AGENT-BASED MODEL FOR SIMULATION OF WEST NILE VIRUS TRANSMISSION

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ABSTRACT

The rapidity at which the West Nile virus (WNV) spreads and its potential for serious medical consequences underscore the necessity for better understanding the virus's transmission pathways and the conditions that affect its transmission. This paper describes an attempt to build a virtual laboratory by using agent-based modeling (ABM) techniques; the laboratory is to be used by WNV epidemiology researchers to study the characteristics of WNV transmission, including transmission pathways and the conditions under which a WNV outbreak might occur. The WNV transmission model uses the Repast ABM toolkit to simulate the dynamic interactions of the entities involved in WNV transmission. The results show that ABM is an effective technique for developing simulations of the transmission of infectious diseases. The modeling approach developed in this study is also applicable to simulations of the transmission of other infectious diseases, such as severe acute respiratory syndrome (SARS), avian influenza, and malaria.

Keywords: Agent-based modeling, West Nile virus, infectious diseases, transmission, avian influenza, SARS

INTRODUCTION

West Nile virus (WNV) is a deadly disease for which there currently is no effective treatment or vaccine. In recent years, WNV has spread across the mainland of the United States, causing a great deal of concern among the public as well as within federal and state public health agencies and natural resource agencies (CDC undated). WNV has been implicated in human fatalities in most U.S. states and identified as the cause of major reductions in native bird populations in many areas. The latest reports also show that WNV, like meningitis, can cause paralysis in humans (Neergaard 2005). The rapid spread of the disease and its potential for serious medical consequences underscore the necessity for better understanding the virus's transmission pathways and the conditions that affect its transmission.

As do other natural phenomena, it is believed that transmission of WNV has its own intrinsic characteristics. A fundamental understanding of these characteristics would assist the research community, government agencies, and local communities in developing more effective monitoring approaches and preventive control measures for the virus. There is a need for a tool

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that can facilitate further understanding of the intrinsic characteristics of various transmission pathways.

The primary pathway for transmitting WNV to humans, wildlife, and domestic animals is through the bites of infected mosquitoes. Mosquitoes become infected when they feed on infected animals (especially birds and mammals) and then re-transmit the virus to other organisms during subsequent blood meals. Once the virus is transmitted to an animal host, it multiplies within that host animal, where it creates a reservoir for further infection. The interactions among mosquitoes and host animals form a cycle of WNV transmission.

Figure 1 illustrates the dynamics of WNV transmission. Agent-based modeling (ABM) techniques are especially well-suited for evaluating such processes. This paper describes an agent-based model (also ABM) that is being developed to simulate the spread of WNV. The objective of this study is to develop a virtual laboratory to be used by WNV epidemiologists to study the intrinsic characteristics of WNV transmission via computer simulations.

WEST NILE VIRUS

WNV is a vector-borne disease. This means that WNV infection is spread via intermediate hosts, such as mosquitoes. The virus is transmitted from infected mosquitoes to hosts and multiplies in the blood of the infected hosts. The most common hosts are avian and mammalian species, such as American crows, blue jays, raccoons, or chipmunks. WNV epidemiology research indicates that certain reptiles, such as crocodiles and lizards, can also serve as hosts for the virus. The virus can transmit back to mosquitoes when noninfected mosquitoes bite the infected hosts. In this way, the virus completes its transmission circle.

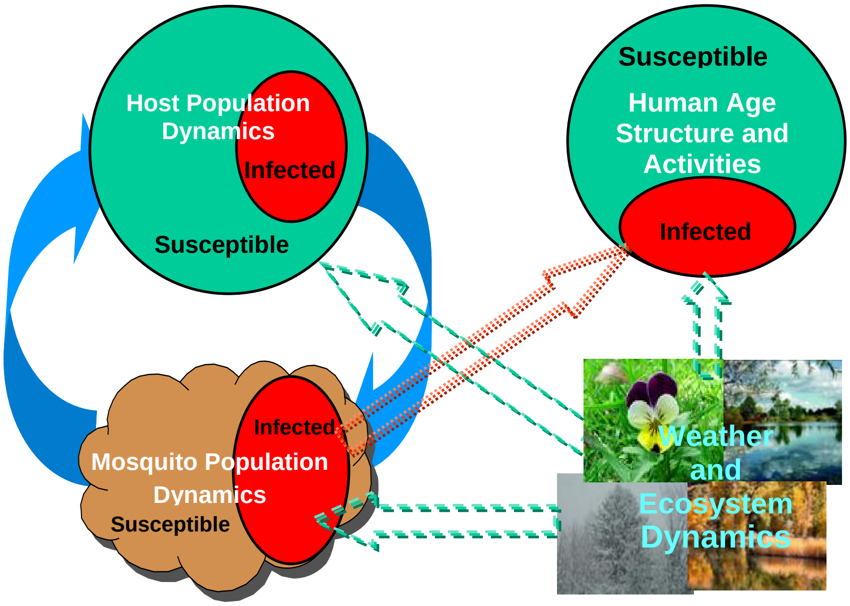

FIGURE 1 Dynamics of WNV transmission

Large-scale geographic spread of WNV has been attributed primarily to the foraging and migration of the avian hosts. Mammalian or reptile hosts do not, in general, transverse great distances and thus are not likely to be responsible for the rapid spread of the virus across the United States. In contrast, the local spread of the virus may be affected by the behaviors and movements of all three types of hosts.

People may become infected when they are bitten by infected mosquitoes. Humans are not in the transmission circle of the virus because a human's blood system cannot serve as a reservoir for the virus. Thus, the virus reaches a dead end in the human body because the virus does not attain a concentration in human blood that is sufficient to infect a mosquito that is taking a blood meal from the infected person.

The dynamics of the habitats of the hosts and mosquitoes are important factors in the WNV transmission process. The qualities of the habitats affect the mosquito and host populations by affecting their reproduction and death rates. In addition, the quality of the hosts' habitats will also affect their foraging behaviors and therefore the transmission speed of the virus, since the home ranges of birds tend to expand as abundant food becomes less available.

The last important component of WNV transmission is weather. Weather conditions are related to the dynamics of all component processes in the WNV transmission circle. First of all, temperature, humidity, and surface moisture are key conditions for mosquito reproduction. Mosquitoes are not be able to produce eggs if the temperature is low or the soil moisture is zero. The larvae and pupae must grow in water as well. Conversely, mosquitoes may have an advantage when soil moisture is relatively low. Although the mosquitoes may face some degree of adversity as moisture decreases, it has been established that paradoxically, relative to their predators and hosts, they suffer less when soil moisture decreases (Marra et al. 2004). The humidity and surface moisture are, in turn, directly related to temperature and precipitation. The soil type, slope, and aspect of a specific geographic location are all factors affecting the surface moisture and availability of water for larvae and pupae to develop. In addition, the mosquito biting rate is also a function of temperature and weather conditions, because these conditions affect the outdoor activities of human beings. It is unlikely that people will stay outside when it is raining or very hot, thus their likelihood of being bitten is reduced. Figure 2 illustrates the interactions among the different agents and dynamics processes in the WNV transmission circle.

AGENT-BASED MODEL FOR EVALUATING WEST NILE VIRUS DYNAMICS

Argonne National Laboratory is using an ABM approach to simulate the spread of WNV. ABMs are tools that can simulate the behaviors of individual entities within a complex adaptive system (Kohler et al. 2000; Woolridge 2002; Ferber 1999). In an ABM, an agent, representing an individual entity, behaves in a specific location by following a set of simple rules and with a limited knowledge of neighboring areas. The key difference between the ABM method and traditional statistical simulation methods is that the ABM method does not attempt to predict what will happen during the evolution of natural phenomena. Rather, it mimics the behaviors of the individual participants in the system to simulate the evolution of a natural phenomenon. The intrinsic characteristics and emergent behavior of the system can then be observed through simulation. Hence, this technique is well-suited for simulating the spread of diseases, in which there is no central control of the process. In the case of epidemic diseases such as WNV, all of the participating entities act as autonomous agents.

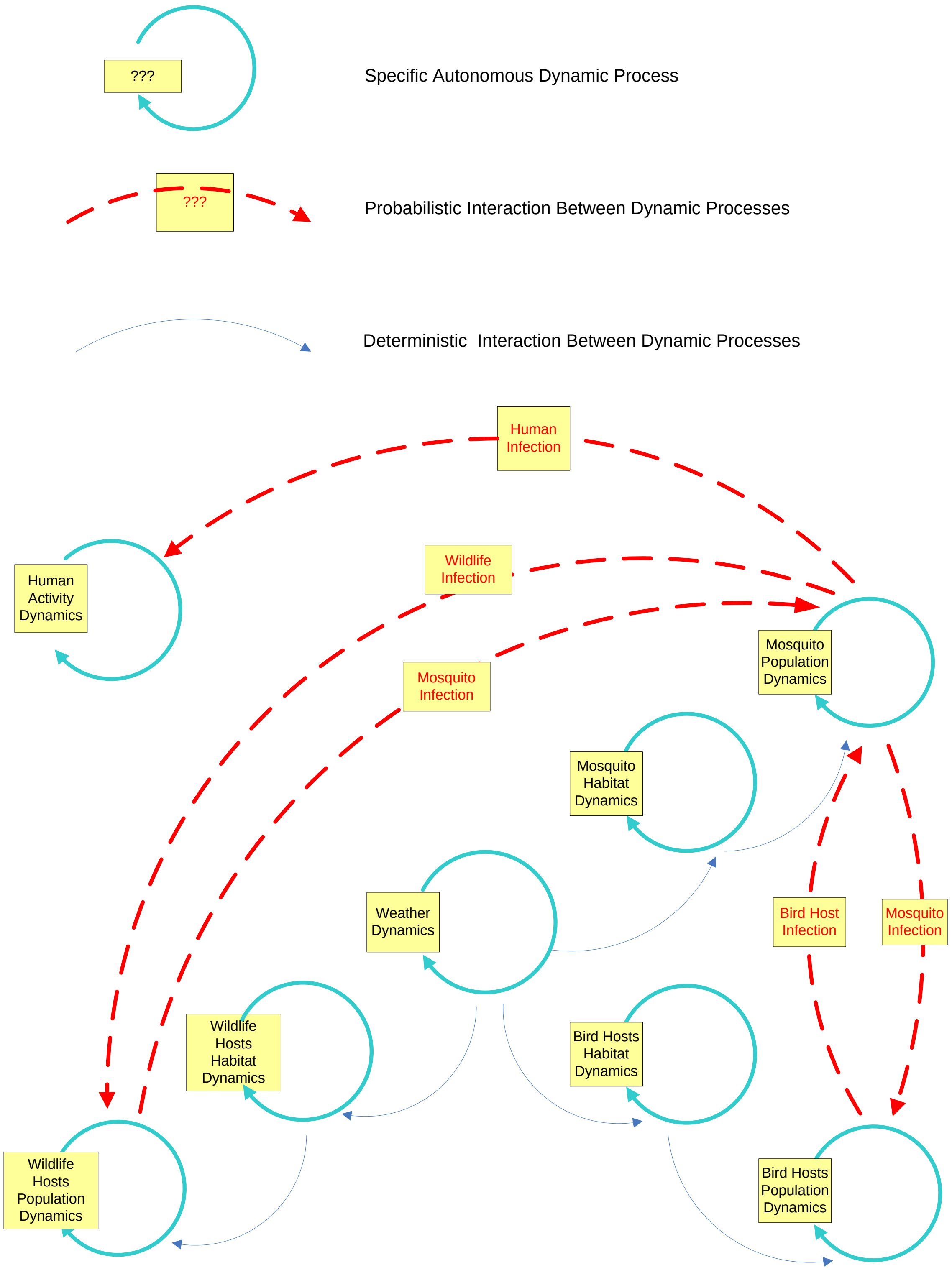

FIGURE 2 Interactions among different agents and dynamics processes in the WNV transmission circle

The ABM being developed simulates the transmission of WNV by using agents to represent mosquitoes, avian hosts, mammalian hosts, and humans. The activities and interactions of these various individual agents are simulated within a specified geographic area. A raster map is used to represent the area as a regular array of cells, which are linked to agent-specific and environmental data, such as habitat suitability values, weather conditions, vegetation cover, and other parameters. Habitat suitability values represent the suitability of specific locations (individual raster cells) for foraging and nesting by mosquitoes, birds, and mammals. A land use map is used to identify the areas where humans are likely to be at risk of being bitten by infected mosquitoes. The simulation also incorporates a weather model, which provides data on the temperature, precipitation, humidity, and surface moisture for each raster cell at each time-step. These meteorological parameters influence habitat quality for the mosquito and various host agents, as well the distribution and activities of human agents within each raster cell. The use of ecological conditions and climate parameters makes it possible to study the combined impact of weather and ecological conditions on mosquito reproduction and host population dynamics.

The ABM for simulation of WNV transmission is developed by using the Repast ABM development platform (Repast 3 undated). The geographic area of the model is an area of about 64 square miles centered on Oak Lawn Township in Cook County, Illinois. This area was chosen for the model because there is an ongoing field survey program for WNV transmission in this area. This field study is being carried out by the Spatial Epidemiology Laboratory at the College of Veterinary Medicine, University of Illinois at Urbana-Champaign, with the support of the Illinois Department of Public Health. Use of this same area for development of the WNV ABM will greatly aid in establishing quantitative relationships between different agents and the various ecological, environmental, and human behavioral parameters.

The WNV model will incorporate a geographic information system (GIS)-based visualization module for displaying the simulation results, including the distribution of infected and uninfected human populations, host populations, and mosquito populations, and the direction and rate that WNV is spreading within the 64-square-mile area at a 1-acre resolution. At this resolution, the model considers 40,600 1-acre raster cells. The selection of this resolution is a trade-off between model accuracy and computer resource availability.

Habitat conditions within each raster cell are used to estimate distributions for selected host species, while home range information for each species will be used to develop movement rules that will determine the movement of individual host agents within the modeled geographic area. Mosquitoes, host agents, and human agents in a given cell will be selected randomly for interactions. The WNV ABM will not predict what is going to happen; rather, it will simulate the self-centered processes that occur in the natural environment (under various environmental and ecological conditions) so that the characteristics that affect WNV transmission processes can be evaluated.

Note that the framework of the WNV model may also be applicable for modeling the transmission of other epidemic diseases, such as SARS, avian influenza, and malaria. Such ABMs for infectious diseases may allow researchers to better explore the conditions under which an epidemic might occur.

MODEL COMPONENTS

The WNV transmission cycle includes several interrelated complex dynamic processes, including weather dynamics, mosquito population dynamics, host agent population dynamics, mosquito habitat quality dynamics, host agent habitat dynamics, and human activities. Among these processes, weather plays a critical role because it affects all other processes, both directly and indirectly. The ABM of WNV transmission must capture these dynamic processes and put them in context. On the basis of the literature on emerging infectious diseases, mosquito entomology, and veterinary epidemiology (Hayse et al. 2005; Bernard et al. 2001; Lanciotti et al. 1999; Ruiz et al. 2004), the quantitative relationships among the different agents and processes can be defined with a flowchart, as illustrated in Figure 3.

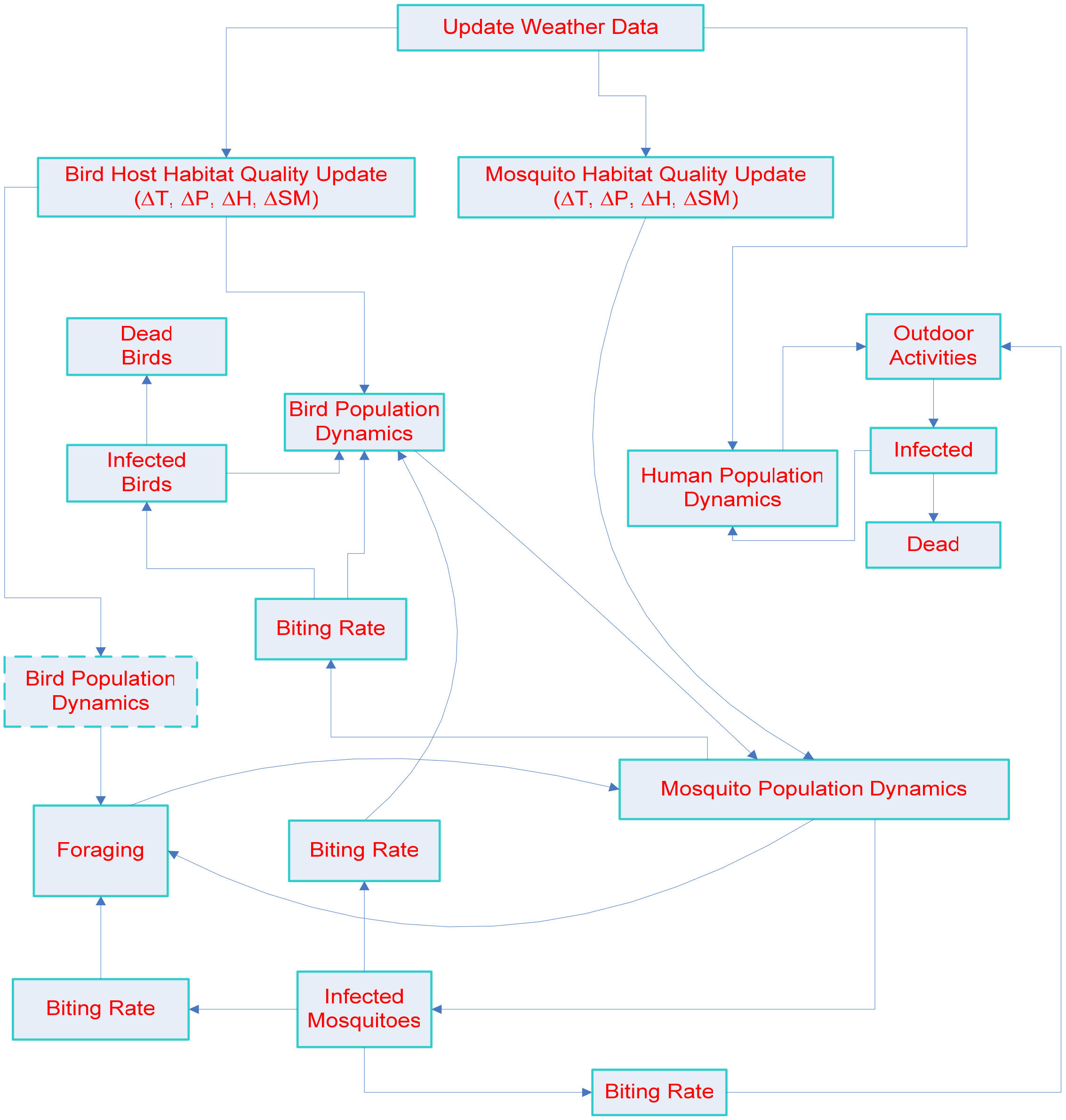

FIGURE 3 Agent-based WNV model

Mosquito Agent and Population Dynamics Model

The mosquito agent is the vector of WNV transmission. Female mosquitoes must take blood meals to develop eggs. Therefore, female mosquitoes will start to hunt for blood when they are ready to produce eggs. Female mosquitoes will take blood from a wide range of animals, including wildlife, domestic livestock, and humans. Mosquitoes may become infected with WNV when they bite infected animals, and animals and humans may become infected after they are bitten by infected mosquitoes. Infected animals may also act as reservoirs and amplifiers of the virus, because WNV can reproduce in many species. The probability of an animal being bitten by an infected mosquito depends largely on the mosquito population where the animal is located and the percentage of that mosquito population that is infected with the virus. While other factors, such as time of day, season, proximity, and the host's blood type, also play a role in the susceptibility of an animal to becoming infected, the model will use the simplified assumption that the likelihood of an animal becoming infected is based primarily on the mosquito population.

Mosquito population growth is a dynamic quantity that depends on the reproduction and death of the mosquitoes. The change in mosquito population can be defined by using the following differential equation:

$$dP(t)/dt = P(t) * (R - D) \ , \tag{1}$$

where P, R, and D are mosquito population density, mosquito reproduction rate, and mosquito death rate, respectively.

Mosquito reproduction and death rates are functions of weather conditions, especially temperature *(T)*, humidity *(H)*, and soil surface moisture *(SM)*. The soil moisture, in turn, is related to temperature, precipitation *(Pr)*, soil type, and the topographic characteristics of the study area, such as slope, aspect, and elevation. Mosquito reproduction depends also on the mosquito population density and habitat quality. Thus, Equation 1 can be expressed more explicitly as:

$$dP(t)/dt = P(t) * \{R[T(t), H(t), Pr(t), SM(t)] - D[T(t)]\} \ . \tag{2}$$

The solution to this differential equation can be obtained as:

$$P(t) = P_0 * \exp\{\int_0^t R[T(t), H(t), Pr(t), SM(t)] - D[T(t)]dt\} \ , \tag{3}$$

where P_0 denotes the initial mosquito population at a specific location. In the spring and summer, as the weather conditions and habitat quality favor mosquitoes, the mosquito reproduction rate increases and its death rate decreases. In the late fall and early winter, the reproduction rate can decrease and the death rate can increase sharply as a result of the sudden reduction of mosquitoes caused by frost. Some mosquitoes may survive over winter, but they are inactive and do not feed and are thus not capable of transmitting the virus during this time.

Host Agent Model

The hosts in the WNV transmission model are agents that maintain, amplify, and spread the virus across geographic locations. More than 100 species have been reported to be capable of serving as host species, including reptiles, birds, and mammals (CDC undated). The initial WNV ABM includes only three host species: black-capped chickadee, blue jay, and American crow. Additional host species will be included in future versions of the model.

The bird host model simulates bird reproduction, foraging, and interaction with mosquito agents. The user specifies a growth rate that does not consider impacts from WNV on the population. In general, bird reproduction is a function of the quality of the habitat in the surrounding area. The ABM assumes that bird reproduction is constant over the bird's reproduction period (i.e., from spring to early summer). Thus, the bird population can be defined as:

$$P(t+\Delta t) = P(t) * (1+r) * \Delta t \quad , \tag{4}$$

where *P, r,* and *t* are population, reproduction rate, and time, respectively.

Within the bird host model, each bird is given a home location within the area from which all subsequent movements will occur. During daytime, birds leave their home locations to forage for food in the morning and return home at dusk. The model assigns a probability for the bird to travel from cell to cell while searching for food. Following the initial movement of the bird to another cell, the likelihood that the bird will move to another cell at the next time-step is a function of the habitat quality of that cell. The bird has a higher probability of continuing to move if the occupied cell has a low habitat quality. In other words, a bird is less likely to move from its present location to another location if it would experience a decrease in habitat quality. The distance the bird travels in each time-step is determined by the home range of the species multiplied by a movement factor that ranges from 0 to 1. The value of the movement factor is randomly selected for each time-step. For a simulation, the model centers a circular home range (the area to which an animal confines its normal activities) on a specific raster cell and then multiplies the radius of that home range by the movement factor. Thus, a movement factor of one results in the greatest distance traveled during the time-step. No bird is allowed to move outside its home range at any time. If a bird goes across the boundary of the area, a similar bird will enter the area from a randomly selected cell from among the boundary cells. The foraging movement of a bird is determined by the following equations:

$$X_{new} = X_{current} + R * \cos(\theta), \tag{5}$$

$$Y_{new} = Y_{current} + R * \sin(\theta) \text{ , and} \tag{6}$$

$$\theta = \pi * \alpha / 180 \quad , \tag{7}$$

where R is a random distance between zero and the radius of the maximum home range of the bird, α is a randomly selected angle between 0° and 180°, $X_{current}$ and $Y_{current}$ are the X and Y coordinates of the cell in which the bird is currently located, and X_{new} and Y_{new} are the X and Y coordinates of the cell to which the bird is moving. Figure 4 illustrates the movement of three hypothetical birds in a day in the study area.

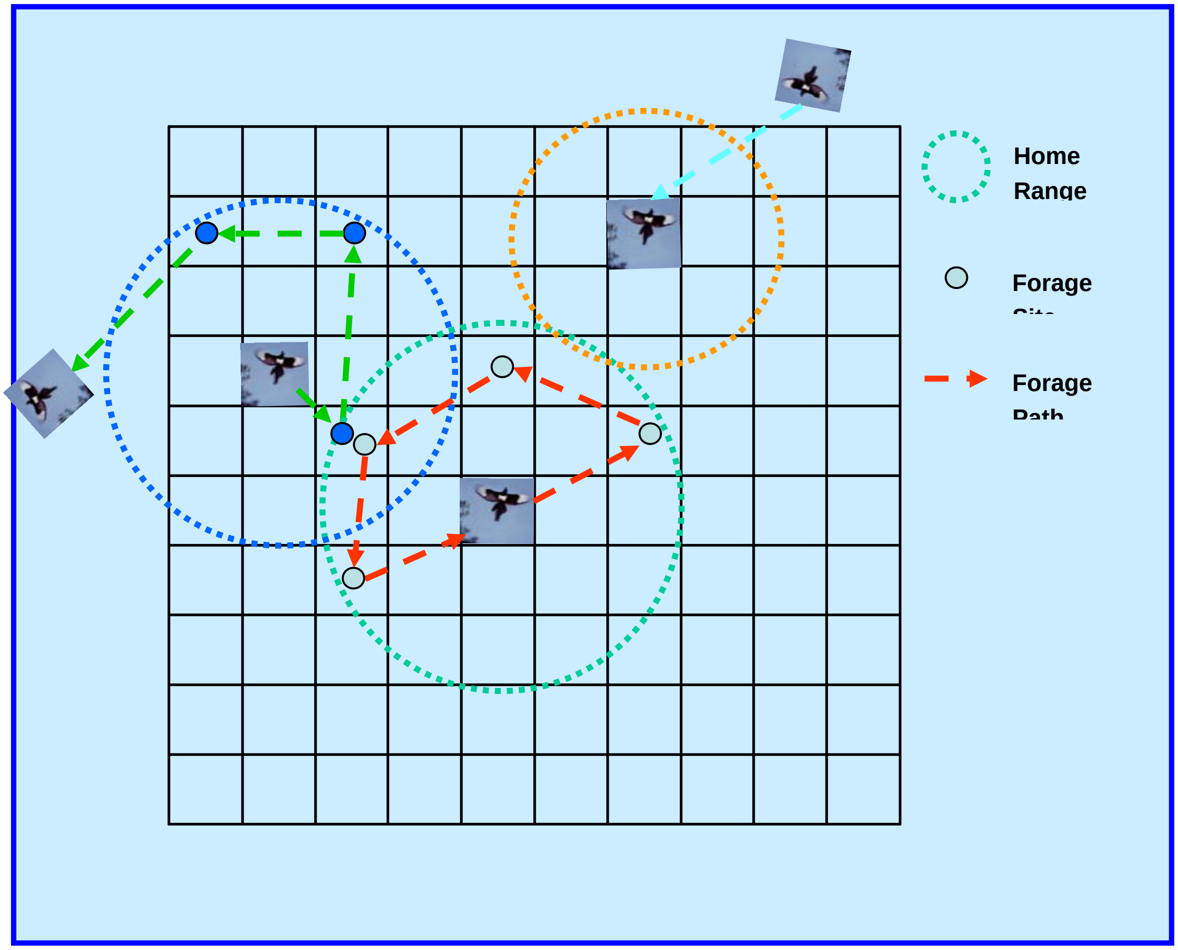

FIGURE 4 Schematic illustration of bird foraging movement

Human Agent

Humans may become infected with WNV when they are bitten by infected mosquitoes. About 6% of infected people will develop symptoms, and a small fraction of these individuals will die as a result of the infection (Hayse et al. 2005). The number of people who will become infected in cell NP_{inf} is estimated as:

$$NP_{inf} = P \times IR_p \times \frac{P_{m,inf}}{P_m} \times BR \ , \tag{8}$$

where P is the human population (density) in a cell, IR_p is the human infection rate, $P_{m,inf}$ is the population of infected mosquitoes in the cell, P_m is the total population of mosquitoes in the cell, and BR is the biting rate of mosquitoes.

The number of human deaths, NP_d, caused by WNV infection can be calculated as:

$$NP_d = NP_{inf} \times DR \, , \tag{9}$$

where *DR* is the death rate due to WNV infection.

The differences in the likelihood of becoming infected reflect differences in the time spent outdoors among the age groups and in the likelihood that individuals in each group will be outside during periods of greatest mosquito activity. Table 1 shows the age ranges of the different age groups used in the model.

In addition, the potential for a human to become infected and, if infected, to die is also a function of age (Hayse et al. 2005). In consideration of these facts, the model uses a different likelihood of infection and death. The infection and death rates for these age groups are calculated from the data published by Hayse et al. (2005).

It is also important to note that the probability for a person to be bitten by infected mosquitoes is extremely small while the person stays in the house. Therefore, we assume that people get mosquito bites only when they are participating in outdoor activities. For this reason, the model tracks the number of people and the time these people participate in outdoor activities.

Land Use

The distribution of agents, hosts, and habitats is a function of the land use in the area of interest. The 64-square-mile area encompassed by the WNV ABM consists of a heterogeneous mixture of 63 land-use types, including residential, commercial, industrial, agricultural, open space, wetlands, and water. Each raster cell may have a single land use or multiple land uses, depending on the location of the cell. The types of land uses within each raster cell are used to determine habitat quality for mosquitoes and birds, human population density, and the likelihood of human outdoor activity.

TABLE 1 Age groups and likelihoods of participating in outdoor activities

Group	Age	Likelihood of Participating in Outdoor Activities
1	0–1	These infants are very unlikely to participate in outdoor activities at the high mosquito blood-meal times, during dawn and dusk.
2	2–15	These children are often outdoors, especially in the afternoons/evenings when transmission is most likely.
3	16–54	People in this group in general spend most of their time in schools or offices and have stronger immune capability. They will hence have a lower probability of getting infected, assuming all people are at the same healthy condition.
4	55 and older	Seniors who do not need to go to work are more likely to participate in outdoor activities.

Mosquito and Bird Habitat Quality

Habitat quality plays an important role in the abundance and distribution of mosquitoes and birds; thus, it is an important parameter that governs the population dynamics of both of these biota. Each raster cell in the model is assigned a habitat quality value that may range from 1 (poor) to 3 (excellent) on the basis of the land use categories present within each raster cell.

The mosquito and the habitat quality values represent the perceived ability of the habitat to support high mosquito densities and are also used to set initial mosquito densities. The values are determined on the basis of land use. Each of the land-use categories identified for the study area is assigned a mosquito habitat quality value of 1 (poor), 2 (good), or 3 (excellent). Land-use categories (such as industrial or commercial) with little or no vegetative cover or surface water are assigned a mosquito habitat quality value of 1 (poor). Alternately, an open space land use (such as a forest preserve or wetland) is assigned a habitat quality value of 3 (excellent). In the model, the land use within each raster cell is identified, and the appropriate habitat quality value is assigned to that cell. For cells encompassing multiple land-use categories, the habitat quality value of a cell is calculated as the weighted mean of the land-use categories within the cell. A higher habitat quality rating indicates that the cell can support a higher mosquito density and reproductive rate and that it also exhibit a higher mosquito biting rate than can/does a cell with a lower habitat quality value.

Bird habitat quality values are determined in a manner similar to that used to characterize mosquito habitat quality. The habitat quality in each raster cell is then used to set the initial distribution and abundance of the bird hosts and to influence the movements of birds. At the start of a simulation, cells with higher habitat quality are assigned higher starting bird densities than cells with lower habitat quality. Bird habitat quality is then used to characterize the likelihood for a bird to move from one cell to another in the next time-step. If the habitat quality of the occupied cell is low, the likelihood that the bird in that cell will move to another cell is high, while if the habitat quality is high, the likelihood that the bird will move is low.

Human Population Density and Probability of Outdoor Activity

The likelihood of a human becoming infected with WNV is a function of the likelihood of a human being present in an area of mosquito abundance and the amount of time an individual would spend outdoors at that location, and both of these conditions are a direct function of land use. Each land-use category present in the study area is assigned a human population density value of 1 (low), 2 (intermediate), or 3 (high). For example, open spaces have a low population density (1), while a commercial shopping mall or office building may have a high density (3). Each land-use category is also assigned a value for its likelihood of outdoor human activity of 1 (low), 2 (intermediate), or 3 (high). For example, on land used for commercial or industrial purposes, most human activity would occur indoors, so the likelihood of outdoor activity is low (1). In contrast, most if not all human activity on a forest preserve or a golf course would occur outdoors; thus, the likelihood of outdoor activity in these areas is high (3). For cells encompassing multiple land-use categories, population density and the likelihood of outdoor activity are estimated as a weighted mean of the land-use-specific population density or outdoor activity likelihood values present within the cell.

Weather Dynamics

Weather is a critical component of the transmission of WNV. It affects all of the agents involved in the model, either directly or indirectly, and is especially important with regard to its effect on mosquito population dynamics and activity. The most important attributes of the weather data include:

1. Temperature,
2. Precipitation, and
3. Humidity.

These three attributes are spatially distributed and temporally variable, and they directly influence surface soil moisture, which is especially important in mosquito population dynamics. The WNV ABM uses real weather data for the study area for modeling mosquito population growth (see Equation 3).

When historic weather data are used, simulations may be conducted under three different precipitation regimes:

1. Dry (lower precipitation in 30% of years),
2. Wet (higher precipitation in 30% of years), and
3. Normal (middle-level precipitation in 40% of years).

The model includes several years of weather data for each precipitation regime. When a precipitation regime is selected for use in a simulation, the model randomly selects a year from the selected regime and uses the observed hourly weather data from that year for modeling mosquito population dynamics. In this way, the model incorporates actual yearly weather patterns to avoid using another model for generating weather data.

SUMMARY AND FUTURE RESEARCH

An ABM for simulating the dynamics of WNV transmission has been developed by using the Repast ABM development environment. The model simulates the distributions, behaviors, and population dynamics of mosquitoes and birds, and it simulates the interactions among these organisms and humans in a spatial and temporal manner.

It is important to point out that the current simulation is not a predictive model. It is a tool for researchers to use as a virtual laboratory to uncover the dynamic behaviors of the system as a result of the interactions among individual agents in the system. The accuracy and usefulness of the model depend heavily on the quantitative definitions of the behaviors of, and interactions among, the individual agents in the model. For an ABM of this type, extensive field research data are needed in order to calibrate it. Using these kinds of data for calibration is an important next step for this research.

The current implementation of the model includes only three types of representative birds as the hosts. In the next phase of our research, we will expand the model to allow for multiple host species, such as mammals and reptiles, as well as multiple species for both mosquitoes and hosts.

ACKNOWLEDGMENT

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