ODD for **AMRO_CULEX_WNV**

Aniruddha Belsare (belsare1@msu.edu)

Contributor: Jen Owen (owenj@msu.edu)

An agent-based model simulating West Nile Virus dynamics in a one host (American robin)-one vector (*Culex* spp. mosquito) system.

Background

West Nile Virus (WNV) is the arthropod virus of largest concern in the United States (Kramer, Li, & Shi, 2007). It is a member of the Japanese encephalitis virus serogroup in the family Flaviviridae and causes morbidity and mortality in wild animals, including birds, mammals, domestic livestock, and humans. WNV is transmitted by infected mosquitoes, primarily *Culex* species (Hayes, 1989). Birds are important amplification hosts in maintaining the virus cycle and passerine birds are particularly competent reservoir hosts. Furthermore, migratory birds are suspected to be one of the key dispersal vehicles for WNV.

American robins (*Turdus migratorius*) play an important role in the transmission dynamics of WNV. They achieve moderately high viral titers and they are also a preferred source of blood meals for the primary mosquito vector, *Culex spp.*. Robins are a ubiquitous species with breeding and wintering range that blankets most of the United States and they are particularly abundant during fall migration when WNV activity is at its peak. Environmental factors that affect host viremia, and consequently reservoir competency, can have profound impacts on disease dynamics of WNV, and ultimately on health of domestic animals and humans. Here we model the impact of acute food stress in robins on transmission dynamics of WNV.

Purpose and patterns

AMRO_CULEX_WNV simulates the enzootic transmission of West Nile virus between an avian reservoir host (American robin, *Turdus migratorius*) and primary mosquito vector (*Culex* spp.). The objective is to quantify how acute food stress experienced by robins influences the proportion of infected *Culex* mosquitoes during peak fall migration when there are large influxes and turnover of robins, particularly susceptible, hatch-year birds.

The model is evaluated by its ability to reproduce the pattern of viremic and non-viremic infected birds as a consequence of the proportion of stressed birds in the population.

Entities, State Variables and Scales:

Entities: AMRO_CULEX_WNV has two entities: Robins (avian hosts) and *Culex* sp. (mosquito vector). Both entities are modeled as individuals occurring in the model landscape. Enzootic transmission cycle of WNV is underpinned by host (robin) - vector (*Culex* spp.) interactions. State variables for the two entities are described in Table 1.

Table 1. State Variables and Scales

Agent	State variable	Interpretation / value
Robins	*age-class*	HY (hatch-year), AHY (after hatch-year; adult)
	stress-status	NS (not stressed), S (stressed)
	viremia	0 (uninfected), 1 to 4 (infected but not infectious), 5 and above (infectious)
	dpi	days post infection
	imm-status	0 (susceptible), 1 (immune or infected)
***Culex* spp.**	*inf-status*	0 (susceptible), 1 (immune or infected)
	ip	counter for days since exposure
	eip	Extrinsic incubation period at 23° Celcius

Spatial scale: The model landscape is a square grid of 39 x 39 patches. Entities (robins and Culex mosquitoes) are randomly located in the model landscape.

Temporal scale: AMRO_CULEX_WNV has a daily time step, and the model is simulated for 92 days (1 August to 31 October).

Process overview and scheduling (Figure 2)

Following processes are executed during each time step (day) in the following order:

1. First day of each week, resident robins depart and new robins arrive
2. Stress status of robins is updated on the first day of each week.
3. Infection stage progresses in infected robins.
4. Infected *Culex* update their days since exposure counter.
5. *Culex* execute the mortality submodel with all mortalities replaced with an equivalent number of adult *Culex*.
6. *Culex* execute the bite submodel.

Additionally, robin population turnover (attributed to the migratory events) is simulated on the first day of each week.

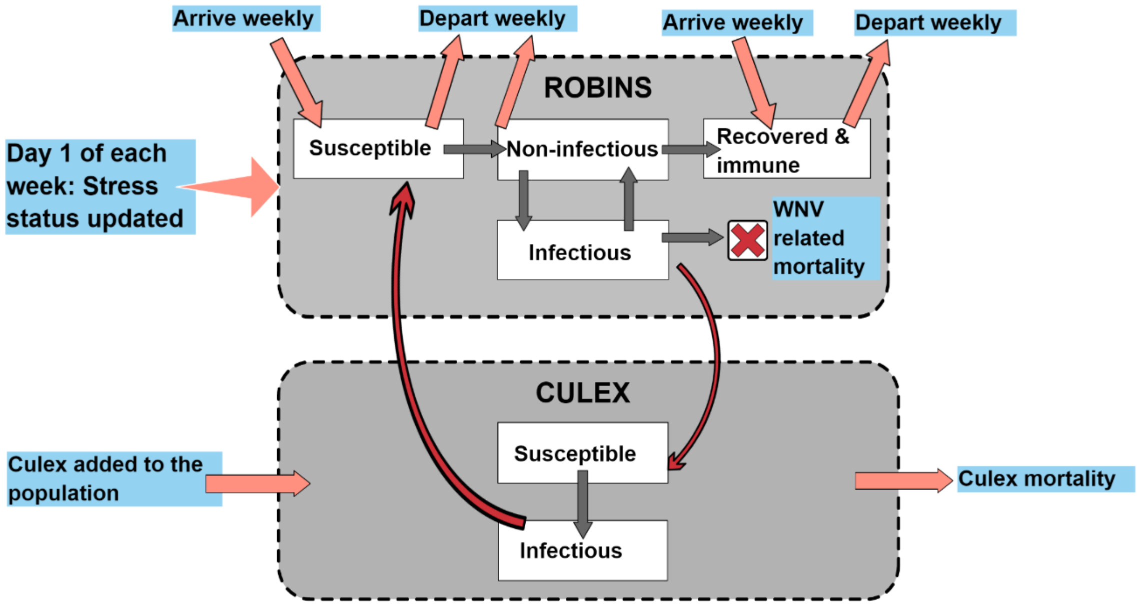

Figure 2. Sequence of events simulated during each time step of the model.

Design Concepts

Emergence: The pattern of infection in *Culex* and robin populations emerges as a consequence of *Culex*-robin interactions.

Adaptation: No adaptation behaviors are simulated in this model.

Sensing: No sensing behaviors are simulated in this model.

Prediction: There is no implicit or explicit prediction occurring in this model.

Sensing: Does not apply to this model.

Interaction: Direct interaction between mosquito agents and bird agents is simulated by the submodel ‘to bite’. Transmission of infection occurs during this interaction.

Stochasticity: User-specified rates determine the proportion of robins with WNV infection and WNV antibodies, but individuals are randomly selected for the assignment of infection and immune status. Similarly, individuals are randomly selected for the assignment of ‘stressed’ status. *Culex* mosquitoes bite randomly selected robins. Natural mortality of *Culex* mosquitoes, is based on a mortality probability and is implemented as a stochastic process.

Collectives: Not applicable to this model.

Observation: Total number of robins, number of infected robins (stressed and non-stressed), and number of infected *Culex* mosquitoes are updated and displayed (graphs and/or monitors) as the model executes. Model output is also stored as a .csv file.

Initialization

Host and vector population in the model is initialized with four user-specified parameters: initial robin population size, WNV prevalence in robins, proportion of stressed robins and mosquito: host ratio. The initial age ratio for the robin population is set at 0.20 AHY to 0.80 HY.

Input data

The model does not use input data to represent time-varying processes.

Submodels

1) *Migration:* This submodel simulates robin population dynamics underpinned by migration events. Robin population turnover occurs on the first day of each week. Uninfected individuals and those with virus titers below 4 logs are selected randomly to 'depart' from the model landscape. An equal number of robins 'arrive' in the model landscape simultaneously (the influx is greater on 19th September and 10th October, see Parameterization and calibration for details).

2) *stress-status-update*: On the first day of every week, randomly selected robins are assigned 'stressed' status. The number of robins assigned 'stressed' status is calculated using the variable '*stressed-prop*' (user-specified).

3) *infection-progression*: The state variable *dpi* (days post infection) is updated for all infected robins and WNV viremia levels are simulated in infected robins. Viremia levels above 4 logs result in transmission of the infection to biting mosquitoes. Based on experimental results, proportion of stressed and infected birds that are viremic 2, 3, 4, and 5 DPI are 90%, 70%, 50% and 30%, respectively. Similarly, proportion of non-stressed and infected birds that are viremic 2, 3, 4, and 5 DPI are 70%, 30%, 10%, and 10%, respectively. Additionally, 10% of the stressed robins with infectious viremia levels die on the 5th day of infection. We assume that all robins surviving the infection will recover and become immune by 6 DPI.

4) *c-mortality*: We model female *Culex* mosquitoes as only female mosquitoes are capable of taking a blood meal and transmitting WNV to reservoir host (robin). Mosquito mortality is simulated using the daily natural mortality probability derived from the literature (See Parameterization and calibration). The abundance of *Culex* mosquito remains constant throughout the model simulation and for every mosquito that dies, one adult uninfected female *Culex* is introduced into the population.

5) *bite*: A blood meal seeking mosquito can bite many hosts, here we assume at least 1 and a maximum of 5. Infected robins with viremia of 4 log pfu/0.1ml and above can transmit WNV virus to susceptible mosquitoes, and an infected mosquito can transmit the infection to susceptible hosts after an extrinsic incubation period (the time needed for the virus to spread from mosquito mid gut to the salivary glands).

Parameterization and calibration

Robin population dynamics is driven by migratory events only – we do not simulate births or natural mortality of robins in this model. The initial age ratio (0.20AHY: 0.80HY) changes twice during the model run. On 19 September (50th day of the model run), the robin population doubles with a large influx of birds with the age ratio of 0.40AHY / 0.60HY. On 10 October (71st day of the model run), another large influx of robins increases the population five times the initial population size with an age ratio of 0.30AHY / 0.70HY. The herd immunity at the start of the simulation and at the start of each week ranges between 0.07 – 0.10 for HY and 0.17 – 0.33 for AHY. The changes in robin population size, age ratio, and herd immunity are derived from a long-term banding data set (Owen unpublished data) and from WNV serosurveillance in robins in MI and NY (Dupuis and Owen unpublished data).

Infected birds in the model recover at a constant rate of 0.17 as the average duration of infection (viremia) in robins is 6 days. Mosquitoes do not recover from infection in the model as they have a short lifespan.

The number of mosquitoes in the simulation is derived from the user-defined mosquito to host ratio. The ranges reported in the literature are between 3 – 20 mosquitoes per host.

We use the temperature-dependent biting rate (the number of bites per day, or the reciprocal of the number of days between blood meals) of 0.17 (at 23°C) to model the number of *Culex* mosquitoes seeking a blood meal during each time step. We use a conservative bite rate in this model. It is important to note that bite rate will vary by mosquito and host species. There are species of avian hosts that are preferred sources of blood meals and will have a higher bite rate than d.

The duration for the virus to spread from mosquito mid gut to the salivary gland is between 7 and 11 days (also called the extrinsic incubation period). The probability of WNV transmission from an infected *Culex* mosquito to a susceptible robin is set at 0.8. The transmission probability of WNV transmission from a robin with viremia above 4 to a susceptible mosquito is set at 0.15 (with range of 0.05 – 0.30). The bird to mosquito transmission rate can vary widely with virus strain, mosquito species/strain, and host species; hence, we chose rates that reflect the variation observed in *Culex pipiens* vector competence experiments with North American strains of WNV.

The daily natural mortality probability for *Culex* mosquito at 23° Celsius is 0.04 derived from.

References

Hayes, C. (1989). West Nile fever. In T. P. Monath (Ed.), *The arboviruses: epidemiology and ecology* (pp. 59–88). Boca Raton, FL: CRC Press.

Kramer, L. D., Li, J., & Shi, P. Y. (2007). West Nile virus. *Lancet Neurology*. doi:10.1016/S1474-4422(07)70030-3