A Climate Based Mosquito Population Model

Hongfei Gong, Arthur DeGaetano, and Laura C. Harrington

Abstract—**A climate based model for predicting mosquito population abundance of the West Nile *Culex* spp. vectors has been developed. The population dynamics are driven by major environmental factors including temperature, rainfall, evaporation and photoperiod. Results show good correlations for timing of early population increases (as early warning of West Nile virus risk) and ending. The parameter space has been explored for model optimization. The relevance of the different parameters has been discussed. This is the first climate based model to simulate population dynamics of each mosquito life stage form West Nile vectors and may have direct applications for mosquito control and West Nile prevention programs.**

Index Terms—**Climate model, Population dynamics, West Nile Virus, *Culex* mosquitoes, Disease risk.**

I. Introduction

Although daily weather and seasonal to inter-annual climatic variability influence mosquito vector biology and risk of vector-borne disease, this information is not readily employed in disease control programs. We developed a new model to predict the activity of West Nile vectors in the Northeastern USA. West Nile virus has become an endemic infection in the United States since its introduction in 1999 in the New York metropolitan area [1].

Numerous models have been developed over the years to describe vector borne diseases [3], [9]. Inherent in these models are assumptions about the basic biology and ecology of mosquitoes that are difficult to validate in a field setting [2]-[6].

While models can be extremely useful for conceptualizing the relative role of different parameters in the vector borne disease cycle, few models have been developed that are employed on a regular basis in vector borne disease studies. We sought to develop reliable predictive models by focusing on *Culex* species that are important in vector borne diseases including West Nile virus.

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We developed a unique model that describes *Culex* mosquito population dynamics by utilizing capture data for the model validation by averaging the daily capture over a weekly period. The model was further optimized by a parameter-space search within biological bounds. Adjustments were made to the correlation of simulated adult population with real field capture to account for the lower magnitude of capture compared with the entire population.

While many parameters may influence the magnitude of mosquito populations, temperature is one of the strongest as it directly influences the rate of mosquito development and population increase. In our model, temperature was the major driving force.

Previous studies have suggested a correlation between rainfall and mosquito abundance [7], [8], but none have been developed specifically for *Culex pipiens* and *Cx. restuans* using a rainfall parameter. In this study, we created a *moisture index* based on 7 days cumulative rainfall and evaporation, studied the correlation between rainfall and 1st instar larvae and adults mosquito population abundance, and developed a function for daily egg laying rate, which depends on the *moisture index*. In addition photoperiod is known to be important in induction of diapause and we incorporated this parameter into our model.

II. Methods

A. Mosquito collection data

New Jersey Light trap data from several mosquito abatement districts was obtained for model development. Data were provided from the following locations and years: Maryland 1980-1985; Rumson and Ocean port, Monmouth county, New Jersey 1990-1995 and 2002-2003; and New Brunswick, Middelsex County, New Jersey 1990-1993， 1997, 1999, 2001. The following parameters were used in the model: daily average temperature, rainfall, evaporation, hours of daylight, and total *Culex* mosquito capture.

B. Model formulation

The mosquito life cycle is composed of four distinct phases: egg, larva, pupa and adult. The first three phases encompass the immature stage. Immature mosquitoes develop in water. After mating and blood feeding, female adults will lay eggs to produce the next generation.

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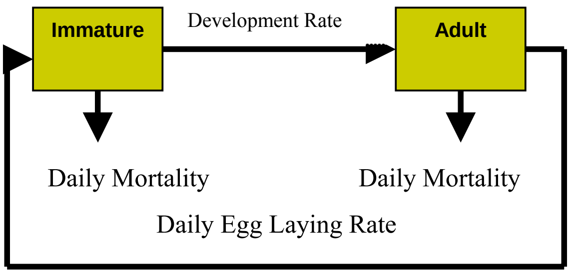

Figure 1. The structure of the model.

The climate based *Culex* population model was developed on several temperature-dependent functions including: *Development rate* and *Survival rate*, and a moisture index dependent function *Daily egg laying rate* (Figure 1).

The following difference equations (1) and (2) were used to calculate the population numbers of mosquito immature life stages and adults on each day:

$$\begin{aligned} &NumberOfImmature(t) = NumberOfImmature(t-1)* \\ &[SurvivalRateImmature(t-1) - DevelopRate(t-1)] + \\ &NumberOfAdults(t-1)*EggLayingRate(t-1) \end{aligned} \quad (1)$$

$$\begin{aligned} &NumberOfAdults(t) = NumberOfAdults(t-1) \\ &* SurvivalRateAdult(t-1) + NumberOfImmature(t-1) \\ &*DevelopRate(t-1)*DiapausingRate; \end{aligned} \quad (2)$$

The simulation started from 1 April and ends on 31st of December for each year. The population was initialized with a given numbers of eggs and adults. The inputs of the model were: daily average temperature, moisture index, and hours of day.

C. Functions and Parameters

1. Daily Survival Rate

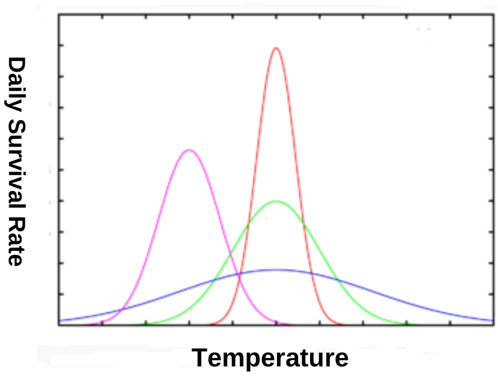

Figure 2. Function *Daily Survival Rate* on Temperature.

Based on our experimental data on temperature dependent development of local *Culex* strains, the approximate shape of the Survival Rate function on temperature nearly resemble the Gaussian function (Figure 2)

$$SurvivalRate(t) = SurvivalRate\_Op * \exp[-\frac{(Temperature(t) - Temp\_Op)}{VarSur}]^2 \quad (3)$$

Where *Temp_Op*, *SurvivalRate_Op*, and *VarSur* are the function parameters presented in Figure 2. *Temperature* is the variable, representing the average temperature during over the interval period. In our model this interval is equal to one day.

2. Development Rate

Temperature has a major effect on insect development; the thermal requirements of development are often used as a basis for prediction. Development times are measured under a constant temperature over a range with interval, the reciprocals of development times are plotted as rates versus temperature, a shallow sigmoid curve results.

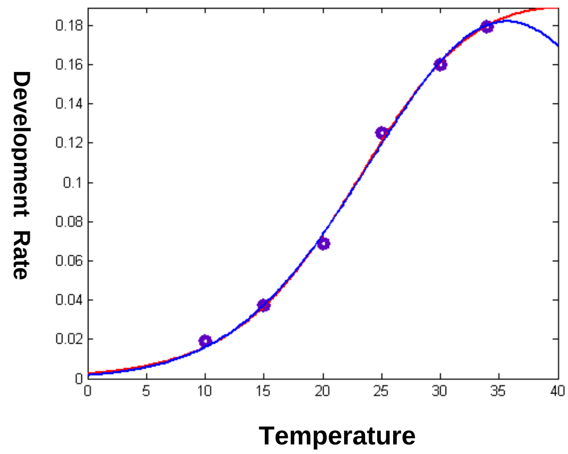

Figure 3. Function *Development Rate* on *Temperature***.**

According to our results from laboratory experiments of development for *Cx. pipiens*, the **Sharpe & DeMichele** equation with 4 parameters provided the best fit (Figure 3). We use it directly in the population model as a function for *Development Rate*.

$$Development\ Rate(t) = A * \frac{(Temperature(t) + K)}{298.15} * \frac{\exp\left[\frac{HA}{1.987} * \left(\frac{1}{298.15} - \frac{1}{K}\right)\right]}{1 + \exp\left[\frac{HH}{1.987} * \left(\frac{1}{TH} - \frac{1}{K}\right)\right]} \quad (4)$$

Where K is the Kelvin Temperature 273.15 and A, HA, HH, and TH are the fitted parameters. *Temperature (t)* is the input variable

3. Daily Egg Laying Rate

Rainfall has two principal influences on the mosquito population dynamics: 1) the increased near-surface humidity associated with rainfall enhances mosquito flight activity and host-seeking behavior, and 2) rainfall can alter the abundance and type aquatic habitats available to the mosquito for deposition of eggs and the subsequent development of immature stages.

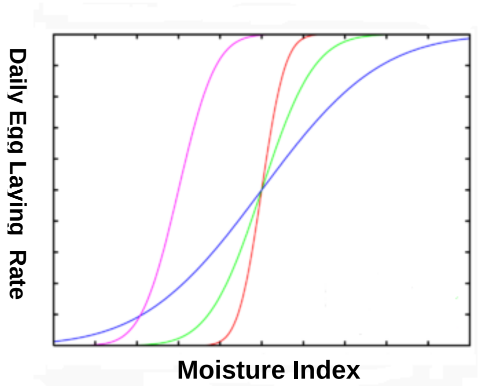

Figure 4. Function *Daily Egg Laying Rate* on *Moisture Index.*

The function *Daily Egg Laying Rate* depends on the moisture index. In principle, we assume that there is a positive correlation between *Daily Egg Laying Rate* and the moisture index.

MoistureIndex is a variable of this function. We created this index by summing the daily difference of precipitation and evaporation (mm) over the preceeding7 days.

$$\boldsymbol{MoistureIndex(t)} = \sum_{D=t-6}^{t} \boldsymbol{precipitation(D)} - \boldsymbol{evaporation(D)} \qquad (5)$$

$$DailyEggLayingRate(t) = BaselineEggrate + \frac{Emax}{1+exp\left[-\frac{(MoistureIndex(t)-Emean)}{Evar}\right]} \qquad (6)$$

Where *Emax*, *Emean* and *Evar* are the function parameters (Figure 4), they correspond to maximum daily egg laying rate, the mean of the function, and the function variance, respectively. The *BaseEggrate* is the base line for the fecundity rate.

4. Diapause by Photoperiod

Our initial model did not include the influence of photoperiod and diapause. As a consequence, the mosquito population always peaked at the end of the mosquito season. Based on the work of Spielman with *Cx. pipiens* in the Northeast USA, we estimated the percent diapause over decreasing *Hours of Daylight* (Fig. 5). The effect of photoperiod on the model started from early September when the hours of daylight drop below 13 hours.

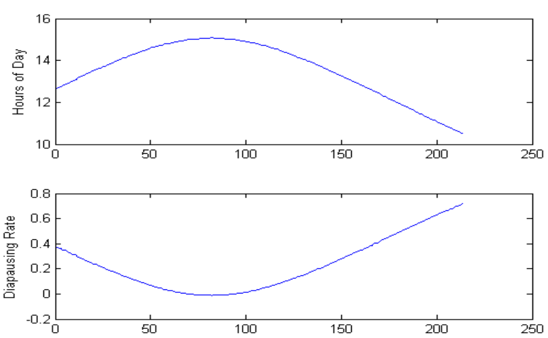

Figure 5. The *Hours of Daylight* and the *Diapausing Rate* over a mosquito season.

D. Parameter Calibration

We based our estimates for function parameters on the most relevant information from the literature and our laboratory studies. But in the realistic condition, the estimates for model parameters might be different. Also, some functions might be not possible to determine, such as *Daily Egg Laying Rate* by moisture index.

In order to get a more accurate model, we explored the parameter space to calibrate the functions. This was conducted by maximizing the correlation *r* between adult population numbers from the model output and the adult capture from trap using 7 years of data from 2 different sites.

III. Results

To date, the best model predicts adult populations with the average *r* values 0.6728 over 7 years at a New Jersey site (shown here). The *r* is the correlation between adult population number from the model simulation and adult capture from surveillance traps (Table 1).

Year	1990	1991	1992	1993	1997	1999	2001	Average
r values	.5478	.7451	.7085	.4280	.6229	.8474	.8103	.6728

Table 1. Correlation between model simulation and actual trap capture in New Brunswick County, New Jersey from 1990 to 2001.

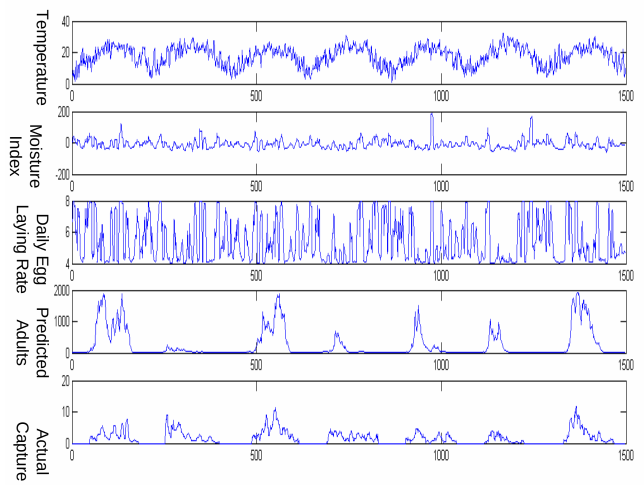

Figure 6. Simulation for the *Culex* mosquito population over 7 years at a New Jersey location.

IV. Discussion

The Simulation results have provided the population dynamic that closely resemble the observation in the filed, especially for the population early rising (early warning) and ending (Figure 6). Availability of weather forecast up to several days allows the prediction of the mosquito abundance. This model will be further developed to present population dynamics of each life stage including larvae, which may provide practical timing information for mosquito control efforts and West Nile risk monitoring programs.

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