Climate, land use and population variability influencing the spatial and temporal distribution of malaria risk in the Amazon

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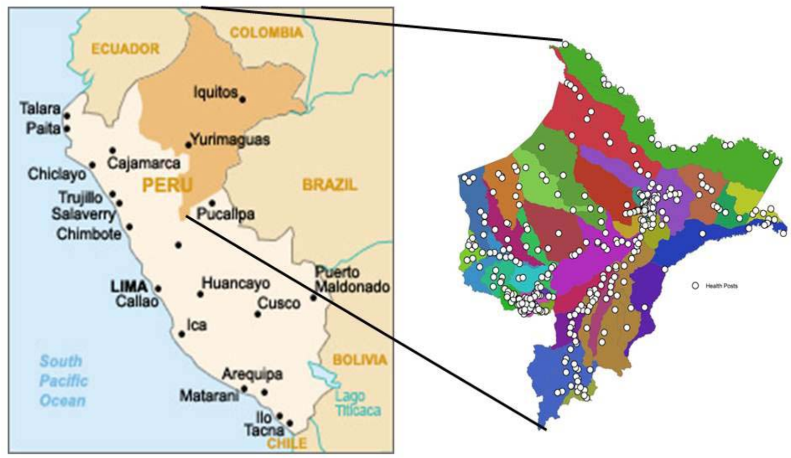
Abstract

Malaria remains one of the world's most devastating public health threats. In Peru, 75% of malaria occurs in the northern Amazon region of Loreto where 80% of cases are concentrated in just 10 districts. Loreto is the least densely populated region of Peru and also the largest. To maintain the declining malaria rates currently seen, better knowledge of where, when and why people are infected is needed. The primary factors affecting malaria endemicity in Loreto are vector habitat expansion from land use change, and social and ecological processes that increase human exposure. To refine and focus prevention strategies, spatially explicit risk estimates are necessary. In this study, we investigate how malaria risk varies across time and space in Loreto by modeling the relationship among climate, land use, and malaria from 2009 to 2012. We incorporate satellite-derived climate and land use variables with data on monthly malaria counts at each government health post in Loreto. Initial models indicate increased malaria risk for lagged rainfall and soil moisture as well as land areas prone to flood. These models will be compared against current forecasting methods to determine if more efficient prevention and control efforts can be implemented.

Introduction

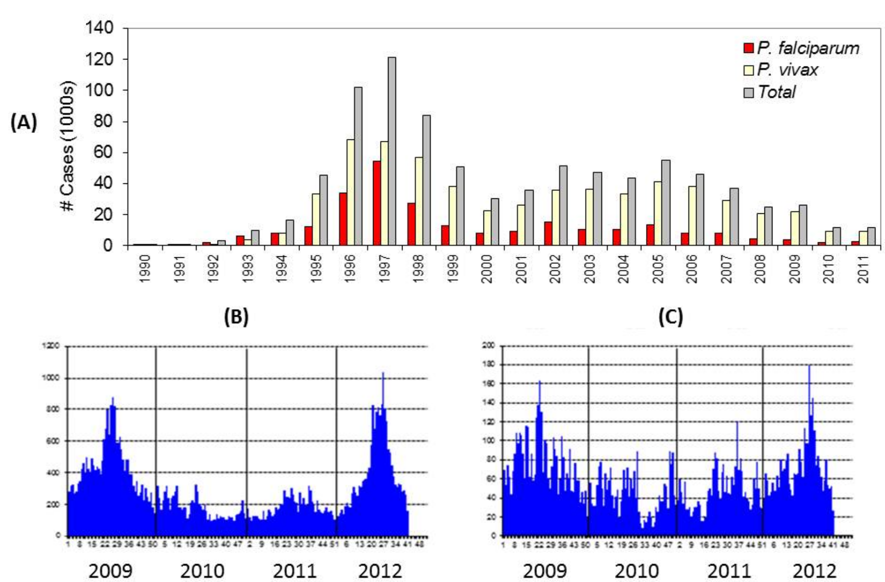
Figure 1: Health posts and *Microreds* in Loreto Province, Peru



Malaria continues to be one of the world's most devastating threats to public health. In Peru, 75% of malaria cases occur in the Department of Loreto, in the Northern Amazonian Region, and most cases (80%) are concentrated in just 10 of the department's 51 districts. Loreto is the least densely populated region of Peru, and also the largest, covering 29% of Peru's land mass (Figure 1). There, fevers suspected to be malaria are the #1 cause of morbidity in adolescents and adults. Malaria cases have declined ~4% per year since 2000; however, to continue reducing the burden of disease in these rural populations, better knowledge of where, when and why people are infected is needed. Key factors related to continued malaria endemicity in this region are the expansion of vector habitats from land use change (deforestation for logging and road development) and social and ecological processes that increase human exposure to the Amazon's most efficient malaria vector, *Anopheles darlingi*. In order to refine and focus prevention strategies across the region, spatially explicit risk estimates are necessary. In this ongoing study, we investigate how malaria risk varies across time and space in this region by modeling the relationship among climate, land use, and malaria risk from 2009 to 2012. We incorporate local climate variables, satellite-derived land use information, elevation and population variability with data on monthly malaria counts at each of the regional government's health posts in the region. To assess malaria risk, we estimate populations associated with delineated geographic catchment areas for each of the health posts within service areas, or Microreds. Our novel approach uses simulated temperature, precipitation, and soil moisture from a Land Data Assimilation System (LDAS) as well as direct information from climate stations. Our spatially and temporally explicit estimations of malaria risk will enable our local partners to implement more efficient prevention and control efforts.

Malaria by Year, Epidemiological week and Parasite in Loreto, Peru

(A) Annually, 1990-2011; (B) *P. vivax*, weekly 2009-2012; (C) *P. falciparum*, weekly 2009-2012

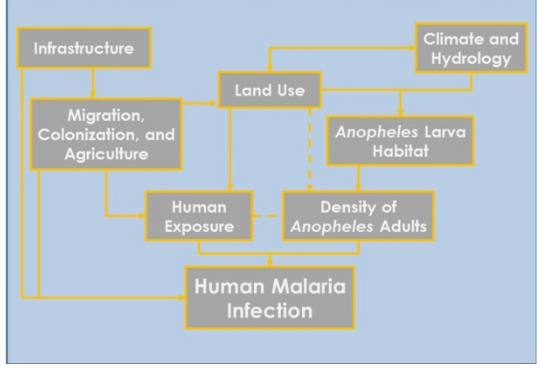


Background

In 2011, there were 356 government-run health posts in Loreto, serving as the main locations for treatment and diagnosis of malaria and other illnesses. Each health post is within a *Microred*, or health service area (Figure 1). Neither health posts nor the underlying population served are homogenous across the region. Figure 2A demonstrates significant progress in controlling malaria incidence in Loreto, with cases declining from around 50k-60k cases annually between 2000 and 2007 to 10k-12k by 2010 and 2011. These declines coincided with various strategies by the Ministry of Health to control vector populations, including indoor residual spraying and bednet distributions. However, recent data from 2012 indicate an upsurge in cases, possibly related to massive flooding in the region due to increased rainfall.

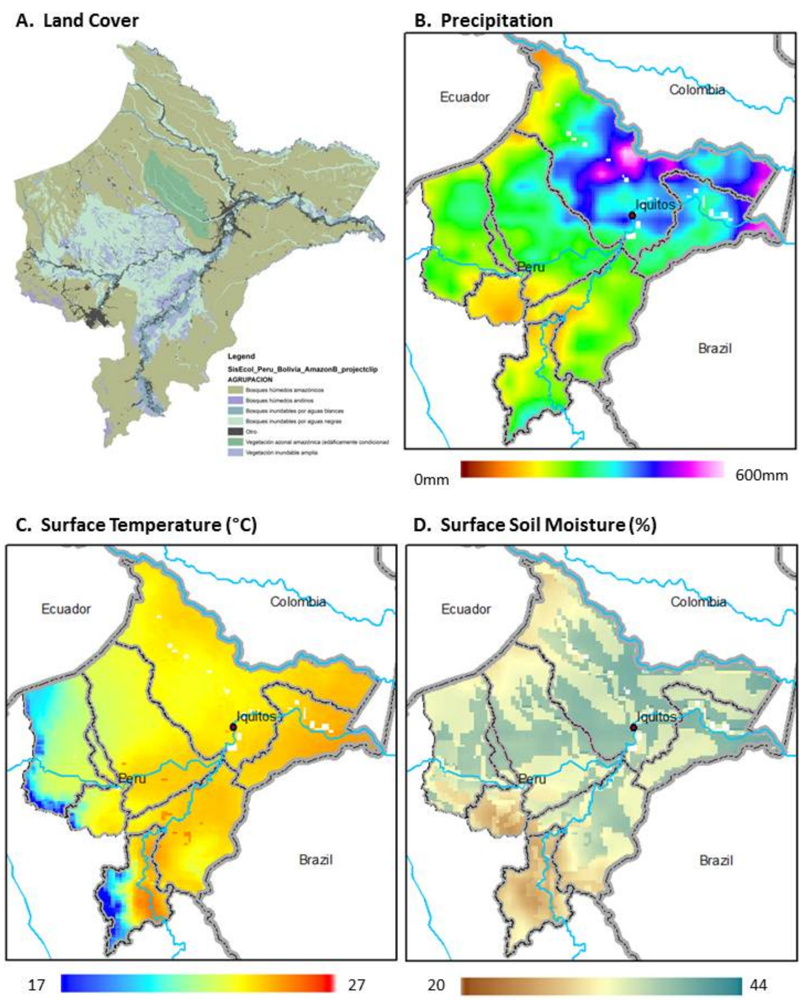
In our analysis, we investigate the relationship between cases, climate, land cover, elevation and population distribution to help predict future cases. Our models are based on specific timing of the malaria lifecycle (i.e., from larval development to adult emergence, blood feeding, parasite development and human transmission) as well as environmental, human and meteorological events that may coincide with increased risk. This model is conceptualized in Figure 3.

Figure 3: Framework: Malaria on the Amazon Frontier



<u>Data and Methods</u>

We obtained all reported cases of malaria from January 2009 through December 2012 in Loreto, by health post. Additional data were available by epidemiological week to 2000, but these data are not deemed reliable. All reported cases by health post were mapped at the *Microred* level to ease visual interpretation for the Ministry of Health (e.g., resources are distributed by *Microred*, thus this is the best level at which to communicate findings, but not necessarily the best for analysis). We determined percent land cover in each *Microred* based on *Ecological Systems of the Amazon Basin of Peru and Bolivia* (Natureserve, 2007) (Panel A below) and extracted climate data corresponding to relevant lag times for a hypothetical case at the geographic coordinate of the health post from our Peruvian Land Data Assimilation System (Panels B-D). We developed a Poisson model of the counts of vivax cases per health post per epidemiological week per year, which will include a random spatial effects for the health post and control for correlations over time (NOTE—results shown in this preliminary



abstract are from an aggregate model of cases per *Microred* per epidemiological week for 2009-2011 as we have not completed specification of the finer-resolution model and do not yet have all the data from 2012). Population at risk was obtained from reported catchment populations for each health post; however, these population estimates will be checked using a spatial population model to predict population counts over space and time, similar to LandScan methodology.

PRELIMINARY RESULTS

The following results are based on a Poisson random effects model at the *Microred* level to control for temporal correlation of observed counts by *Microred*. We are in the process of developing our health-post level analysis for the purposes of this paper.

VARIABLE	ESTIMATE	IRR	STANDARD ERROR	P VALUE
Temperature (13-15 weeks prior)	0.00897	1.009	0.03742	0.8105
Temperature (22-27 weeks prior)	-0.02087	0.979	0.03763	0.5793
Rainfall 22-27 wks prior (HIGH)	0.04803	1.049	0.03415	0.1596
Rainfall 22-27 wks prior (LOW)	0.41660	1.517	0.03344	<.0001
Soil Moisture 35-42 wks prior (HIGH)	0.18020	1.197	0.04370	<.0001
Soil Moisture 35-42 wks prior (LOW)	0.02307	1.023	0.05052	0.6479
Forest inundated by black water (%)	0.15740	1.171	0.03868	<.0001
Amazonian Zone Vegetation	0.04454	1.046	0.03542	0.2086
Inundated vegetation	-0.12810	0.880	0.05866	0.0290
Humid Amazonian Forest (%)	0.08058	1.084	0.03031	0.0079
Humid Andean Forest (%)	-0.05982	0.942	0.1060	0.5726
Forest inundated by clear water (%)	-0.04760	0.954	0.07250	0.5114

As we only have produced preliminary results, interpretation and implications of the findings are not complete. Overall, the analysis by *Microreds* demonstrates the following trends:

- Climate and land cover variables are associated with *P. vivax* malaria rates across Loreto between 2009 and 2011. Lower rainfall four weeks before symptoms and higher soil moisture six weeks before symptoms is associated with higher incidence rate of malaria. An increase in the percent of forest inundated by black water was associated with 17% higher incidence rates of malaria. In future models, we will look at the interaction of this and rainfall, as its effect has been shown in other work to be dependent on rainfall. An increase in the percentage of highly flooded vegetation areas reduces the incidence rate ratio by 12%, perhaps because the areas are too flooded for larval growth and survival.
- Cases peaked between March and May each year. This finding will likely stay consistent regardless of the finer spatial resolution of the data we will obtain.
- Model fit was examined by looking at AIC, and plots of residual vs. predicted observations. The model demonstrated good fit, but overdispersion exists, possibly due to spatial correlation. We will incorporate spatial contiguities and relationships in the next iteration of our models to be presented (if accepted) at IUSSP.
- Land cover data are based on cross-sectional coverages. We are now exploring incorporating satellite derived land use change variables into the model; however, given the size of the study area, it is very difficult to obtain times series of images given the amount of cloud cover for the Amazon.

- Incidence rates are currently produced based on estimated catchment population size of each health post. We will compare these population estimates to those produced by CIESEN's Gridded Population of the World.

Previously thought to be on the decline, malaria cases are thus far surging in 2012. The number of cases reported by September 1, 2012 exceeded the total cases reported in 2010 and 2011 combined, with the total expected to be the highest reported since 2007. This is a serious blow to malaria prevention and control efforts in Peru. We expect our models to shed light on some of the reasons for this resurgence as well as help identify where and when disease risk is expected to be high in years to come.