 inhabitants in 1992 to 237 case per 1,000 inhabitants, in 1995.[8]

Changes in population characteristics, which constitute risk factors, help to explain the decline in malaria prevalence. The sex ratio remains the same for all census tracts combined in 1992 and 1995, but decreased for mixed census tracts (from 1.50 in 1992 to 1.38 in 1995) and increased for urban census tracts (from 1.07 to 1.10) and rural areas (from 1.23 to 1.26). A decreasing sex ratio for mixed census tracts may reflect the exodus of garimpeiros, since garimpo mining was a declining in the period and employed men almost exclusively (Barbieri, 1997).

The decline of garimpo activity and the consequent lowering of the itinerant garimpeiros population (Barbieri, 2000) can also explain the smaller proportion of people living in provisional housing. The proportion of the population living in permanent housing in urban and rural census tracts increased from 91% in 1992 to 98% in 1995, while the proportion for mixed census tracts increased from 67.6% in 1992 to 93.6% in 1999. The decline

[7] The sede municipal of Peixoto de Azevedo concentrated most of the urban cases of malaria in both years (Barbieri, 2000; Ministério da Saúde/FNS/Gerência Técnica de Malária, 2003).

[8] Malaria rates in Northern Mato Grosso between 1992 and 1995 were, on average, substantially higher compared with rates for the entire Amazon in 1990 (34 positive cases per 1,000 population), the state of Rondônia (179 per 1,000) (Sawyer, 1999), and the *município* of Machadinho D'Oeste, Rondônia (252 per 1,000 in 1990) (Castro, 2002). Sawyer (1999) found, for some areas in Rondônia, malaria rates of 3,000 per 1,000 (similar to the rate for mixed census tracts in Northern Mato Grosso in 1992).

Table III. Descriptive Statistics for Type of Census Tracts: Total Population, Growth Rate, Sex Ratio, Proportion of People Living in Permanent Housing, Percentage of Population in the Age Group 20–34, Number of Cases and Type of Malaria, and Malaria Rates—Northern Mato Grasso, 1992 and 1995

Variable	1992				1995			
	Total	Urban	Rural	Mixed	Total	Urban	Rural	Mixed
Population[a]	88,361	58,085	12,415	17,861	83,746	54,010	14,030	15,706
Population in the year (%)	100.00	65.74	14.05	20.21	100.00	64.49	16.75	18.75
Population growth rate, 1992–1995 (%)[b]	—	—	—	—	−1.79	−2.42	4.08	−4.29
Sex ratio	1.17	1.07	1.23	1.50	1.17	1.10	1.26	1.38
Proportion of people living in permanent housing (%)[c]	91.16	96.96	99.37	67.56	98.02	99.03	99.66	93.56
Population in the age group 20–34 years (%)	29.70	30.39	24.27	31.23	27.49	28.57	25.05	25.99
Number of cases of malaria	76,658	20,108	1,217	55,334	19,863	4,754	590	14,519
Cases in the year (%)	100.00	26.23	1.59	72.18	100.00	23.93	.97	73.09
Variation in the number of cases of malaria, 1992–1995 (%)	—	—	—	—	−74.09	−76.36	−51.52	−73.76
Proportion of *P. vivax*[d]	0.58	0.56	0.63	0.52	0.71	0.69	0.77	0.64
Malaria rate (per 1,000)[e]	867.56	346.19	97.99	3,098.07	237.18	88.03	42.06	924.42

Source: IBGE, Censo Demográfico de 1991 Contagem population de 1996 (HYPERLINK http://www.ibge.gov,br); Barbieri, 2000.

[a]Population by census tracts was interpolated to 1992 and 1995, to match the years of available information on malaria prevalence by *localidades*. These numbers differ minimally from those presented in Table I because they include only census tracts with localities that presented cases of malaria in 1992 or 1995. The census tracts for which there were no cases of malaria represent a small share of the population of Northern Mato Grasso (5.4% in 1991 and 6.6% in 1995).

[b]Exponential Annual growth Rate of Population in the period 1992–1995: $r = [\ln(pop95/pop92)/t]*100$, $t = 3$ years.

[c]Refers to the quality of housing, usually built with wood. Provisory housing is built with materials of poor quality and inadequate materials (e.g., canvas), and are usually shelters for *garimpo* population.

[d]Defined by the relation between number of cases of *P. vivax* and the sum of cases *P. vivax* and *P. falciparum*.

[e]Defined by the relation between number of cases of malaria and the population in the year, with the result multiplied by 1,000.

of garimpos may also explain the reduction in the 20–34 age group in the mixed census tracts from 31.2% in 1992 to 26.0% in 1995, and in urban areas from 30.4% to 28.6%. On the other hand, rural areas showed a small increase from 24.3% to 25.1%.

The demise of garimpo mining, lower population mobility, and the resumption of agricultural activities seem related to a pattern where *P. vivax* is more prevalent. The proportion of cases of *P. vivax* to the total cases of malaria increased from 0.58 in 1992 to 0.71 in 1995 with increases occurring for all census tracts (urban, rural, and mixed). Still, garimpeiros and colonists living in mixed census tracts had a relatively higher risk of contracting *P. falciparum*, the more dangerous form of malaria. The proportion of *P. vivax* in mixed census tracts was 0.64, compared to 0.69 and 0.77 in urban and rural census tracts, respectively, in 1995.

In summary, Table III shows that populations living in mixed census tracts had some distinguishing characteristics compared with populations in urban and rural census tracts: (a) poorer housing conditions, (b) a higher proportion of young adults, (c) a higher sex ratio, and (d) a relatively higher proportion of population having *P. falciparum*. These characteristics are also typical of garimpeiros, the population with a higher risk of malaria (Sawyer, 1995; Barbieri, 1997, 2000).

Table IV shows the parameters fitted by the log-linear Poisson model (Equation 1). It shows a large differential in malaria rates among population characteristics. The last column presents relative malaria prevalence, which indicates how much larger or smaller the malaria prevalence of one category is in relation to the last category of the variable. In 1992, the relative malaria prevalence in rural census tracts was about 80% (100*[1–0.215]) smaller than in mixed census tracts. Census tracts with a lower sex ratio had less than half the prevalence of those with a higher sex ratio; the malaria prevalence was 26.5% higher in census tracts where housing were not adequate and 34.8% higher where the proportion of young adults was higher. Although those differentials were statistically significant in the first fit of the model, the only difference that remained unchanged after overdispersion adjustment was between malaria rates of rural and mixed census tracts. This indicates that the variability of malaria rates across the population characteristics were higher than those assumed by the model.

In 1995, the statistical significance held after the overdispersion adjustment. The difference in malaria rates by types of census tract heightened: urban and rural census tracts had, respectively, 70% and 90% less relative malaria prevalence than mixed tracts, and those with a lower sex ratio had 63% less malaria prevalence than census tracts with higher sex ratios. The proportion of permanent housing was omitted because most (98%) were

Table IV. Estimates of Parameters of the Log-Linear Poisson Model Fitting Malaria Rates with Census TractVariables, Adjusted by Overdispersion-Northern Mato Grasso, 1992 and 1995.

Parameter	Categories	Estimate	Standard error	Chi-square	Pr>chisq	Relative prevalence
			Year=1992			
Intercept	—	−0.486	0.323	2.270	0.132	0.615
Type of census tract	Urban	−0.175	0.833	0.040	0.834	0.839
	Rural	−1.537	0.697	4.860	0.028	0.215
	Mixed	0.000	0.000	—	—	1.000
Sex ratio	Less than 1.2	−0.877	0.797	1.210	0.271	0.416
	1.2 or more	0.000	0.000	—	—	1.000
Proportion of permanent houses	Less than 20%	0.235	0.414	0.320	0.571	1.265
	20% or more	0.000	0.000	—	—	1.000
Proportion age 20–34	26% or more	0.298	0.453	0.430	0.510	1.348
	Less than 26%	0.000	0.000	—	—	1.000
Scale		20.607	0.000	—	—	—
Scaled Pearson X2	5	—	—	—	—	—
			Year = 1995			
Intercept	—	−0.469	0.271	2.980	0.084	0.626
Type of census tract	Urban	−1.166	0.487	5.730	0.017	0.312
	Rural	−2.298	0.698	10.860	0.001	0.100
	Mixed	0.000	0.000	—	—	1.000
Sex ratio	Less than 1.2	−1.001	0.479	4.360	0.037	0.368
	1.2 or more	0.000	0.000	—	—	1.000
Proportion age 20–34	26% or more	−0.246	0.344	−0.510	0.474	0.782
	Less than 26%	0.000	0.000	—	—	1.000
Scale	—	0.000	0.000	—	—	—
Scaled Pearson X2	12	—	—	—	—	—

permanent, with only a small variance across census tracts. In addition to the linkages between population characteristics and malaria prevalence, Table IV shows evidence of association between malaria rates and type of land use, indicating that census tracts with garimpos (mixed census tracts) had an excessively higher malaria rate compared with other census tracts. In a situation similar to the Northern Mato Grosso, where a combination of diverse land uses with garimpo prevails, the sex ratio is a reliable symptomatic variable of malaria prevalence. Moreover, as will be shown below, the spatial proximity of garimpos and other rural activities accentuates the differentials.

Land Uses and Malaria Prevalence

While Tables III and IV suggest a relationship between land uses and malaria prevalence at the census tract level between 1992 and 1995, the validity of such a relationship—hypothesis two—is more adequately addressed by spatial analysis conducted at both localidade and census tract levels. Figure 4a depicts buffers representing 178 localidades with malaria cases recorded between 1992 and 1995 and their corresponding land uses. From the 178 localidades, 12 (7% of the total) are urban, 71 (40%) are *garimpos*, and 95 (53%) are rural. Figure 4b depicts the trend of malaria prevalence in localidades between 1992 and 1995 and, together with Fig. 4a, allows an analysis of malaria prevalence among types of land use. In some cases, when distinct localidades are separated by short distances along roads or rivers, it is not possible to clarify boundaries distinguishing buffers; in these cases, buffers in Figs. 4a and 4b may indicate a cluster of two or more localidades.

Thirty-nine localidades in Fig. 4b had a growth trend in malaria prevalence between 1992 and 1995 (i.e., the number of cases of malaria in a year was always higher compared with the previous year). Of these localidades, 42% were garimpos, 58% were rural, and none were urban. Rural localidades were mostly new colonization areas in the east and north of the study area and older colonization areas in the south. Farmers in these areas had to clear secondary forests thereby creating new habitats for the vectors transmitting malaria. For example, Fig. 3 shows an increase forest regrowth clearing between 1991 and 1994. Eighteen localidades had a declining number of malaria cases in the first years of the period, but a growing number of cases in the last year or years (48% garimpos, 14% urban, and 38% rural). Most garimpos showing this trend from decline to growth were in the central part of Northern Mato Grosso.

Most *garimpos* in the center of Northern Mato Grosso, along the River Peixoto de Azevedo and in the northwest, showed a remarkable declining

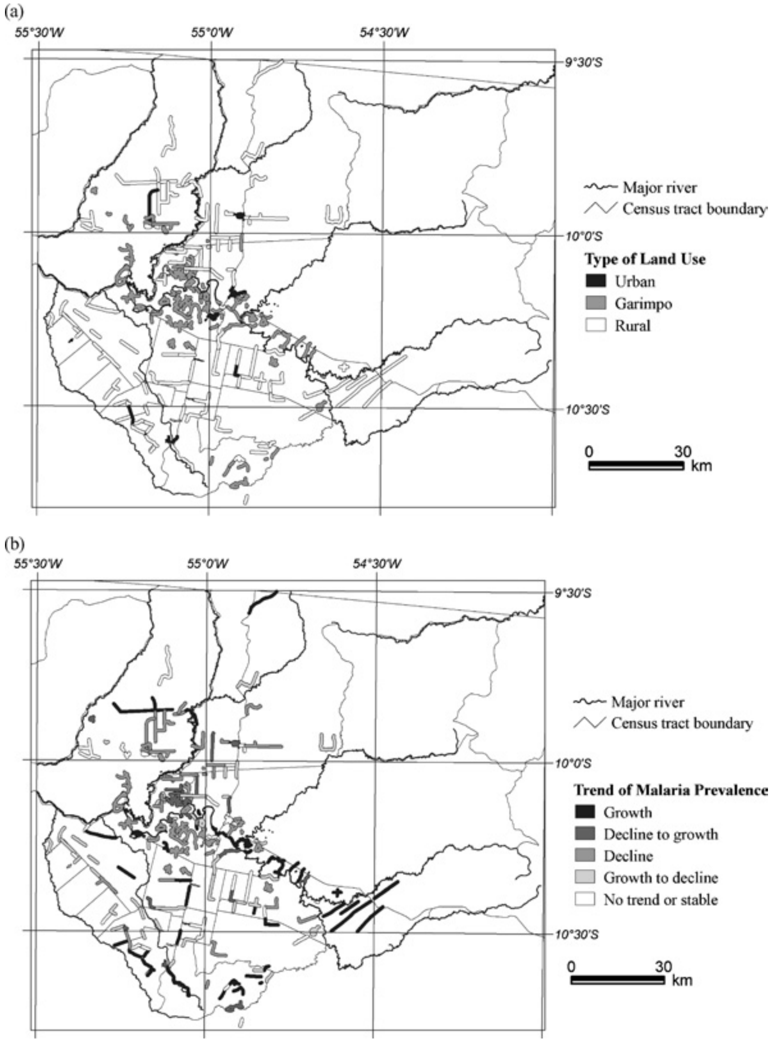

Fig. 4. Analysis of land use and malaria prevalence by *localidades*: (a) type of land use by *localidades* in Northern Mato Grosso, 1992–1995; (b) trend of malaria prevalence by *localidade* in Northern Mato Grosso, 1992–1995.

trend in the number of malaria cases which is associated with the decline of mining and the departure of garimpeiros (Barbieri, 2000). Of the 52 *localidades* with this declining trend (56%) were garimpos, and 37% were rural concentrated in the north and south. The most important urban area in Northern Mato Grosso, Peixoto de Azevedo, showed a decline following the decline in nearby *garimpos*. Of the 43 localidades with a reversion from growth to decline (a growing number of cases in the first years of the period, but a decline in the last year or years), 28% were *garimpos*, 65% were rural, and 6% were urban.

Of the 26 localidades including the sede municipal of Matupá, with no systematic growth or decrease in number of cases, 66% were rural—most located far from garimpos—and 28% were garimpos. Overall, 68% of the localidades in Northern Mato Grosso experienced a declining trend, reversion from growth to decline, or no trend, between 1992 and 1995. This shows the sharp reduction in malaria prevalence in Northern Mato Grosso despite the impact of some still active garimpos, new colonization areas, or rural areas where activities were being resumed.

While Fig. 4 displays the spatial distribution of malaria prevalence by land uses, it does not associate malaria prevalence to population size (malaria rates). However, it is possible to identify how changes in malaria rates are associated with a predominant land use in a census tract. Figure 5a shows the classification of census tracts by type of land use (urban, rural, or mixed), and Fig. 5b shows the trend of malaria rates between 1992 and 1995 for census tracts with at least one malaria case in the period ("high" indicates malaria rates greater than seven cases per inhabitant per year; "medium" indicates rates between 1.5 and 7, and "low" indicates rates indicating rates below 1.5).

There is a clear pattern in which mixed census tracts present much higher malaria rates compared with urban and rural tracts. Only two mixed census tracts in Peixoto de Azevedo retained high or medium malaria rates in both years; only one mixed census tract presented low malaria rates in 1992 and 1995. All the other mixed census tracts showed a reduction in malaria rates from high to medium or low, and from medium to low. Except for a small urban area surrounded by garimpos which had a reduction in malaria rates from medium to low (northwest of the study area, in the município of Guarantã do Norte), all urban areas presented low malaria prevalence in 1992 and 1995, including the sede municipal of Peixoto de Azevedo, which despite the high *absolute* number of cases, presented low level malaria rates (low for Northern Mato Grosso patterns), because of its relatively high population (Barbieri, 2000). Rural census tracts also presented low malaria rates over the period.

Population Mobility and Malaria Prevalence

The analysis of malaria prevalence by land uses supports the second hypothesis of higher malaria prevalence in garimpos or in new rural settlements, and a lower prevalence in long-settled rural areas and in urban

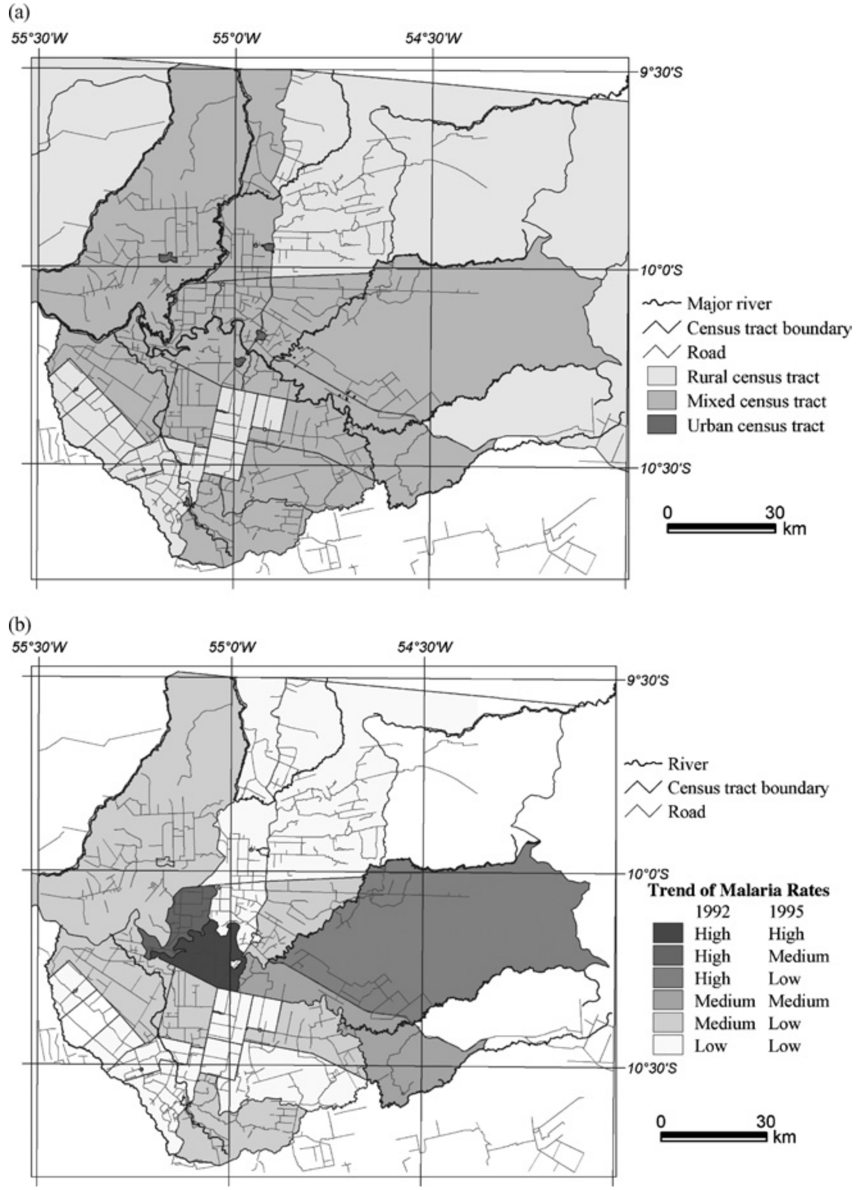

Fig. 5. Analysis of land use and malaria prevalence by census tracts: (a) type of land use by census tracts in Northern Mato Grosso, 1992–1995; (b) trend of malaria rates by census tracts in Northern Mato Grosso, 1992–1995. (High malaria rates: above 7 cases per person; medium: between 1.5 and 7 cases; low: below 1.5 cases. Census tracts shown in white had no registered malaria cases between 1992 and 1995; these are mostly unoccupied census tracts).

areas. However, the third hypothesis suggests that these results should be conditioned by the degree of interaction (spatial proximity and human population mobility) between areas of higher and lower malaria prevalence that explains the relatively high prevalence in some urban and rural areas. The spatial proximity between localidades acts as a facilitator of human population mobility between them. In fact, human population mobility between areas of high and low malaria prevalence has been a typical feature of Northern Mato Grosso since early stages of human occupation in the 1970s (Barbieri, 2000; Cedeplar/UFMG, 1997; Schwantes, 1989).

The sede municipal of Peixoto de Azevedo is a typical center of circulation and residence of garimpeiros, and had most of the urban malaria cases depicted in Table III. Two urban localidades experienced reversion from decline to growth in Fig. 4, the *sede municipal* of Guarantã do Norte and Terra Nova, apparently associated with the circulation of infected people from nearby rural localidades. A large number of rural localidades showing reversion from growth to decline were concentrated in the south (the *município* of Terra Nova) which had a large population partially or fully engaged in garimpos near their farms or in other areas in the region (Cedeplar/UFMG, 1997; Barbieri, 2000). Once garimpo activity started to decline at the beginning of the 1990s, population mobility from garimpos to farms decreased, and colonists started to resume their farming activities. The high malaria rates in the first years probably reflect the fact that many individuals returning to their farms were still infected and that some, especially those who partially or totally abandoned their farming activities, had to clear secondary forests on their plots. Furthermore, new colonization areas in the east and north of the study area, which showed growth of malaria prevalence between 1992 and 1995, were mostly settled by former garimpeiros—a great number of them being asymptomatic but still infected with malaria (Sawyer, 1995; Barbieri, 2000).

Figure 5 shows a pattern of higher malaria rates in mixed census tracts, where there is a higher spatial proximity and population mobility between garimpos and rural areas. Furthermore, Table III suggests that as population characteristics in mixed census tracts changed over time and became more similar to urban and rural census tracts, malaria prevalence decreased. For example, sex ratio increases for urban and rural census tracts between 1992 and 1995 is likely to reflect the redistribution of men and women in the region, in which former garimpeiros settle permanently in urban or rural areas. On the other hand, the increasing proportion of permanent housing for mixed census tracts—from 67.56% in 1992 to 93.56% in 1999—may also indicate that former garimpeiros remaining in mixed census tracts started to engage in rural activities (and were more likely to build and live in permanent housing).

DISCUSSION AND CONCLUSIONS

This paper is intended to provide three main contributions to the literature on human population and the environment in frontier areas, specifically the Northern Mato Grosso area of Brazil. These contributions derive from the analysis of the three hypotheses discussed earlier. First, there is an association between high malaria prevalence and population characteristics related to occupational risk profiles—garimpeiros, colonists (rural), and urban workers/residents—especially regarding a high sex ratio, younger adult population, poor housing quality, and higher prevalence of *P. falciparum*. These results suggest the importance of local-level policies involving localidades, communities, or their aggregation at the census tract level, to influence individual or household behavior. Policies regarding malaria control or vaccine tests should focus on the populations at higher risk—especially garimpeiros, the more mobile populations (e.g., those moving between garimpos and rural areas), and colonists in the initial years of farming activities. This recommendation of policy focus on higher risk populations also reinforces the arguments of Castilla and Sawyer (1986) and Singer and Sawyer (1992) regarding garimpeiros and rural workers involved in land clearing (a) for privileging them as targets in the public programs of antimalarial drugs distribution, and (b) for improving their access to pharmacies, physicians, and health clinics. Initiatives, such as improved housing quality, in areas facing new colonization and areas near garimpos, and focusing vector control programs on locations with a higher prevalence of *P. falciparum* would also help to control malaria in the Amazon. Furthermore, community-based educational campaigns addressing the ecology of the disease, its prevention, and treatment, are fundamental in the study area as well as in other parts of the Brazilian Amazon.

The second contribution is the validation of previous empirical research in the Brazilian Amazon which associates higher malaria prevalence with garimpos and new rural settlements. And the third contribution is to the understanding of the linkages among garimpos, rural and urban land uses, and malaria prevalence over time. The analysis of the evolution of malaria prevalence at the localidade and census tract levels reveals evidence of how interactions (spatial proximity and population mobility) between garimpos and rural and urban localidades foster the diffusion of malaria, particularly due to the "contagion effect" of garimpos and new rural settlements. In this sense, the spatial analysis highlights the importance of understanding land use changes and occupational mobility in the region as a means to monitor and control the diffusion of disease; people moving from areas of higher prevalence to areas of lower prevalence induce changes in the environment and on the ecological equilibrium between humans and vectors.

Furthermore, while malaria prevalence in new settlements and areas where farming activities are being resumed tends to lower after some years garimpos tend to show higher malaria prevalence while they are most productive. Thus, further declines in malaria prevalence and its stabilization at lower levels will depend basically on the balance between the production dynamics of garimpos, as well as the growth of new settlements in the vast expanses of still untouched forests in this part of the Amazon.

The analysis of our second and third hypotheses also involves an important methodological matter: that an adequate understanding of associations between land use and malaria prevalence in the Brazilian Amazon as a whole, and Northern Mato Grosso in particular, is better addressed by multiscalar approaches which integrate information at distinct units of analysis. In this paper, the analysis by localidades, which shows higher malaria prevalence in garimpos and new rural settlements, as well as rural and urban localidades interacting with them, is supported by analysis at census tracts levels, which provides an association between malaria prevalence and populations at risk.

Policy Issues and Considerations

The association of malaria prevalence with land uses and their interaction suggests that local-level policies are necessary, but not sufficient, to anticipate and remediate impacts on human health. Combining local and regional policies should be regarded as a fundamental ingredient in regional development and health policies in the Amazon. In fact, Axinn and Barber (2003) suggest that local-level policies affecting the behavior of individuals and households is a primary step to regulate natural resource utilization at the regional level, and Marcoux (1993) suggests that regional agriculture policies should be grounded on occupational patterns at the microlevel (households or communities). The aim of such combined local and regional policies would be to shape the behavior and attitudes towards malaria in households or localidades and to coordinate land uses in the region. It would maximize the socioeconomic benefits of economic activities and minimize impacts on human health and on the environment (e.g., providing more institutional presence in terms of health assistance and more stringent programs of malaria control in areas of higher interaction between land uses characterized by high and low prevalence).

Another key policy issue is better articulation between sector policies focusing on transportation infrastructure, economic development and land use, and public health. This is particularly necessary given recent trends and future prospects in Northern Mato Grosso, which show a huge decline of garimpo activities, expansion of agriculture and cattle ranching—especially commodities articulated to international markets such as soy and beef—and rampant deforestation (Barbieri, 2000; Soares *et al.*, 2001). These land use changes in more recent years parallel a drastic decline in malaria rates—from about 100 per 1,000 in 1996, to only 10 per 1,000 in 2000 (Ministério da Saúde/FNS/Gerência Técnica de Malária, 2003). However, the paving and extension of the section of highway BR-163 between Guarantã do Norte and the port of Santarém, in the state of Pará, is expected to provide easier export access for soy and beef production, as well as to provide access to new colonization and garimpo areas along the route of the road (Soares *et al.*, 2004). A potential result will be the reproduction of the high levels of malaria prevalence in the study area in Northern Mato Grosso. Anticipation of these effects and the design of appropriate health and land use policies, such as ecological and economic zoning, rather than only remedial policies should be an essential requirement for this and other development projects in the Amazon. In order to produce more effective results, such policies should involve both local and regional scales. They should also utilize data on population characteristics associated with distinct occupational profiles as a way to target populations at higher risk of malaria prevalence, and spatial information on areas with distinct land uses, as well as the interaction between areas of higher and lower malaria prevalence.

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