Mathematical Biosciences 281 (2016) 9–23

Contents lists available at ScienceDirect

Mathematical Biosciences

journal homepage: www.elsevier.com/locate/mbs

Human behaviors: A threat to mosquito control?

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ARTICLE INFO

Article history:
Received 31 October 2015
Revised 22 August 2016
Accepted 24 August 2016
Available online 31 August 2016

MSC:
34C12
91BXX
92C60

Keywords:
Population dynamics
Vector control
Human behaviors
Cooperative system
Impulsive differential equation
Numerical simulations

ABSTRACT

In this work, we consider a simple theoretical model that enables us to take into account private human decisions that may interfere with public mosquito control. The model reflects the trade-off between perceived costs and observed efficacy. Our theoretical results emphasize that households may reduce their protective behavior in response to mechanical elimination techniques piloted by a public agent, leading to an increase in the total number of mosquitoes in the surrounding environment and generating a barrier for vector-borne diseases control. Our study is sufficiently generic to be applied to different arboviral diseases. It also shows that vector-control models and strategies have to take into account individual behaviors.

1. Introduction

Many preventive technologies are among the most inexpensive ways to promote good health and are often cheaper than curative healthcare. However, how people make decisions about the use of low-cost preventive technologies remains unclear. Education may influence the adoption of health technologies or counteract the natural tendency to do the wrong thing [1,25,31]. High returns to adoption could be an additional incentive [1,9]. The unobserved characteristics of adopters may account substantially for the value assigned to protective or curative measures [13,26,32]. For instance, in the case of vector-borne diseases such as malaria, unobserved reasons for not using insecticide treated nets (such as personal beliefs, perceived temperature, smell, number of mosquitoes or comfort) have often been presented as evidence to explain the low adoption or use of nets. However, health care researchers have traditionally regarded such reasons as the result of irrational, misinformed or subjective behavior.

In this work, we study a related process at the heart of community-based healthcare strategies, with an emphasis on vector-control programs:[1] households' protective behaviors in the context of a public intervention. We focus on *mechanical elimination - as opposed to chemical control* - techniques which, in this study, refer primarily to the physical elimination of breeding sites to reduce the mosquito population around the house (e.g. the elimination of water containers). Mechanical elimination is among the cheapest interventions mentioned above and can therefore result in high monetary returns. Such methods have been recommended by the World Health Organization (WHO) for the control of arboviral diseases or malaria (for exophagic/exophilic *aedes* or *anopheles* that are best controlled through the destruction of breeding sites) and can be implemented either by an external agency or directly by households in their private dwellings [42]. Mechanical control is particularly recommended during inter-epidemic stages and has previously been modeled in [22–24] to study its impact on the *Aedes albopictus* population and on the epidemiological risk. We argue that eliminating breeding sites is a choice made by the household and, consequently, adoption rates reflect the household's trade-off between perceived costs and observed efficacy. In addition, we show that a mechanical elimination intervention piloted by an external agent might act as a substitute for private protection rather than a complement. Furthermore, if the intervention

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[1] Vector control is any method to limit or eradicate the mammals, birds, insects or other arthropods which transmit disease pathogens.

http://dx.doi.org/10.1016/j.mbs.2016.08.011

induces a psychological effect (a perceived improvement in safety or well-being), community (aggregate) protection level might be lower in the intervention group. As a result, those who received the intervention may be worse off than if they had not received it.

Based on previous works, done by the authors, our study focuses on *Aedes* species, and in particular *Aedes albopictus* [10], also called the tiger mosquito. It is particularly threatening due to its potential for transmitting a wide range of arboviruses, including dengue, chikungunya, yellow fever, zika, and several other types of encephalitides [2,18,28,35]. *A. albopictus* is now well established in places where the socioeconomic level of the population is high such as Southern Europe for instance. Education levels are also high in these places, as is knowledge of disease transmission and recommended practices specific to the elimination of larval sites. Moreover it has been shown that household-level expenditure on chemically-based protective measures is high when compared to the investment made by public entities to achieve vector control [41]. Similarly, households may play an important role in mechanical control. At this stage, we should mention that is it not possible to eradicate all larval sites even trough chemical action, because some of the sites are not accessible. Therefore, the action of each actor - individuals or public health agents – contributes to the containment or resurgence of epidemics. Studying the interactions between these actors is one of the goals of this paper.

Though our study is applicable to risk from arboviral diseases[2] and *Aedes* mosquitoes, it holds implications for other vector-borne diseases control. Numerical simulations of our model focus on Réunion Island. Réunion is one of the places in the world that has experienced a number of epidemics due to the favorable environment it provides for the mosquito species to thrive. Past outbreaks of chikungunya and dengue prompted authorities on the island to implement strategies to control mosquito density. Indeed, since the resurgence of dengue in 2004, and the major chikungunya outbreak in 2005–2006, Health authorities have set up entomologic surveillance of *Aedes albopictus* in all urban areas. This (intense) surveillance effort still continues today through the monitoring of traditional stegomyia indices at immature stages (i.e. Container Index, House Index, Breteau Index)[3] as are used in other control programmes [36]. *Aedes albopictus* remains the main target of the work of the LAV (*Lutte anti-vectorielle*), a vector-control service which is organized by the Regional Health Agency in Réunion. The vector-control strategy integrates five core activities: vector surveillance, environmental, mechanical, and chemical control (larvicide being rarely implemented by administrative services), and public health education campaigns. Vector control services also undertake the early clinical detection and treatment of cases of arboviral infection to prevent the spread of new epidemics. Importantly, we notice that transmission of arboviruses in Réunion is currently inter-epidemic and our model and numerical simulations aims at describing this situation. We also note that public intervention is defined in the rest of this article as an external intervention – with respect to the individuals' or households' private decisions living in Réunion – and human behaviors refer to private individuals' or households' behaviors.

Given the investment of both financial and human resources toward the control of *Aedes albopictus* and the observed rise of *Aedes albopictus* density in Réunion from 2006 to 2011 despite public action [12], we begin by modeling the household decision to eliminate larval sites before providing an experimental test of the theory. While it fits to the most recent bio-mathematical models applied to vector-control, the model differs from a mere bio-mathematical approach and accounts for selfish externalities and human behaviors, reflecting the trade-off between perceived costs and observed efficacy.

The rest of this paper is organized as follows. In Section 2 we present our Mosquito model and provide some qualitative results. In Section 3, we include Individual behaviors in the entomological model. Then, in Section 4, we provide numerical simulations and we discuss several scenarios. Section 5 discusses the results and Section 6 concludes.

2. The Mosquito Model

2.1. A minimalistic Mosquito Model

Before combining individual behaviors with an entomological model, we will first build a rough Mosquito Model, based on models developed and studied in Dumont and Tchuenche [24] (see also the related epidemiological models [22,23,34,37], and references therein). Mosquito population, as well as other insect/pest population, can be decomposed in different stages, like eggs, larvae, pupae, and adults. Here for sake of simplicity, we will only consider two main stages: an aquatic stage (eggs, larvae and pupae), and an adult stage. We consider the following entomological model:

$$\begin{cases} \dfrac{dL_v}{dt} = rbA_v\left(1-\dfrac{L_v}{K_v}\right) - (\nu_L+\mu_L)L_v, \\ \dfrac{dA_v}{dt} = \nu_L L_v - \mu_v A_v, \\ L_v(0) = L_0, \\ A_v(0) = A_0, \end{cases} \tag{1}$$

where A_v represents the adult mosquito population, and L_v, the "aquatic" population, including eggs, larvae, and pupae. The biological parameters of the models are described as follows: r is the sex ratio, b is the mean number of eggs laid by a female mosquito per day that have emerged as larvae, K_v is the maximal breeding capacity, μ_L is the aquatic daily death-rate, ν_L is the transition rate from the aquatic stage to the adult stage (such that $1/(\nu_L+\mu_L)$ is the mean time a mosquito stays in the aquatic stage measured in days), μ_v is the female mosquito mean death-rate per day.

The non-linear term $rbA_v(1-\frac{L_v}{K_v})$ is a bit specific to some mosquito species, and in particular Aedes spp, and deserves some explanations. Indeed, it is now acknowledge that *Aedes albopictus* (and even *Aedes aegypti*) performs "skip oviposition" behaviors. In other words, they are capable to select their breeding sites, seeking for oviposition sites with high food content and low intraspecific competition pressure (see for instance [16,17,43]). Thus, if breeding sites, in a given area, already contain a lot of larvae, then the females will not deposit eggs or only very few. In other words, the hatching rate rbA_v is limited by the available space in breeding sites, $1-\frac{L_v}{K_v}$, which implies that the birth rate in the aquatic compartment is modeled by the nonlinear term $rbA_v(1-\frac{L_v}{K})$.

The right-hand side of system (1) is a continuously differentiable map ($\mathcal{C}^1$). Then, by the Cauchy–Lipschitz theorem, system (1) provides a unique maximal solution. System (1) is biologically well posed: if the initial data are in $\mathbb{R}^2_+$, then the solution stays in $\mathbb{R}^2_+$: $L_v=0$, and $A_v=0$ are vertical and horizontal null lines, respectively. Thus, no trajectory can cut these axes. In fact, it is straightforward to show that the compact

$$\mathcal{K} = \left\{ (L_v, A_v) \in \mathbb{R}^2_+ : L_v \le K_v, A_v \le \frac{\nu_L}{\mu_v} K_v \right\}$$

[2] There are no specific antiviral medicines or vaccines against Chikungunya and Dengue.

[3] The house index is defined as the percentage of houses infested by larvae and/or pupae. The container index is defined as the percentage of water-holding containers with active immature stages of mosquitoes. The Breteau index is defined as the number of positive containers per 100 houses, a positive container being one that contains larval and/or pupal stages of mosquito.