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A model for the dynamics of malaria in Paria Peninsula, Sucre State, Venezuela

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ABSTRACT

Malaria is a serious public health problem, with close to half of the world population at risk of infection. Mathematical models have been useful to guide malaria control. Most models have assumed that vector population density is constant over time. This assumption can introduce serious errors at time scales where mosquito density is variable. In the present work a model is constructed which takes into account the dynamics of the disease transmission between host and vector, and assumes that vector population density is a dynamic variable. The model assumes that vector population regulation occurs during the larval stage, and the density dependence is modeled with a hyperbolic function. Rainfall in the region changes dramatically and has annual seasonality, but temperature is almost constant during the year; so the only exogenous factor considered in the model is rainfall. The resulting model has four state variables. The original 4-dimensional system was reduced to a one-dimensional equation, with 4 delays, that tracks the dynamics of infected humans, the only state variable for which long time series are available. Parameters of the resulting equation were estimated by fitting the model to time series of human incidence from several localities of Paria Peninsula in Sucre State, Venezuela. About eighty per cent of the incidence records fall within the 95% confidence intervals of model predictions. There is also evidence that different localities have different dynamics. Finally, we compare our model with other modeling approaches in malaria studies, and its usefulness is discussed.

1. Introduction

Malaria is a disease mainly affecting humans in tropical regions worldwide. It is the third most important human disease because of its morbidity and mortality (Noya et al., 2012). Each year up to 500 million cases are reported, causing more than one million deaths, and near one million of people have their health seriously and permanently affected because of the disease (Greenwood, 2004; Shetty, 2012). The economic consequences of the disease are enormous: countries with malaria have gross domestic products one fifth those of non-malarious countries (Gallup and Sachs, 2001), and their economic growth is severely impaired by the disease (Sachs and Malaney, 2002).

The disease is caused by *Plasmodium* spp. parasites, which are transmitted to humans by *Anopheles* spp. mosquitoes. To combat this disease several methods have been applied: insecticide spraying, insecticide bed nets impregnation, application of larva and adult mosquito pesticides, development and use of anti-malarial drugs and vaccines (Campbell and Butler, 2004; Gravitz, 2012), and biological control that exploits the interactions of mosquitoes through their life cycle with other organisms (Zoppi de Roa et al., 2002; Pernia et al., 2007; Ramirez et al., 2009). The deployment of these control tools can benefit from mathematical models that can both predict and optimize their effectiveness (McKenzie, 2000; Smith et al., 2012).

The mathematical modeling of malaria dynamics has had two modeling approaches. The first starts with assumptions about the processes and mechanisms of the parasite transmission between humans and vectors, and the demography of both populations, and makes predictions about the dynamics of the system (Smith et al., 2012). The second approach is more assumption free, and uses experimental data of time series of the disease and environmental factors (i.e. climatic data) and, using regression techniques, makes inferences about trends and relations between the incidence and external and internal regulating factors (Chaves and Koenraadt, 2010). Most models in the first approach consider that both, total human and mosquito population sizes, are constant. These approximations have been done in view of the enormous

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difficulties associated with the estimation of demographic parameters for the vectors, as well as mathematical complications arising from considering both vector and host population dynamics. For the mosquito population this means that it does not grow or decay in the interval considered (Koella, 1991), or that its dynamics is so fast that it is always at dynamical equilibrium (Koella and Antia, 2003). However, this assumption is erroneous when considering time intervals too small or too large. These errors are even greater when the time unit considered in the model is much shorter or longer than a few weeks, time scales at which parasites either cannot develop, a minimal realistic assumption for a malaria model (Macdonald, 1953), or mosquito abundance is unlikely constant. This is particularly important when the climatic variables, like temperature and rainfall, fluctuate, because of the susceptibility of the vector population to these changes.

In Venezuela there has been a sustained increase in malaria incidence since 1970 (Noya et al., 2012). Sucre State, at the North East coast of Venezuela, is an endemic malaria region, and is considered one of the three malaric foci of the country (Delgado et al., 2003a). It has one of the highest incidence in Venezuela, around 10,000 cases per year, being *Plasmodium vivax* the parasite responsible for over 99% of the cases (Caceres, 2008). The main vector in Sucre State is *Anopheles aquasalis* (Berti et al., 1993), which is present in a wide variety of humid environments (Delgado et al., 2004).

Here we study the dynamics of human malaria in several locations of Sucre State, Venezuela. We construct a dynamic model of malaria transmission that considers mosquito population density as a dynamical variable, and develop a methodology that allows estimating parameters for the whole dynamical system using only time series of human incidence. Finally, we compare the predictions of our model with the original incidence data, finding that around 80% of the observations are predicted by the model. The usefulness of the model is discussed, and our results are compared with those from other mathematical models for malaria dynamics, and with the malaria dynamics in Paria Peninsula.

2. Methods

2.1. Area of study

Paria Peninsula, Sucre State, north eastern Venezuela is shown in Fig. 1. The peninsula is located between meridians 61°32′00″ W and 63°11′00″ W, and parallels 10°27′00″ N and 10°42′31″ N, with an extension of 11,800 km^2 (Delgado, 2005). It configures an extended and horizontally oriented land belt, at the west end in the continent and the east one being the true peninsula at the open Caribbean Sea just in front of Trinidad and Tobago Islands (Fig. 1). At the center of the land belt there is a backbone mountain system, with an abrupt north slope facing the Caribbean Sea, and an extended south slope with a smooth altitudinal gradient which contains diverse types of wetland landscapes that form the Gulf of Paria coast. These wetland landscapes have their own gradients due to temporally and spatially varying salinity: at the west end there are continental

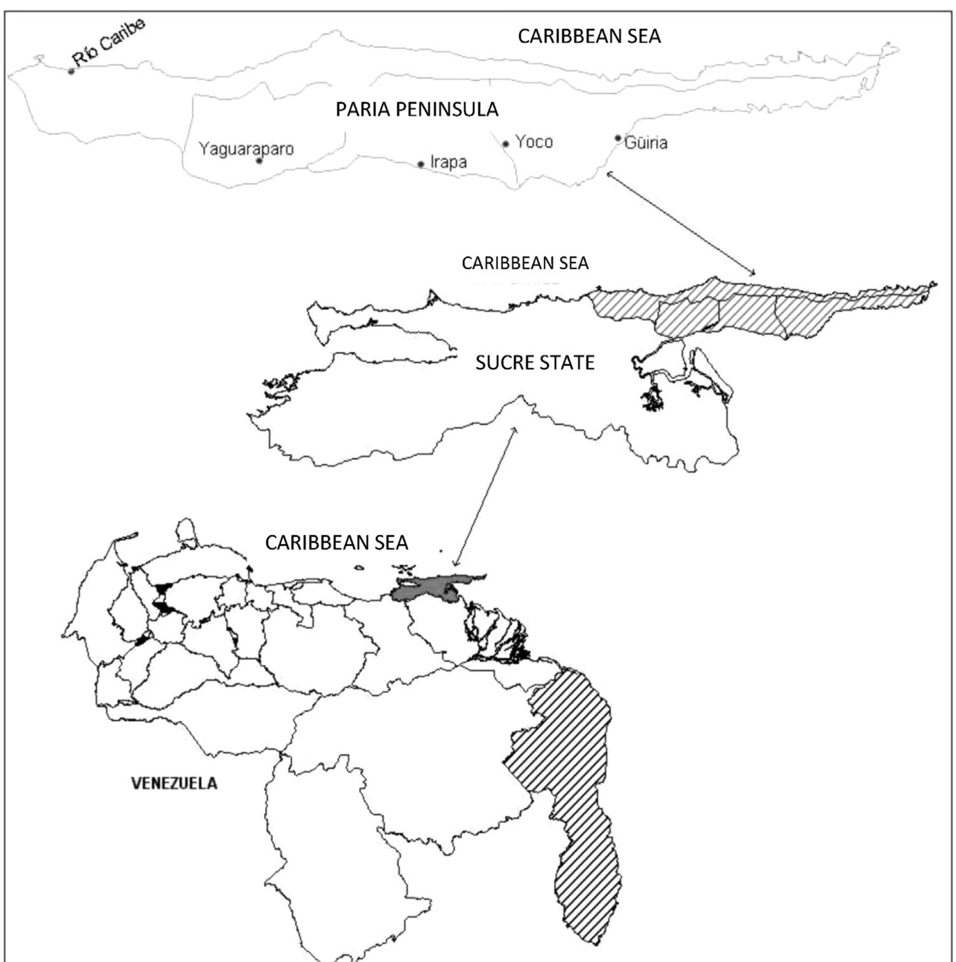

Fig. 1. Map of Venezuela, showing Sucre State and Paria Peninsula.