Journal of Theoretical Biology 443 (2018) 28–38

Contents lists available at ScienceDirect

Journal of Theoretical Biology

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

Temperature-driven population abundance model for *Culex pipiens* and *Culex restuans* (Diptera: Culicidae)[☆]

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ARTICLE INFO

Article history:
Received 22 November 2016
Revised 17 January 2018
Accepted 18 January 2018
Available online 3 February 2018

Keywords:
West Nile virus
Culex
Mosquito
Abundance
Temperature
Surveillance
Population
Trap data
Simulations

ABSTRACT

We develop a temperature-driven abundance model for West Nile virus (WNV) vector species, *Culex pipiens* and *Culex restuans*. Temperature-dependent response functions for mosquito development, mortality, and diapause were formulated based on results from available laboratory and field studies. Numerical results compared to observed mosquito trap counts from 2004–2016 demonstrate the ability of our model to predict the observed trend of the mosquito population over a single season in the Peel Region, Ontario. The model has potential to be used as a real-time mosquito abundance forecasting tool with applications in mosquito control programs.

1. Introduction

Since the first appearance of West Nile virus (WNV) in New York in 1999 (Centers for Disease Control and Prevention CDC, 1999a, 1999b), the mosquito-borne disease has rapidly spread across the North American continent establishing itself as a seasonal endemic infection (Sejvar, 2003; Reisen, 2013). By 2004, WNV had been detected in all states in the continental US; in 2002, the first WNV human infection was reported in southern Ontario, Canada and has since been detected in all provinces except Prince Edward Island and Newfoundland (Infection Prevention and Control Canada, 2017). As there is no vaccine or specific antiviral treatments for WNV infection (Centers for Disease Control and Prevention, 2017), the primary strategy for decreasing the risk of human infection is the implementation of mosquito control methods. In an era of climate change and global warming, it is increasingly important to understand how mosquito population dynamics are affected by changes in climate variables (temperature, precipitation, humidity, and wind) to inform public health policy in the effort to control the disease.

Mosquito population dynamics directly affects the transmission of mosquito-borne diseases such as WNV, Zika, malaria, dengue, and chikungunya (Beck-Johnson et al., 2013; Erickson et al., 2010; Gunaratne et al., 2016; Mordecai et al., 2017; Shaman and Day, 2007). Mosquitoes are exotherms, and thus are highly sensitive to changes in ambient temperature. The effect of temperature on mosquito biology (development, mortality, life-history traits, diapause, and oviposition) has been studied extensively and remains a topic of intense research (Ciota et al., 2014; Eldridge et al., 1976; Kiarie-Makara et al., 2015; Madder et al., 1983; Nasci et al., 2001; Paaijmans and Thomas, 2011; Shelton, 1973; Spielman, 2001). Application of the knowledge gained from these studies in mathematical models enable us to gain a more realistic and qualitative understanding of the relationship between temperature and mosquito biology as well as help to identify the mechanisms that drive their population dynamics.

A substantial number of mathematical and statistical models have been developed to assess the influence of climate variables, such as temperature and precipitation, on the population dynamics and behavior of various mosquito species (Ahumada et al., 2004; Cailly et al., 2012; Cochran and Xu, 2012; Ezanno et al., 2015; Gong et al., 2010; Gu and Novak, 2006; Otero et al., 2006; Tran et al., 2013; Wang et al., 2011; Yoo et al., 2016). Tachiiri et al. (2006) created a raster-based mosquito abundance map for two species, *Culex (Cx.) tarsalis* and *Cx. pipiens*, which

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[☆] This research was supported by NSERC and CIHR of Canada.

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https://doi.org/10.1016/j.jtbi.2018.01.024
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allowed them to identify areas of greatest potential risk of WNV in British Columbia, Canada. Cailly et al. (2012) developed a generic climate-driven mosquito abundance model that could be run over several years. Their model identified several potential control points in the biological system of mosquitoes that could be used to reduce the risk of mosquito-borne disease outbreak. Otero et al. (2006) developed a temperature driven stochastic population model for the species *Aedes aegypti* and identified temperature and environmental conditions that are needed for the survival of a local population of mosquitoes in a temperate climate. Spatio-temporal dynamics of mosquito host-seeking behavior were examined in the study by Cummins et al. (2012), where they developed an agent-based/continuum model to explore the effect of behavioral decisions and spatial heterogeneity on the contact rate between mosquito vectors and bird hosts. The study by Gunaratne et al. (2016), used agent-based modeling to describe the population dynamics of Zika vector *Aedes aegypti* subjected to spatial and climatic constraints. Wang et al. (2011) developed a predictive statistical model for mosquito abundance which defined threshold criteria for temperature and precipitation conditions for the population growth of WNV vector species *Cx. pipiens* and *Cx. restuans*. The model developed by Yoo et al. (2016), used harmonic analysis and kernel density estimation as a means of examining the associations with major landscape predictors, including land-use type, population density, and elevation, on the spatial patterns of mosquito abundance.

In the studies that account for temperature, various approaches have been used to model the effect of temperature on the mosquito life cycle. For example, some dynamical models use temperature-dependent development rate functions (Abiodun et al., 2016; Cailly et al., 2012; Lana et al., 2011) to determine the instantaneous rate of development at each time-step. Gu and Novak (2006) developed a stochastic phenological model which calculated probabilities of individuals residing in larval, pupal, and emerging adult stages as a function of temperature. A drawback of using instantaneous rate functions to model mosquito development is their limitation to capture certain population dynamics, such as sudden population increases caused by weather patterns that allow for the simultaneous eclosion of multiple generations. Some studies also estimate the daily mortality rate of developing mosquitoes based on the ambient temperature for a single day (Ewing et al., 2016; Otero et al., 2006; Shaman et al., 2006; Tachiiri et al., 2006); however, immature mosquitoes can survive exposure to high or low temperatures for short periods of time without significant impact on their mortality (Bayoh and Lindsay, 2004). Thus, mortality rates can potentially be overestimated in temperate climates that experience a wide range of diurnal temperature fluctuations.

An often neglected, but important factor in mosquito population dynamics is the diapause phenomenon. Environmental conditions trigger a physiological response in developing mosquitoes which enables them to survive harsh winter conditions in a form of metabolic dormancy until more favorable conditions induce their emergence in the following season (Denlinger and Armbruster, 2014). Exclusion of this phenomenon may cause an overestimation of the active mosquito population in model simulations during the latter half of the mosquito season when diapause destined mosquitoes begin seeking shelter for the upcoming winter months (Gong et al., 2010; Denlinger and Armbruster, 2014). Some of the models that do account for diapause consider photoperiod alone to determine the fraction of diapausing mosquitoes (Gong et al., 2010; Cailly et al., 2012); however, there is evidence that temperature influences the proportion of mosquitoes destined for diapause at a given photoperiod (Eldridge, 1966; Madder et al., 1983; Spielman, 2001).

Fig. 1. Map of the Peel Region (shaded grey) and other municipalities in the Greater Toronto Area.

In this study, we focus on the aspects of mosquito biology where temperature has been found to have significant influence: aquatic development, mortality, and diapause. We formulate temperature-dependent response functions for these key aspects of the mosquito life cycle based on the results of available laboratory and entomological field studies. The model is designed to simulate aquatic and adult *Cx. pipiens* and *Cx. restuans* population dynamics over a single season. To demonstrate the capacity of our model to describe the observed dynamics of mosquito abundance in a given area, we apply the model to the Peel Region, Ontario using mosquito surveillance data from 2004–2016. Simulation results showed the model could capture the general trend of observed mosquito surveillance data for most of years. The proposed model has potential to be used as a real-time mosquito abundance forecasting tool having direct application in mosquito control programs and can also be coupled with epidemiological models to assess the impact of diurnal fluctuations in temperature on the dynamics mosquito-borne disease transmission.

2. Materials and methods

2.1. Study area

The Regional Municipality of Peel (also known as Peel Region) is a regional municipality in southern Ontario, Canada with a total population of 1,296,814 and a total area of 1246.89 km^2 (Canada 2011 census). It consists of three municipalities: the cities of Brampton and Mississauga, and the town of Caledon (Fig. 1). The four seasons in the region are clearly distinguished. Spring and autumn are transitional seasons with generally mild or cool temperatures with alternating dry and wet periods. Summer runs from June until mid-September with an average monthly temperature of 20 °C for the warmest months of July and August. Temperatures during summer can occasionally surpass 32 °C.

2.2. Surveillance program and mosquito data for the Peel Region, Ontario

Mosquito surveillance in southern Ontario was started in 2001 by the Ministry of Health and Long-Term Care. The Peel Region Health Unit used the CDC miniature light trap (Service, 1993) with