SYFAM (Sylvatic Yellow Fever Agent-based Model)

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ODD PROTOCOL

1. Model overview

Purpose and patterns. The model aims to simulate the transmission dynamics of the yellow fever virus (YFV) after its introduction into a forest fragment where populations of the vector mosquito, howler monkeys, and other vertebrate animals inhabit. The purpose of the model is to answer the following question: which conditions (parameters) have a greater influence on the virus prevalence in the mosquito population, the mortality of the howler monkeys, and the virus persistence in the environment?

The following patterns observed empirically are used as criteria for the usefulness of the model: 1) once inserted in the environment and under suitable conditions, the virus must spread between vectors and hosts, reducing the population of howler monkeys; 2) The model must reproduce similar patterns found in mosquito populations (e.g., parity, longevity, infection rate, seasonal changes in abundance and larval development time).

Entities, state variables, and scales. The model consists of four entities: mosquitoes, monkeys, other-hosts, and patches. The 'mosquitoes' represent female individuals of the genus *Haemagogus*, the main vectors of YFV in Brazil. The 'monkeys' represent howler monkeys (genus *Alouatta*), whose populations show high lethality during YFV epizootic outbreaks (Mares-Guia et al., 2020). In turn, 'other-hosts' represent species of terrestrial vertebrates whose populations inhabit the forest fragment. The other-hosts agents can assume two different holes when in contact with the virus: 1) individuals are dead-end hosts, which means they are not able to replicate the vírus at sufficient levels in the bloodstream to transmit it again to mosquitoes; or 2) individuals are alternative hosts able to replicate the virus and transmit it to vector mosquitoes. Finally, the model distinguished the patches as 'forest' or 'breeding sites'. The virus circulation is represented by different state variables of the vertebrate hosts and mosquitoes: susceptible, exposed, infectious, and immune.

The agents that represent mosquitoes can assume four state variables: 'newly emerged', 'blood-seeking', 'engorged', and 'gravid'. As for the condition of mosquitoes concerning the virus, they can be 'susceptible', 'exposed' (the individual has been infected but is not yet able to transmit the virus to another host), or 'infectious' (when the individual can already transmit the virus to a susceptible host it feeds on). Each mosquito also has quantitative state variables to indicate the number of oviposition events it has performed, amount of blood ingested, and blood digestion time. In addition, parameters that define biting success, daily survival rate, and detection radius of hosts and breeding sites are set to the population.

Five groups of six individuals representing monkeys are allocated in the grid, and each group moves through a limited territory. Each individual has a number that relates him to the group it belongs to, a list containing the patches that represent the group's territory (a radius of 18 patches around a central patch), and the status of each monkey in the group, alpha or subordinate. The alpha individuals define the direction towards which the group will move and whether or not any movement will be performed at each time step. Concerning the status for YFV, each individual in the group may be 'susceptible', 'exposed', 'infectious', or 'immune'.

The other-hosts have a state variable that defines the individual as a dead-end host or alternative host. Individuals can be 'susceptible', 'exposed', 'infectious', or 'immune' by acting as alternative hosts. It is possible to set the average lifespan for the populations. Mortality due to YFV infection is considered null.

Except for dead-end hosts, all agents have parameters that define the virus latency period and transmission competence. In addition, monkeys and alternative hosts have parameters that define the viremic period of the individuals when in an infectious state, while mosquito individuals once infectious remain in this state.

Patches of the type 'forest' have no state variables other than their location on the grid, while 'breeding site' patches represent places in the forest where mosquitoes in the state 'gravid' can lay their eggs. The breeding site patches have lists that indicate if there were and how many eggs were laid in the patch, the time elapsed since each oviposition event, and if an infectious mosquito performed given oviposition. There is also a mechanism that controls larval density so that when the patch receives a high number of eggs, larval mortality also increases (see submodels section).

Each time step of the model represents one hour of the day. For modeling purposes, the day lasts 10 hours (10 time-steps), representing the diurnal activity of howler monkeys and *Haemagogus* mosquitoes since both have daytime behavior and usually rest in the nighttime. The grid consists of 101 x 101 patches with a bounded space, simulating an isolated forest fragment with approximately 102 hectares. Each patch represents an area of $100m^2$, and the linear distance between the center of two adjacent patches represents 10m.

Process overview and scheduling. The model has two main processes: 1) *the mosquito population dynamics* consisting of the gonotrophic cycle, larval development, and control of mosquito abundance and larval density; 2) *the virus transmission dynamics* consisting of vector-host interaction, incubation period in vector and hosts, and recovery or death of hosts. Table 1 shows the order of events performed at each time step.

Table 1. Model actions at each time step according to the order of events, type of variable, and model entity (using the conventional terminology of Netlogo).

Order	Action	Type of variable	Model entity
1	Update the current-*K* parameter	global	observer
2	Update the time elapsed since oviposition and count the number of immatures in the patch	patch	breeding-site patches
3	Check and control larval density at the patch	patch	breeding-site patches
4	Update and check the newly emerged mosquitoes	turtle	mosquitoes with 'newly emerged' status
5	Move monkeys	turtle	monkeys
6	Move other-hosts	turtle	other-hosts
7	Digest the blood meal	turtle	mosquitoes with 'engorged' status
8	Search a host for a blood meal	turtle	mosquitoes with 'blood-seeking' status
9	Search a breeding site to lay eggs	Patch and turtle	breeding-site patches and mosquitoes with 'gravid' status
10	Vector-host interaction	turtle	mosquitoes with 'blood-seeking' status, monkeys, and other-hosts
11	Check extrinsic incubation period	turtle	mosquitoes with 'exposed' status
12	Check incubation period	turtle	monkeys and other-hosts with 'exposed' status
13	Recovery or die	turtle	monkeys with 'infectious' status
14	Check and eliminate mosquito	turtle	mosquitoes

15	Mosquitoes adult emergence	patch and turtle	breeding-site patches and mosquitoes with 'newly-emerged' status
16	Check other-hosts lifespan	turtle	other-hosts
17	Insert infected mosquitoes	turtle	mosquitoes
18	Update the outputs, check stop conditions, and update the time step	global	observer

2. Design concepts

Basic principles. The model explores the idea of pathogen invasion, spread, and persistence between vectors and wild vertebrates. The YFV circulation in Brazil occurs in a sylvatic (or jungle) cycle. The virus is transmitted in the forests among sylvatic mosquitoes and non-human primates and can infect humans who live close to or enter the areas where the virus circulates (Monath and Vasconcelos, 2015; Possas et al., 2018). Transmission of the virus occurs when an infected mosquito (a female individual) feeds on the blood of a susceptible vertebrate host or, conversely, when a susceptible mosquito becomes infected by feeding on the blood of an infectious host. The blood that the mosquitoes ingest from the host assists in developing the eggs, which are deposited in aquatic larval habitats found by the females a few days after the blood meal. In turn, the eggs hatch and release the larvae that will develop in this aquatic environment and become new adult individuals in few weeks. These newly emerged adults will allow the virus to remain circulating if already infected (via vertical transmission from the gravid female to its progeny) or if they feed on the blood of infectious hosts.

By simulating the above-depicted processes, the present model reproduces the basic conditions for epizootics of YFV in a forest fragment to investigate ecological determinants that influence the magnitude of these events. As in classical epidemiological models, individuals are classified as susceptible, exposed, infectious, and recovered or immune (SEIR).

Emergence. The characteristics, behaviors, and interactions between the different entities in the model allow visualization of how the virus, after the invasion, circulates between different hosts, causes the death of monkeys, and sustains itself in a fragment of forest over time. In addition, the population dynamics of the vector is also an emerging process driven by the search for a source of blood meal, the search for breeding sites for oviposition, larval development, and the emergence of new adult mosquitoes.

Adaptation. Mosquitoes have adaptive traits concerning the direction and intensity of movement, which will vary in response to the stage of the individuals' gonotrophic cycle. For example, mosquitoes looking for a blood meal move randomly, but after detecting a host, they start to move in a targeted manner. The same occurs with gravid mosquitoes in search of oviposition sites. The time elapsed from oviposition to the emergence of the adult also simulates an adaptive process since it depends on the environmental conditions, controlled by the parameter *current-K*. This mechanism allows in unfavorable seasonal periods a prolonged time from oviposition to the adult mosquito's emergence.

Monkeys move in predefined groups, following the movement of an alpha individual. If the alpha dies, a new alpha is selected randomly among members of the group, and the other members start to follow its movement.

Objectives. The only entity in the model that has an objective is the mosquito population. The behavior of individuals seeks to maximize reproductive success with the search for sources of blood meal and breeding sites for oviposition. Mating was not explicitly modeled because we understand that this process would have little or no influence on the model outputs.

Sensing. Mosquitoes sense the presence of hosts and breeding sites in the vicinity and direct their movements towards them. Once reaching the hosts, mosquitoes in search of blood try to perform the blood meal. Gravid mosquitoes on a breeding site patch lay their eggs. Monkeys are sensitive to the area belonging to their group's territory; if the individual exceeds the limits of its territory, the individual makes a return movement. Subordinate individuals in the group can also perceive the alpha individual's movement and thus direct their movements to keep the group less dispersed. The breeding site patches sense the environmental conditions that determine whether newly adult mosquitoes can emerge (parameter *current-K*), thus controlling the total abundance of mosquitoes in the environment.

Interaction. The contact between mosquitoes and howler monkeys or other vertebrate hosts in the environment is simulated by interactions that represent mosquito blood meals. These interactions allow both the development of eggs and the circulation of the virus in the environment. In addition, mosquitoes interact with the breeding site patches available in the environment by laying their eggs, and breeding site patches interact with the environment allowing the control of mosquito abundance. Finally, an indirect interaction between mosquitoes is also assumed, based on an intra-specific competition for resources, which occurs through a density-dependent control mechanism in breeding-site patches.

Stochasticity. Several processes in the model represent the natural variability of the events. One of the main stochastic events present in the model is the movement of agents, assumed to be random most of the time.

Other stochastic events present in the model are: 1) the random initial allocation of mosquitoes, other-hosts, and breeding site patches in the grid; 2) a female with the status blood-seeking when detecting more than one host at the same time will randomly select one of them to interact with; 3) the introduction of the virus into the environment occurs after a random selection of some mosquitoes, changing their status from susceptible to infectious.

Some of the modeled stochastic processes depend on numbers generated from a uniform random distribution between 0 and 1, that when below or above a specific input parameter or a reference value, determines which event will occur, examples are: 1) if the mosquito will or not die; 2) whether or not there will be an interaction between a given blood-seeking mosquito and a selected vertebrate host; 3) the amount of blood ingested by a mosquito during the interaction with the host; 4) whether or not the virus will be transmitted through an interaction between a susceptible and an infectious agent; 5) whether the breeding site patch will eliminate one or more immature individuals in a given time step; 6) whether a monkey with infectious status will die or become immune to the virus after the viremic period; 7) if a newly emerged mosquito from a progeny of an infected female will have the status 'infectious' or 'susceptible'.

When asked to eliminate an immature, the breeding site patch chooses the individual based on a number generated by uniform random distribution, the range of possible values defined according to the number of immatures in the patch.

Finally, the lifespans of alternative and dead-end hosts are randomly assigned according to a mean value of a Poisson distribution (the user defines the value).

Collectives. The only collectives simulated in the model are the monkey groups (representing howler monkeys). Each group has its territory and an alpha individual that determines the group's movement on the territory. The model does not assume other social and behavioral processes in the groups of howler monkeys.

Observation. The display in the NetLogo interface allows the view of agents' movements, interactions, and status changes. Different shapes and colors allow identifying the model entities and the status changes related to virus transmission.

The following outputs were observed for model parameterization: 1) average and maximum survival time in the mosquito population, 2) temporal variation in the proportion of parous and nulliparous mosquitoes, 3) temporal variation in the abundance of mosquitoes, 4) average and maximum time elapsed from oviposition to the emergence of adult mosquitoes.

To sensitivity analyses of important input parameters, the model behavior was observed by the following outputs: 1) the maximum proportion of infected mosquitoes, 2) the proportion of dead monkeys, and 3) the number of days YFV persists in the environment.

3. Details

Initialization. For model initialization, five groups of monkeys with six individuals each and a defined initial number of dead-end hosts, alternative hosts, and mosquitoes are inserted in the grid. Since the maximum supported abundance of mosquitoes in a given environment also depends on the availability of breeding sites, the model was balanced so that the number of breeding site patches depends on the initial number of mosquitos, being one breeding site patch inserted for every twelve mosquitoes. The mosquitoes and other-hosts are randomly allocated in the grid, while monkey groups start in the center of their territories. The breeding-site patches start the simulation contained between zero and 89 immatures. The development time for each immature is also selected at random (between 1 and 150 time-steps). All mobile agents start the simulation in the susceptible status for YFV.

Mosquitoes initialize with the following state variables: 1) number of ovipositions performed = 0; 2) amount of blood ingested = 0; 3) blood digestion time = -1 (this value is changed to 0 immediately after obtaining the blood meal); 4) the biting success for each interaction with a host = 0.5. The mosquito parameters daily-survival-rate = 0.93 and host-and-breeding-site-detection-radius = 4 were parameterized using sensitivity tests. The same proportion of mosquitoes (25%) are initially set to each of the four states of the gonotrophic cycle. Based on this configuration, the mosquito population dynamics tend to last around 150 time-steps to stabilize.

For the agents representing the monkeys, the initialization comprises creating an individual allocated in the center of their territory. This individual receives 'alpha' status and immediately generates five other individuals who will receive 'subordinate' status. All individuals also have state variables that define their group and the patches that comprise their territory.

For other-host individuals, remaining lifetimes ranging from 0 to the parameter that defines the average lifespan of the population are assigned to each individual. For example, if the average lifespan of other-hosts is set to 1000 days, each initial individual will be assigned a random value between 0 and 1000 that will define their remaining lifetime.

Input data. The model does not use input data to represent time-varying processes or spatial configurations.

Submodels. The actions performed each time step and their empirical and theoretical bases are described below.

1) *Update the current-K parameter***.** The abundance of mosquitoes, including those of the genus *Haemagogus,* is influenced by seasonal variations in rainfall, temperature, and relative humidity (Marcondes and Alencar, 2010; Ribeiro et al., 2012; Couto-Lima et al., 2020). For example, Chadee et al. (1992) observed that the abundance of *H. janthinomys* was up to six times greater in rainy periods when compared to dry periods in Trinidad. To simulate the effect of seasonal variations on the mosquito populations, the proposed model uses a parameter that controls the carrying capacity in the environment, here called 'current-*K*'. The current-*K* has two functions: 1) simulate the effect of seasonal variations in the abundance of mosquitoes during a year (that last 3,650-time steps); 2) controlling the emergence of new adult mosquitoes in the grid, as the breeding-site patches access its information.

The *current-K* is updated at each time step by the following equation:

$$\textit{current-K} = \alpha + \beta \sin\left(2\pi t\left(\frac{180}{\pi}\right)\right) + \gamma \cos\left(2\pi t\left(\frac{180}{\pi}\right)\right)$$

Where,

α = (*k-max* + *k-min*) / 2

k-max = initial number of mosquitoes

k-min = *k-max* / 6

β = - (*k-max* - *k-min*) / (3650 / 2)

γ = α – *k-max*

t = 0.5 + (time / 3650)

2) *Update the time elapsed since oviposition and count the number of immatures in the patch.* Each breeding-site patch contains a list called 'larval development time' that records the number of immatures at the site and updates the development time for each individual. For each 'egg' laid in the patch, a new item of value 0 is added to the beginning of the list. Each new time step adds a unit to all items in the list.

3) *Check and control oviposition density at the patch*. Each breeding site patch in the model represents an area of 100 m² with larval habitats for mosquitoes (*Haemagogus* mosquitoes usually lay their eggs in tree holes and bamboo internodes). At each time step, the breeding site patch checks the total number of larval individuals it has and, according to a probability *P*, which increases with the larval density, it can select and eliminate one or more individuals at random. This mechanism aims to simulate a density-dependent intraspecific competition (Walker et al., 1991).

The parameter *P* follows a logistic distribution (Figure S2) and is obtained by assigning the following values: $sv_1 = 0.99$, $sv_2 = 0.5$, $lv_1 = 15$ and $lv_2 = 90$. Where *sv* is the survival probability and *lv* is the number of larvae in the patch. The parameter *P* is calculated as follows:

$D = ln\ (sv_1 / (1- sv_1))$

$C = ln\ (sv_2 / (1- sv_2))$

$B = (D – C) / (lv_1 – lv_2)$

$A = D – B * lv_1$

$Z = exp\ (A + B * lv)$

$P = Z / (1+Z)$

When fifteen or fewer immatures (lv_1) are in the same patch, each individual's survival probability is above 99% (sv_1). It was then sought to parameterize a value for the density of immatures in which the probability of survival becomes 50% (sv_2). The average time taken from oviposition to adult emergence was used to fit this parameter so that the average time should be short in favorable seasonal periods and relatively long in unfavorable seasonal periods. For this purpose, values of 60, 90, and 120 immatures were tested, adjusting these to a 50% probability of survival. It was then opted to select 90 immatures (Lv_2) since this value allowed for a plausible pattern in the average times for adult emergence, accounting for ~20 days in favorable periods (at maximum *current-K*) and ~60 days in unfavorable periods (at minimum *current-K*). For *Haemagogus* and other Aedini mosquitoes, it is expected that in colder, less rainy periods, the time until the adult emergence exceeds months since the eggs are resistant to desiccation and can diapause for periods of up to one year (Marcondes and Alencar, 2010).

4) *Update and check the newly emerged mosquitoes*. The time elapsed since the emergence of the new adult individual is updated. After ten time steps, the status of the individual is changed from newly-emerged to blood-seeking. As soon as a new adult emerges, the individual is kept immobile in the same patch it emerged until its status changes. This action simulates the time it takes to exoskeleton hardens and the copulation of newly emerged females (Forattini, 2002).

5) *Move monkeys*. Firstly, it is checked whether there is an alpha individual in the group; if not, another individual among the group members is randomly chosen to become the alpha. Next, the individuals will check if they are within their group's territory limits, returning to the territory if outside the limits. Then, the alpha individuals of each group move, and the subordinate individuals move next. The alpha chooses a random direction within a 360° radius and can move in a single time step from 0 to 10 patches at random. Subordinate individuals will select a direction that will not vary by more than 10° from the direction selected by the alpha individual and will move the same distance (with a variation of up to 1 patch). This mechanism allows keeping the group less dispersed while moving in their territory. Even in their activity period, howler monkeys do not move much and spend most of their time sleeping or eating (Crockett and Eisenberg, 1987). In this way, the model allows groups of monkeys to move at each time step with a probability of only 20%.

The area of each group's territory is a radius of 18 patches around a central patch so that the territories have an approximately circular shape arranged on the grid so as not to overlap. As the distance between the center of two adjacent patches is considered to be 10 meters, the total area for each monkey group is equivalent to $\pi * 180^2 = 101{,}788\ m^2$, a value close to the average living area for howler monkeys, which is around 10.2 hectares (Bica-Marques et al., 2018).

6) *Move other-hosts*. Each individual randomly selects a direction within a 360 ° radius and moves from 0 to 5 patches. For simplicity, the movement behavior is random, and there is no interaction with other individuals of the same species.

7) *Digest the blood meal*. The time since the mosquitoes in the 'engorged' state obtained blood from the hosts is verified. In the case of having fed more than 50-time steps ago, the individual's status is updated to gravid, starting to move in search of breeding site patches to lay their eggs. If the individual has been fed with blood at 50-time steps or less and has obtained enough blood for the development of the eggs, it will move slowly and randomly in the environment (no more than 0.5 patches per time step). If the individual has not obtained enough blood, he will remain in search of hosts. The time taken between blood digestion and oviposition was selected to represent a period similar to that of the *Haemagogus* gonotrophic cycle (around 5-7 days) (Mondet 1997; Dégallier et al., 1998).

8) *Search a host for a blood meal*. The mosquitoes in the blood-seeking status will search for hosts in their surroundings according to the parameter that controls the host detection radius. If any host is detected, the mosquito will move towards it. The movement of the mosquito towards the host is randomly assigned, varying from 0 to the distance to the host. If the blood-seeking mosquito detects no host, the individual moves random distances of up to one patch per time-step in a radius of 360º.

9) *Search a breeding site to lay eggs*. The mosquitoes in the gravid status will search for a breeding-site patch in their surroundings according to the parameter that controls the breeding-site detection radius. If any breeding site patch is detected, the individual moves toward the patch. If no breeding site patches are detected, the individual keeps moving at random distances of up to 1 patch per time step in a radius of 360º. When the individual is on a breeding site patch, the oviposition is immediately performed. After that, the individual immediately changes its status from gravid to blood-seeking, and the number of oviposition events the individual has performed is updated. In turn, the patch that received the oviposition updates its two lists; the first includes information about each immature individual's development time, and a second list stating whether the individual came from an infectious female or not. Oviposition is interpreted here as the deposition of the entire egg load of a gravid female in a gonotrophic cycle, which is around 15 to 40 eggs for *Haemagogus* (Chadee and Tikasingh, 1989, Mondet 1997). Therefore, assuming that a gravid female lays a mean of 30 eggs in her gonotrophic cycle, half of which will become adult females, for the model purpose, each mosquito lays a mean of 15 eggs at the breeding site, according to a Poisson distribution.

10) *Vector-Host interaction*. Mosquitoes with blood-seeking status detect whether there is any vertebrate host less than five meters (0.5 patches) away (see Breugel et al., 2015); if any host is detected, an interaction can occur. For situations where two or more hosts are detected, the mosquito will select one of them at random. The interaction between a mosquito and a host will only occur if a random value generated between 0 and 1 is less than 0.5, which is the value assumed to the biting success parameter. After the interaction, the mosquito's status changes to engorged, and if it has obtained enough blood, it will stop looking for a blood meal.

When the individual does not obtain enough blood from the host, it remains trying to perform new blood meals until it can obtain the minimum amount of blood necessary for egg development (see Farjana & Tuno, 2013). Once the interaction has occurred, a random number between 0 and 1 is generated; if this number is less than 0.5, the mosquito has not obtained sufficient blood for the development of the eggs and will try to obtain a new blood meal in the same or another host. The value of the following blood meal is added to the value of the previous ones; when it reaches 0.5, the mosquito will be satiated and will no longer be on blood-seeking status. After an interaction between the mosquito and the host, the digestion time of the ingested blood starts to count even if the mosquito has not yet obtained enough blood (in this case, the individual will be simultaneously in engorged and blood-seeking status).

At each interaction, virus transmission between vector and hosts can occur, depending on the status for YFV of each individual and parameters that control the transmission competence of the model entities. For example, if a mosquito with susceptible status interacts with (feeds on the blood of) an infectious monkey or other-host, the mosquito has a probability of becoming infected with the virus and moving to 'exposed' status. In turn, mosquitoes with infectious status can transmit the virus by interacting with susceptible hosts, thereby changing the host's status to exposed.

A random number between 0 and 1 is generated during an infective contact according to a uniform distribution; if the value is lower than the infectious individual's transmission competence parameter, the virus is transmitted.

11) *Check extrinsic incubation period.* The time since the infection of the mosquitoes in the status 'exposed' is checked and updated; as individuals complete the extrinsic incubation period, their status change to infectious. Based on observations obtained in studies with the vector *Aedes aegypti* (Johansson et al., 2010), the extrinsic incubation period for YFV was assumed to be twelve days.

12) *Check incubation period*. The time since the infection of exposed monkeys and alternative hosts is checked and updated. If the individual has reached the latency period of the virus, the status 'exposed' is updated to infectious. A latency period of 3 days is assumed for both monkeys and alternative hosts (Moreno et al., 2015).

13) *Recovery or die*. Once the monkeys entered the viremic period (infectious status), the time elapsed is checked and updated. If the entire period has elapsed, the status is updated according to the probability of death (M_d) of infected individuals. A random number between 0 and 1 is generated from a uniform distribution; if greater than M_d, the individual's status updates from infectious to immune, and if less than M_d, the individual is eliminated from the simulation. The viremic period considered for monkeys was four days (Moreno et al., 2015), and the probability of death for infected monkeys was set to 0.8 (Mason et al., 1973).

14) *Check-and-eliminate-mosquito*. From a uniform random distribution, a number between 0 and 1 is generated for each mosquito. If the number is less than the hourly mortality rate of mosquitoes, the individual is eliminated from the simulation. The hourly mortality rate (μ_h) can be obtained based on the daily survival rate (S) of *Haemagogus* using the following calculation: $\mu_h = - \ln S / 10$

15) *Mosquitoes adult emergence*. Each breeding-site patch accesses information about the abundance of mosquitoes in the environment and the value of parameter *current-K*. If the abundance is less than *current-K* and some immature in the patch has reached the minimum development time, a new adult mosquito emerges. The minimum development time from egg to adult emergence was assumed 12 days (Alencar et al., 2008).

If the newly emerged mosquito comes from an infected female's oviposition, the individual has a probability of starting its adult phase in the infectious status, depending on the vertical infection rate (VIR) parameter. A number between 0 and 1 is randomly generated according to a uniform distribution; if the number is less than VIR, the new mosquitoes will have the status infectious, and if it is greater than VIR, they will have the status susceptible. After the emergence of a new adult, the patch eliminates the information it contained about this individual.

16) *Check other-hosts lifespan.* The time 'lived' for each individual is updated. If the lifespan has been reached, the individual is eliminated from the simulation. After dying, the individual

generates another one in order to keep the population size constant. The generated individual starts the simulation with 'susceptible' status if alternative hosts or 'immune' if dead-end hosts. The time the new individual will 'live' is assigned according to the lifespan parameter representing a mean of a Poisson distribution.

17) *Insert infected mosquitoes*. At a certain point in the simulation, individuals from the mosquito population will be randomly selected, and their status will be changed from susceptible to infectious to start the virus transmission cycle. To account for mosquito population dynamics stabilization during the model simulation, the mechanism that simulates viral transmission is inserted into the model 365 days after the start (3,650-time steps), coinciding with a period of maximum mosquito abundance (maximum *current-K*). For this purpose, 2% of the mosquito population will change their status to infectious. This procedure can be compared to an imaginary experiment in which the transmission dynamics are observed by introducing a certain number of infected mosquitoes into a controlled natural environment.

18) *Update the outputs, check stop conditions, and update the time step*. After updating the outputs, the stop conditions are checked. Three criteria are needed to stop de simulation: 1) the time step must be greater than 3,650 (when the virus starts to circulate); 2) there are no mosquitoes, monkeys, or other-hosts with infectious or exposed status; 3) there are no oviposition events of infectious mosquitoes in the breeding-site patches. Once these three rules are met, the simulation is completed since there is no more virus circulation in the environment. If the stop condition is not met, the time step is updated and returns to the first action of the simulation (Table 1).

4. Model parameters.

Table 2. Model parameters and their assigned values based on empirical data, calibration, and plausible assumptions. Nine from the 35 parameters were subjected to sensitivity analysis for their influence on the outputs.

Input parameters	**Description**	**Value / range**	**Assignment source**
alpha	base coefficient in the equation of current-K	(*k-max* + *k-min*) / 2	fitted
beta	trend coefficient in the equation of current-K	- (*k-max* - *k-min*) / (3650 / 2)	fitted
Gamma	seasonal coefficient in the equation of current-K	α – *k-max*	fitted
k-min	minimum value to *current-K*	*k-max* / 6	fitted; Chadee et al., 1992
Lv1 (99%)	maximum number of larvae in a single breeding-site patch in which the survival probability is over 99%	15	fitted
Lv2 (50%)	number of larvae in a single breeding-site patch in which the survival probability is 50%	90	fitted
time since emergence	time required for newly emerged mosquitoes to move to blood-seeking status (time steps)	10	Forattini, 2002
time to blood digestion	time required for engorged mosquitoes to move to gravid status (time steps)	50	Dégallier et al., 1998
virus-incubation	time of virus incubation in an infected mosquito (time steps)	120	Johansson et al., 2010
monkey territory size	the area where a monkey and its group move around. The total number of patches considering a radius of 18 patches around a central patch	1009	Bica-Marques et al., 2018
monkey group size	the initial number of monkeys in each group	6	Bica-Marques et al., 2018
monkey population	the initial population size of monkeys	30	assumption
latent-period	time elapsed from the infection to infectiousness in the vertebrate hosts (time steps)	30	Moreno et al., 2015
viremic period	the period when an infected monkey is infectious to susceptible mosquitoes (time steps)	40	Moreno et al., 2015
Probability of death for infected monkeys	The probability a monkey has of die when infected with YFV	0.8	Mason et al., 1973
monkey movement probability	the probability of a monkey group moves during a time step	0.2	Crockett and Eisenberg, 1987
subordinate monkey direction variance	the direction variance of subordinate monkeys in relation to the alpha individual of the group (degrees)	0 (±10)	assumption
subordinate monkey forward variance	the movement variance of subordinate monkeys in relation to the alpha individual of the group (patches)	0 (±1)	assumption

mosquito detection radius	the maximum distance that mosquitoes can detect vertebrate hosts and breeding sites (patches)	4	fitted; Breugel et al., 2015; Marinkovic et al., 2014
my blood source	the maximum distance in which blood-seeking mosquitoes can select the host to interact (patches)	0.5	Breugel et al., 2015
biting success	The probability of a blood-seeking mosquito has success (bite the host) during an interaction with a vertebrate host	0.5	assumption
minimum blood meal level required	the minimum amount of blood that needs to be ingested by the blood-seeking mosquito so that it stops looking for a blood meal (0 = empty, 1 = full)	0.5	assumption
daily survival rate	the probability that a given individual of the mosquito population will be alive at the end of a day	0.93	fitted; Marcondes and Alencar, 2010; Hervé et al., 1985
hourly mortality rate	the probability that a given individual of the mosquito population will die during a time step	0.007257	fitted
minimum larval development time	the minimum time required for new adult mosquitoes to emerge after the oviposition event (time steps)	120	Alencar et al., 2008
number of breeding site patches	number of breeding site patches randomly allocated in the grid	*k-max* / 12	assumption
vertical infection rate	the probability of newly-emerged adults from a progeny of an infectious mosquito be infectious	0.05 - 0.15 default = 0.1	sensitivity analysis
initial number of mosquitoes (*k-max*)	the initial number of mosquitoes and maximum value of the parameter *current-K* (individuals)	600 – 1800 default = 1200	sensitivity analysis
dead-end abundance	the number (constant) of dead-end hosts in the simulation (individuals)	30 – 90 default = 60	sensitivity analysis
alternative hosts abundance	the number (constant) of alternative hosts in the simulation (individuals)	15 – 45 default = 30	sensitivity analysis
other-hosts mean lifespan	the mean of a Poisson distribution representing the expected lifespan for the population (days)	730 – 2190 default = 1460	sensitivity analysis
alternative hosts viremic period	the period an infected individual is infectious to a susceptible mosquito (days)	6 – 18 default = 12	sensitivity analysis
alternative hosts transmission competence	the probability of an infectious alternative host transmits the virus to a susceptible mosquito during an interaction	0.2 - 0.6 default = 0.4	sensitivity analysis
mosquito transmission competence	the probability of an infectious mosquito transmits the virus to a susceptible vertebrate host during an interaction	0.2 - 0.6 default = 0.4	sensitivity analysis
monkey transmission competence	the probability of an infectious monkey transmits the virus to a susceptible mosquito during an interaction	0.2 - 0.6 default = 0.4	sensitivity analysis

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