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Coupling of an agent-based model with a mathematical model of water pond dynamics for studying the impact of animal herd mobility on the *Aedes vexans* mosquito populations

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Abstract
In this paper, an agent-based model coupled with water pond dynamics was used to describe interactions between mosquitoes, hosts, water ponds in a virtual environment taking into account climatic factors. The objectives of the developed model were to build a virtual environment with the multi-agent platform CORMAS containing virtual mosquitoes and its behaviors, virtual hosts and its behaviors, virtual water ponds and its behaviors and used the data coming from interactions between virtual agents to study the impact of animal herd mobility in search of a water ponds on the growth of the mosquito populations. The results showed that, in the period of heavy rains, when the distance traveled by animal herd increase, the mosquito populations also increased. The different simulations showed that the growth of the number of mosquitoes in each water pond agent depends on the degree of animal herd mobility. The present study provides a framework that permits the control of the dynamics of mosquito populations in the virtual environment taking into account the mobility of animal herd and climatic factors.

Keywords: Vector-borne diseases, rift valley fever, multi-agent system, diseases modeling, agent based, entomology modeling

1. Introduction
In Senegal, the *Aedes vexans* type of mosquito is responsible for the emergence and maintenance of the virus in the inter-epizootic period via transovarial virus transmission [1] of Rift Valley Fever in Ferlo (Senegal). Indeed, the infected female *Aedes* can transmit the virus to eggs she will lay [2]. The population of *Aedes,* which is mostly present at the beginning of the rainy season, declines fairly rapidly in the middle of the season to make way for Culex which would play an amplifying role [3, 4]. Temporary water ponds are a common place mosquitoes use for breeding sites. Climatic factors have been the impact study subject on water ponds, mosquito populations, as well as the transmission of the Rift Valley Fever [5-7, 8]. The agent-based model has been used to model the complex environmental phenomena [9, 10], but also in epidemiology in the field of vector-borne diseases [8]. RVF is an acute fever responsible for premature abortion and perinatal mortality in livestock and for hemorrhagic fever and encephalitis in humans. Indeed, veterinary offices in Kenya are the first to report RVF among livestock in the early 1900s. Numerous epidemic/epizootic outbreaks have been reported periodically in many African countries in the past 30 years [11, 12]. Since 2000, the virus has been located outside the African continent, mainly in Saudi Arabia and Yemen [13] and in Mayotte in 2008 [14]. In West Africa particularly in Senegal and southern Mauritania, RVF epidemics do not seem to follow trends as they do in East Africa [15]. RVF is associated with years of unusual heavy rainfall events [7]. In Senegal, many mosquito species were found infected with the RVF virus [16]. After the RVF outbreak of 1987, entomological studies were carried out in Senegal from 1991 to 1996 to identify the sylvatic vectors of the virus [17]. These studies proved that the epidemiological role of mosquito species involved in the RVF transmission cycle in Senegal is peculiar. Herd mobility plays a great role on vector borne-disease. The impact of herd mobility on dynamic transmission modeling of that vector borne-disease is a challenge of Sahelian research laboratories. Many mathematical models and agent

based models have been the subject of research on vector borne-disease [18]. Other scientists have worked on the outbreak factors of the disease. Paul Python *et al.* [19] studied the impact of the mobility of herds of animals on the outbreak and transmission of Rift Valley Fever in Ferlo (Senegal), but did not study the impact of the mobility of herds of animals on the dynamic of population of Aedes and Culex mosquitoes. The agent based models allows for modeling and simulation of numerous complex phenomena [10]. These models are increasingly used in environmental sciences [20, 21]. As of now, very few studies have included modeling and simulation using agent-based systems in the epidemiology of vector-borne diseases [22]. Previous studies have suggested a correlation between the mobility of an animal herd and the outbreak of RVF in new areas. However no studies in this area have used the agent based model to study the impact of the mobility of animals on the dynamics of populations of the *Aedes vexans* mosquito which is responsible for transmission of RVF. The aim of present study is to firstly design an agent based model coupled with water pond dynamics of mosquito-animal interactions around ponds taking into climatic factors, and secondly implemented the model on a multi-agent simulation platform, CORMAS. The software interface created in the CORMAS environment will be used to compute the number of mosquitoes at each step of simulation as the function of the distance cover by animal herd when they are in search of a water pond. With obtained results we will able to study the impact of animal herd on the dynamics of populations of the *Aedes vexans* mosquito.

2. Material and Methods

2.1. Study Area

The Ferlo zone is located in the West African Sahel between 15° and 16°30 north and 13°30 and 16° West. Ferlo extends from the valley of Senegal River, in the north, to the limits of edges of the peanut basin in the South, covering more than 60,000 km^2. The study was conducted between the months of June and September during the year 2010 in five particular locations: Widou, Tessekere, Labgar, kamb, Deali. The selection of these sites was motived by the rainfall intensity during the month of August. The climate of the Ferlo region is similar to much of the sahelian and characterized by two main seasons: a dry season and a rainy season. Ferlo is endowed with a Sahelian climate characterized with a rainy season from June to October. In this period, the area is under the whims of maritime influence from the deflected trade winds and water vapor advection from the eastern Atlantic Ocean. The mean annual rainfall there is mainly provided by squall lines, and ranges from 300 mm to 500 mm [23]. During the summer monsoon, a large quantity of small and temporary water ponds are thus formed, leading to an environment favoring in the breeding and hatching of mosquitos including *Aedes vexans arabiensis* and *Culex poicilipes* associated with the RVF [16, 24]. In fact, these seasonal ponds are seen as key places where cattle and vectors meet, and, as such, become potent sources for epidemics. In the Ferlo region, water ponds are widely distributed, some isolated, and others organized in clusters of all sizes. Different types of ponds exist with different levels of vegetation [16].

2.2 General definitions

Software agents are computer programs that use artificial intelligence technology to learn and automate the procedures and processes. A software agent is a program that is executed in a certain environment autonomously and is capable of making decisions based on data obtained from the environment and from other agents. They are also computational entities which can act on behalf of other entities. Agent systems are self-contained software programs possessing domain knowledge and an ability to behave with some degree of independence to carry out actions to achieve specific goals. They are designed to operate in dynamically changing or unstable environments. Software agents may be autonomous or work together with other agents. They have the ability to act autonomously, to react to the environment and adapt its behavior accordingly. They also have the capability to exchange messages with each other and with the external users and systems. Agent-based modeling belongs to the domain of software agents that interact with each other to create a working dynamic model of a real system.

2.3 Model structure

The general architecture (Fig. 1) of the mosquito-host interactions in the water pond is shown in Fig. 1. In this architecture, the Mosquito Agent represents a mosquito with similar attributes and behaviors. The Host agent behaves similarly as an animal such as eating habits, drinking habits. The Water Pond agent is a zone where animals and mosquitoes can meet. Climate Agent is a database containing all the climatic data such as temperature, humidity, precipitation.

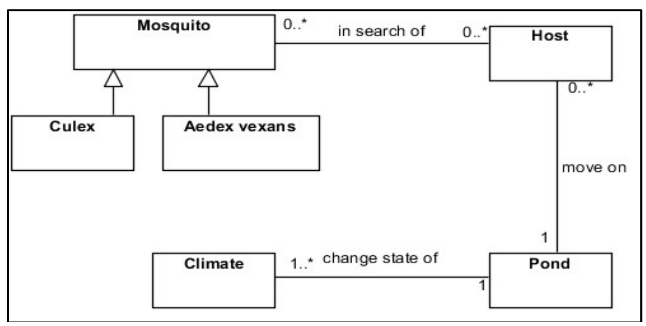

Fig 1: General structure of the model. We used the unified modeling language (UML) formalism in the representation of entities.

Mosquito Agent must search Host Agent to have a blood meal for the fertilization of eggs. Host Agent must move on Pond Agent to have water to drink. Water Pond Agent changes its physiological state at each step as the function of temperature coming from the Climate Agent.

2.2. Methods

There exist several platforms used in the implementation of agent-based models. CORMAS [25] is an experimental platform used to create all the agents in the virtual environment. CORMAS provides standard libraries to support various types of operations for agents. All Agents used in this work are developed with Smalltalk language. It is a simulation platform based on the Visual Works programming environment which allows the development of applications in the Smalltalk object oriented language. It facilitates the construction of agent based models and the design, monitoring and analyzing of agent-based simulation scenarios. CORMAS provides some interesting features for real life applications [26]. It offers the possibility to observe graphically the output results. The model in the CORMAS environment consists of entities. Each entity has attributes, the dynamic perception of the environment, an initialization control and local control procedure for each entity, as well as actions implemented as methods for the entity to interact with its environment. CORMAS model has an environment consisting of a set of cells. For the simulation, we must also define the procedures for initialization and control for the whole model. The different agents can then move from cell to cell.

The proposed model has five principal agents: Mosquito, Host, Pond, and Climate. Each agent can be identified by its attributes and behaviors. In the description of the attributes and behaviors of each agent, we will only focus on the most important ones. CORMAS platform has the ability to simulate different types of scenarios and gives the opportunity to create the attributes and adjust the behavior of all agents. The model of the Ferlo environment was represented by two groups of agents: a set of mobile agents consisting of host agents and vector agents (mosquito) and the second group consists of water pond agents, and climate agents. At each step of the simulation, the various agents interact and each updates its different memory of knowledge storage. Some agents were reactionary and others were cognitive and change throughout their life cycle by forming a multi-agent able to virtually reproduce the outbreak system and transmission phenomena of the Rift Valley Fever in Ferlo, northern Senegal.

2.2.1 Water Pond agent

The water pond agent is the central element of the outbreak and spread of RVF. Indeed it is the meeting place for the animals that are in search of water to drink and mosquitoes that must at all costs take a blood meal to fertilize their eggs. At the beginning of the rainy season, all Pond agents are in lack of water. As soon as the first rains fall, water ponds begin to fill. This filling will cause the impoundment of mosquito eggs and four days after the first rains, the first adult mosquitoes will emerge. The filling dynamics of Water Pond agents depends on climatic factors. Interactions between Water Pond agent and Climate agents determine the life cycle of mosquitoes *Aedes vexans* in the Ferlo region in Senegal. Each Water Pond agents performs two major functions: a filling function according to the water pond, and a water loss function. The filling function is ensured by the rain that falls directly on the ponds and also water runoff from elsewhere. The water loss function is provided by the phenomenon of evaporation, infiltration and water consumption by the animal herds. The Infiltration essentially depends on the kind of soil, resulting from the soil permeability. There are different types of infiltration functions used in the literature [27]. Nevertheless, it is possible to calculate the soil permeability by means clustering of experimentation. The Evaporation takes place at the surface of a liquid. When this happens, the average kinetic of the liquid is lowered. It is strongly linked to the climate of the concerned area, in our case, the Sahelian area. The amount of consumption essentially depends on the configuration of the different settlements around the water point and on the size of the livestock which come to drink, the pastoralists acknowledge.

Attributes:

- List Vecteur: list containing the number of mosquitoes at each step of the simulation.
- Water Lever: indicates the level of the water within the pond.
- Soil Type: indicates the type of soil
- Pond State: indicates the state of the pond. This variable indicates if the pond is dry or has a water.
- List Climate: list containing the various values of temperature, humidity, precipitation around each pond
- List Evaporation: list containing the various daily evaporation rate of each pond.
- List Infiltration: list containing the various daily infiltration rate of each pond.
- List Run Off: list containing the various rate of water leaving of each pond.

Behaviors

The behaviors of each pond in the agent-based model are described by the computer program called method. The methods used by each pond are listed as follows:

- initPont ( ) : method allowing to initialize the parameter values of each pond at the beginning of the simulation.
- waterClimate( ): method allowing to update the climatic parameter values of each pond.
- waterDynamic( ): method allowing to calculate at each step of simulation the quantity of water within the pond taking account to the water loss(infiltration, runoff, evaporation).

This method uses the following mathematical model:

$$\frac{dv(t)}{dt} = p(t)a(t) - r_o(t) + r_i(t) - e_r(t).v(t) - i_r(t).v(t) - c.v(t) \quad (1)$$

Where v(t) represents the volume of water in the pond at time t,

a (t) represents the area occupied by water volume at time t,

$r_i(t)$ represents the runoff of incoming water volume at time t,

$r_0(t)$ represents the runoff of outgoing water volume at time t,

p (t) represents the precipitation calculated at time t,

$e_r(t)$ represents the rate of water volume lost per unit area per day due to

evaporation,

c represents the rate of water consumption by hosts

$i_r(t)$ represents the rate of water lost per unit area per day due to infiltration.

Algorithm used to solve the ordinary differential equation

The dynamics of each water pond is defined as follows:

$$v_t'(t) = p(t) * a(t) - r_o(t) + r_i(t) - e_r(t) * v(t) - i_r(t) * v(t) - c * v(t)$$

The Runge-Kutta method is a mathematical algorithm used to solve systems of ordinary differential equations. The general form of the equation (1) is as follows:

$v' = f(t, v)$ with $v(t_0) = v_0$. v is the water volume at time t within the water pond agent.

The fourth Runge-Kutta method is given by:

$v_{i+1} = v_i + (k_1+2(k_2+k_3)+k_4)/6$ and $t_{i+1} = t_i + h$, v_i is the water volume within water pond at the step i.

where h > 0 is a step size parameter, i=1, 2, 3... and:

$k_1 = f(t_i, v_i)*h$

$k_2 = f(t_i + \frac{h}{2}, v_i + \frac{k_1}{2})*h$

$k_3 = f(t_i + \frac{h}{2}, v_i + \frac{k_2}{2})*h$

$k_4 = f(t_i + h, v_i + k_3)*h$

The Runge Kutta algorithm was used by agent water for computing at each step i of the simulation the volume of water within the pond. The algorithm is defined as follows: suppose n is the number of steps.

Input: integer n;
Input: Real p, a, r_out, r_in, e_rate, i_rate, c;
*/*p: precipitation, a: area occupied by water volume, r_out: rate of outcoming water, r_in: rate of incoming water, i-are: rate of infiltration, e_rate: rate of evaporation, c: rate of water consumption */*
Output: integer v;
Method: v is computed at each step of the simulation by water pond agent using the mathematical model of water pond dynamics.

***Input** (n, p, a, r_out, r_in, e_rate, i_rate, c);*
v = 0; / All water ponds were dry at the beginning of the rainy season*/*
t = 0;
***for** I = 1 to n*
begin
$k_1 = f(t_i, v_i)*h$;
$k_2 = f(t_i + \frac{h}{2}, v_i + \frac{k_1}{2})*h$;
$k_3 = f(t_i + \frac{h}{2}, v_i + \frac{k_2}{2})*h$;
$k_4 = f(t_i + h, v_i + k_3)*h$;
$v_{i+1} = v_i + (k_1+2(k_2+k_3) + k_4)/6$;
$t_{i+1} = t_i + h$;
$print(v_i)$;
***end**;*
***function** f(Real t, Real v): return real*
***Return** (p*a-r_out+r_in-e_rate*v-e_in*v-c*v);*
***end** f;*

Algorithm 1. Computation of water pond dynamics

2.2.2 Agent Vector (Mosquito)

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. The mosquito vectors of the Rift Valley Fever denoted *Aedes vexans* and *Culex poicilipes* follow a biological cycle taking place partly in the water. After hatching the eggs, the larvae and pupae grow in the water. Once fecundated, the females need a blood meal necessary to the maturation of the eggs that will be laid on the banks for the *Aedes* or on the surface of the water for the *Culex*. The development duration of mosquito is about three days in the Ferlo Region. At the end of the cycle, the mosquito becomes capable of transmitting the virus to a new animal if the latter is not immunized.

Attributes:

- physioState: indicates the physiological state of the mosquito. This variable takes one of the following value at each step of the simulation: egg, larva, pupa and adult.
- sanitaryState: indicates the healthy state of the mosquito. This variable takes one of the following value at each step of the simulation: healthy, infected and infecting.
- numberPond: indicates the number of the water pond where belong the mosquito.

Behaviors

The behaviors of each mosquito agent in the agent-based model is described by the computer program called method. To react with the environment, the mosquito agent uses the following methods:

- bite Host ( ) : method allowing to sting the host and take the blood meal. It is during that sting that the host can be infected.
- Searching Host ( ) : method allowing to look for the host in the vicinity of the water pond
- Lay Egg ( ) : method allowing it to lay eggs.

Each mosquito agent is in direct interaction with Water Pond agents and Host agents. The Water Pond agent serves as a habitat while the Host agent allows her to have a blood meal to fertilize her eggs (Fig. 2).

2.2.3 Host Agent

In the Ferlo region in northern Senegal, animals like cattle, sheep, camels and goats are infected by Aedes mosquitoes during the rainy season from June to October each year. Each of these animals is modeled by the Host agent.

Attributes:

- physioState: indicates the physiological state of the host. This variable takes one of the following value at each step of the simulation: cattle, sheep, goat, camel.
- sanitaryState: indicates the healthy state of the host. This variable takes one of the following value at each step of the simulation: healthy, infected and infecting.
- mobilityDegree: indicates its degree of mobility, which is a number specifying the maximum distance from which it can find a water pond and thereby consume the water.

Behaviors

Each Host agent unconsciously interacts with one or more other agents in the environment, but primarily to the agent Vector (mosquito). Each Host agent also interacts with an agent that corresponds to each step of the simulation by impacting the decline of the water level (Fig. 3) of the water pond where it is located. The behaviors of each mosquito agent in the agent-based model is described by the computer program called method. To interact with other agents, the host agent must run the following methods:

- search Water( ) is the method that allows it to identify a water pond.
- Water Consumption( ) is a method that allows it to consume water.
- Move Pond( ) is a method that allows it to move in a water pond by using a degree of mobility.
- Health dynamic( ) is a method that allows it to update its sanitary state.

2.2.4 Climate Agent

In the study area, rainfall is between 300 mm and 500 mm. The intra-annual variability is characterized by the presence of long dry spells over five days between two rain events.The Ferlo annual temperatures range from 21.2 °C to 36.6 °C with an average of 29.6 °C. Maximum temperatures are observed in May and October, and the coldest months are January and August. The annual relative humidity average is 47% with a maximum usually in August around 73% and a minimum in February around 10%. Water losses due to evaporation have a monthly average of 6.4 mm / day. The climate is characterized by the rains that start in the first or second week of June. Rainfall reaches its maximum value in the middle of August. In periods of dry spells, daily temperatures tend to increase. Moisture in the area reaches its maximum value towards the end of August. The climate agent is characterized by the daily temperature, daily humidity and daily precipitation.

Attributes:

- temperature: indicates de daily temperature of the day
- humidity: indicates the daily humidity of the day.
- precipitation: indicates the daily precipitation of the day.

2.2.5 Description of the flowchart of the main behaviors

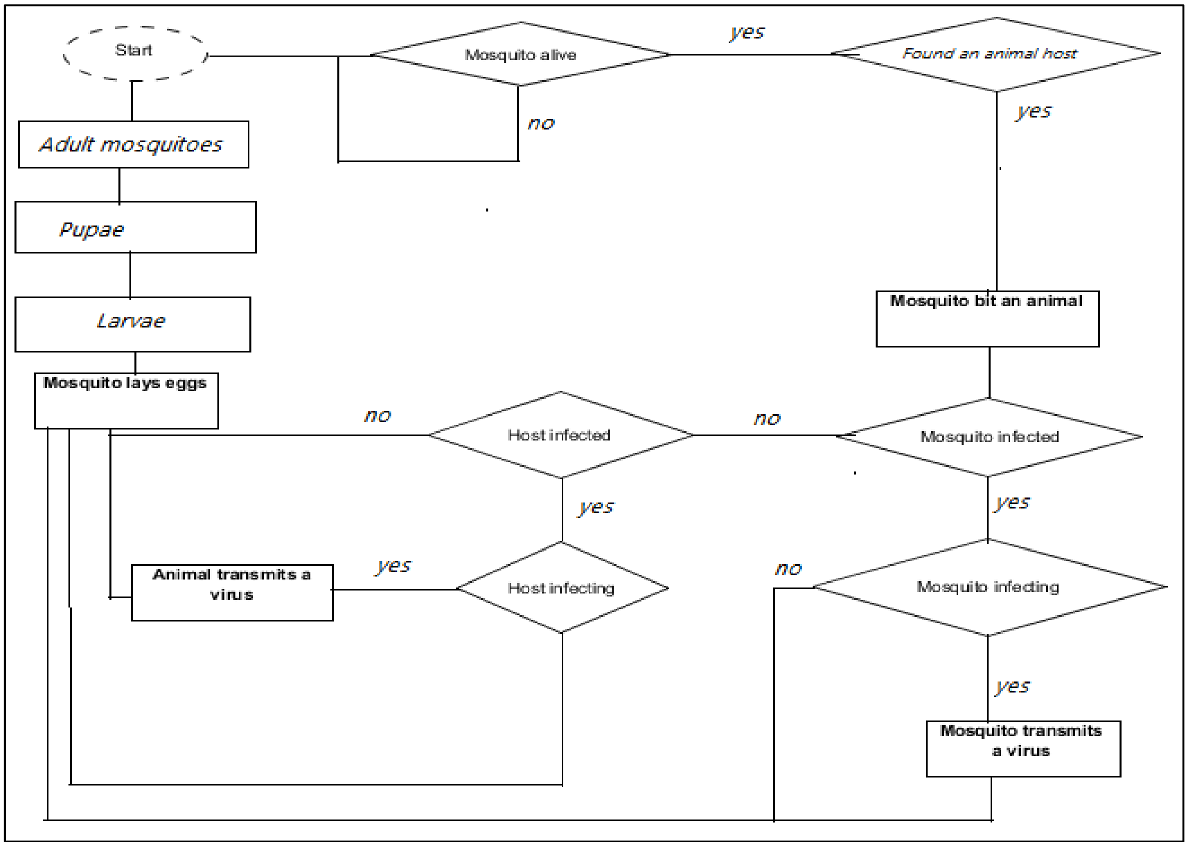

Fig 2: Flowchart showing the interaction between mosquito agent and animal host agent. This flowchart also shows the behaviors of mosquito agent.

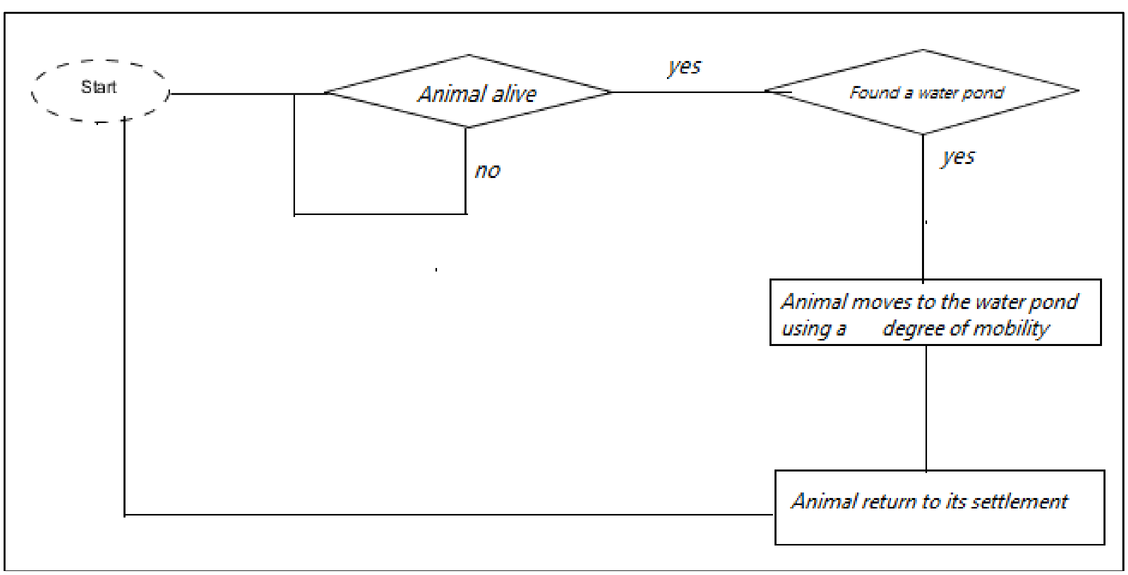

Fig 3: Flowchart showing the interaction between mosquito agent and animal host agent. This flowchart also shows the behaviors of Host agent

2.2.6 Structure of the coupling

Coupling is a measure of how strongly one model is connected to, has knowledge of, or relies on many others models. In software development, coupling refers to the degree to which software components are dependent upon each other. Coupling is also the act of joining two or several models to work together. A multi-agent model is a computer program describing interactions between objects in a virtual environment. These interactions show how the various agents were connected. The following figure (Fig. 4**)** explains how the coupled model is defined.

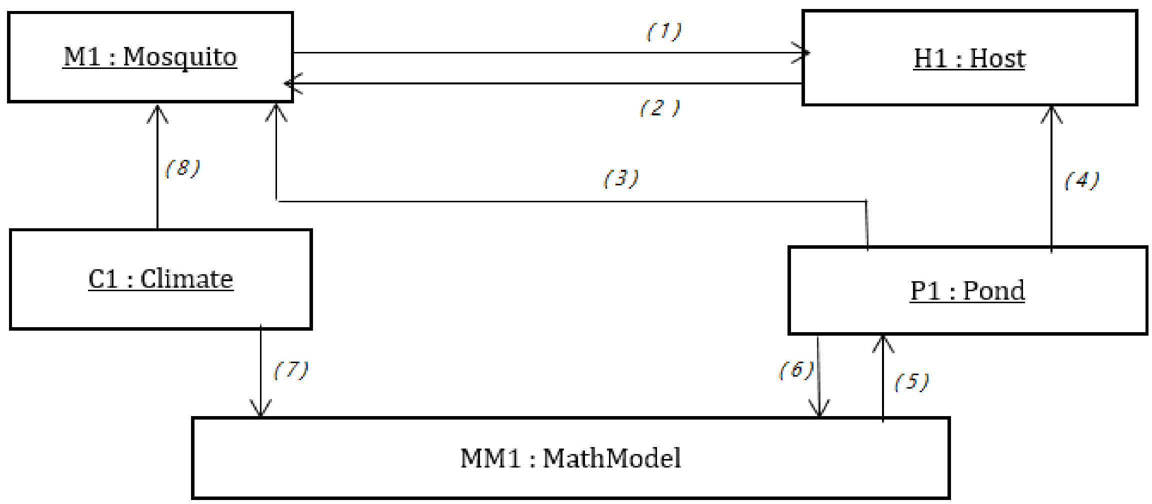

Fig 4: Coupling of the various agents with a mathematical model allowing water pond agent to update the volume of water.

1. Viruses are transmitted from mosquito to Host.
2. A blood with viruses is taken by a mosquito.
3. A mosquito needs to know the state of the pond before the laying of eggs.
4. A host needs water coming from the pond.
5. At each step, a pond agent needs the additional value of volume calculated by the mathematical model.
6. A mathematical model needs evaporation rate, infiltration rate runoff value for calculate the volume of the pond.
7. A mathematical model needs the daily value of precipitation for calculating the volume of the water within the pond.
8. A mosquito agent needs the temperature value coming from climate agent for hatching eggs.

3. Simulation and Results

In this section, we used the platform CORMAS for the implementation of the agent-based model. We have chosen the platform CORMAS because it gave the opportunity to create, analyze and study the various links between entities of the model. Others advantages of the platform CORMAS was the fact that, users can execute simulations easily by just adjusting the parameter values of the model. We created all agents and defined interactions between them. We analyzed functionalities of the proposed model. When agents were created with the platform CORMAS, the source code can be requested from the authors and used by creative Commons copyright licenses. All the simulations used the same initial parameter values. From the first step to the last simulation step, one can know: number of mosquitoes for each degree of mobility. One can also know the number of eggs laid by female mosquitoes. After the initialization of the model, mosquito agents was presented in red color, water pond agents in dark green, host agents in yellow, the settlement agents in black triangle (Fig. 5).In the model, several simulations were done in 100 steps corresponding to 100 days of the rainy season. The rainfall data of the year 2010 was used to carry out each simulation. The rainy season of the year 2010 started at the first week of June and finishing in September (about 100 days). All mosquitoes at the beginning of each simulation were as eggs. Hatching eggs of *Aedes vexans* started from the beginning of the first rains of June. Each mosquito agent in the simulation had has a lifetime between 21 and 28 days. The various agents were randomly placed in the environment at the beginning of the simulation. Only Host agents moved to the water Pond, the vectors (mosquitoes) in this model did not leave the water pond. To study the impact of the mobility of animal agents on the *Aedes vexans* mosquito populations, we carried out simulations corresponding to five different degrees of mobility of the animals on the respective ray of 0 km (animals receive water and grazing in place), of 10 km, 20 km and 30 km (Fig. 7). With 50 *Aedes vexans* mosquito eggs early in the simulation from the beginning of the first rains, the onset of adult mosquitoes is observed. By taking the blood meal during the mobility of host agents (animals), mosquitoes can lay eggs that turn into adult mosquitoes. The results associated with the simulations was presented in Fig. 6 and Fig. 7. Fig. 6 shows the various dynamics of mosquito populations as a function of the distance that can be travel each host animal in search of water pond. Fig. 6 shows the average number of mosquitoes obtained as a function of mobility degree for each 100 steps of simulation. Fig 4. Shows the coupling of an agent-based model and a mathematical model of water pond dynamics.

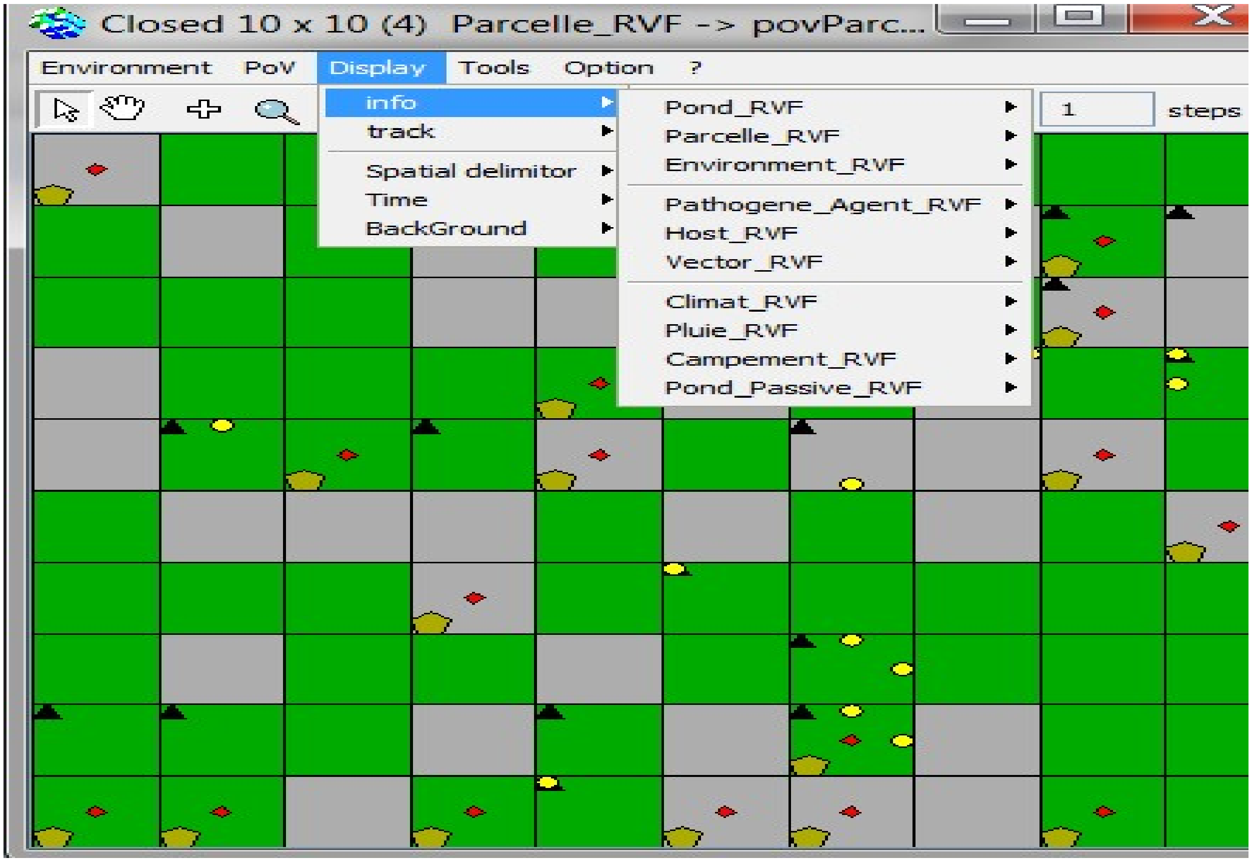

Fig 5: CORMAS platform interface showing agents at the first step of simulation.

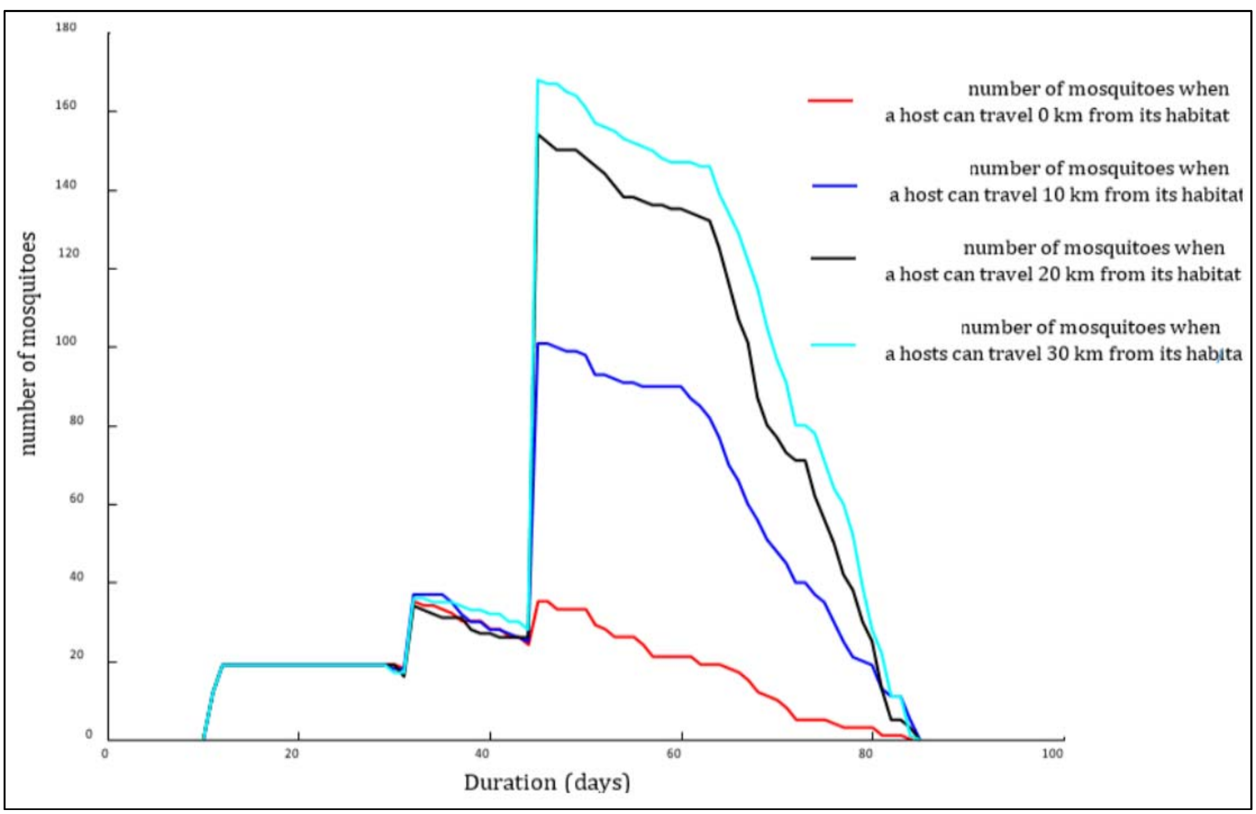

Fig 6: Dynamics of *Aedes vexans* mosquito populations during the 2010 rainy season for the degrees of mobility 0 km, 10 km, 20 km and 30 km.

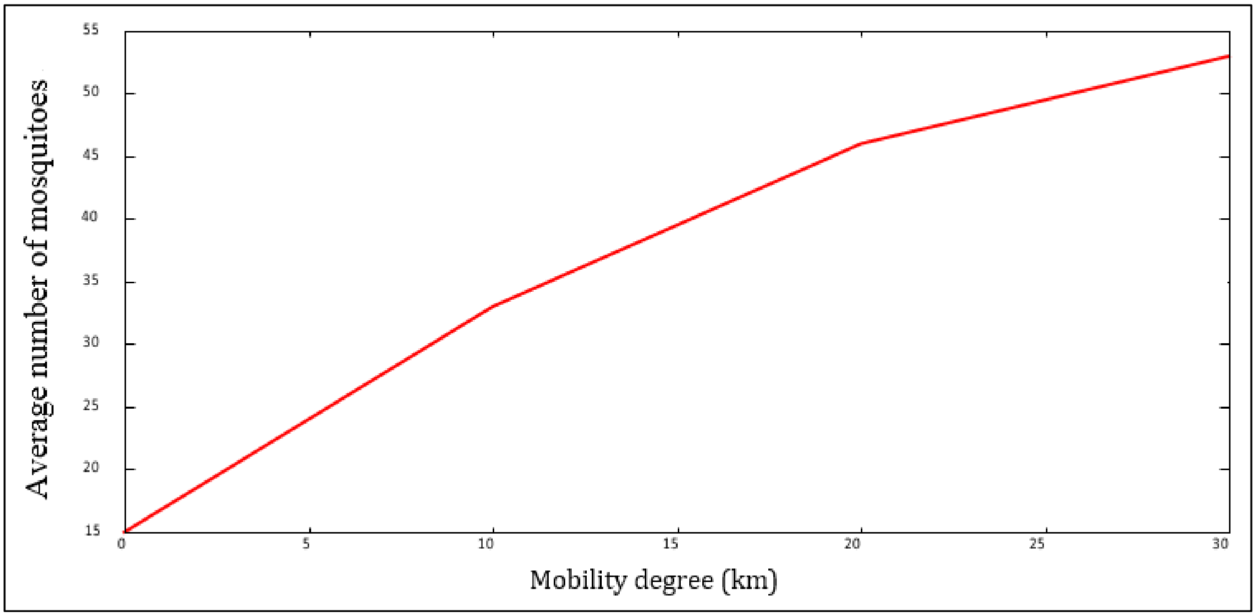

Fig 7: Average number of mosquitoes as function of degree of mobility.

Discussion

At each step of the simulation, animals moved in search of pasture or a water source. During the simulation, each Host agent randomly chose an agent Water Pond located in an environment based on the degree of mobility. We chose the first 100 days of the rainy season period from June 2010 for the simulation. Rainfalls of 2010 had two dry spells that go from the 10th day and the 22th day and the 30th day to the 38th day from the beginning of the rainy season. The advantage of these dry spells (seven successive days without rain) for mosquitoes lies on the fact that they allowed the desiccation of *Aedes vexans* mosquito eggs and will give them the opportunity to hatch and emerge later into adult mosquitoes. The degree of mobility in the model represents the maximal distance that each host agent can cover from the water pond. Upon arrival in the water pond, the animals will be bitten by mosquitoes in order to fertilize their eggs. If any animal did not move in each water pond, the mosquito population will decrease due to the fact that no eggs will be fertilized, and therefore cannot hatch. For the simulation corresponding to the mobility of animals within the perimeter of the neighboring water ponds of their settlement (0 km) after a 100-day period, the maximum number of mosquitoes observed was 35 (Fig. 6). For respective degrees of mobility of 10 km, 20 km, and 30 km, the maximum number of mosquitoes obtained after a simulation of 100 days was respectively 103, 155, 168 (Fig. 6). We can say that when the degree of mobility grows, then the dynamics of the population of *Aedes vexans* mosquitoes also grows (Fig. 7). Each mosquito agent did not leave the water pond environment and therefore cannot come into contact with animal agents if unless the latter was in constant mobility in search of pasture or water to drink. The dry spells being strategic periods for laying eggs and dryness for *Aedes vexans* mosquitoes. Results that we obtained confirm the fact that if we reduce the scope of movement of herds of animals, the number of *Aedes vexans* mosquitoes will drop, resulting in a decrease in the number of infections of the Rift Valley Fever [27, 28]. Acevedo MA *et al.* [29] have explored, analytically and through numerical simulations, how human mobility connects spatially heterogeneous mosquito populations, thereby influencing disease persistence (determined by the basic reproduction number R_0), prevalence and their relationship. They used a mathematical model to describe the interactions between hosts and mosquitoes and not taking into account of the behaviors of hosts contrary to our model where we built an agent based model taking into account of the behaviors of mosquitoes and hosts during the step of implementation. Adam *et al.* [26] also used a mathematical model to investigate the role of human movement in the epidemiology of vector-borne pathogens. They used the multi-patch to describe the movements of human and, in our agent based model, we used the degrees of mobility to describe the mobility of animals. The obtained results provide a better basis for understanding the interplay between spatial transmission heterogeneity of Rift Valley fever and animal mobility.

Conclusion

In this paper, our contribution was firstly to build an agent based model describing interactions and behaviors in an virtual environment where they was mosquitoes, animals, climate and ponds. The mathematical model of water pond dynamics coupled with pond agent and climate agent was helped to observe and analyzed the various physiological stage of mosquito populations. Secondly we created a virtual environment using the multi-agent platform CORMAS which can help to perform the various point of view in the mosquito control. The code source that we have created could help in other scientific domain to study the impact of climate changes in the increase of mosquito populations.

This work allowed us to show that the abundance of *Aedes vexans* mosquitoes is also related to the mobility of animal herd. The results show that the growth of infections due to *Aedes vexans* mosquitoes during the rainy season is conditioned by the maximum distance that a host animal in search of water and pasture can cover. The developed model showed that if we reduced the mobility of the animals during the rainy season, the population of *Aedes vexans* mosquitoes will decrease and the number of infections caused by Rift Valley Fever will also decrease. This agent-based model of *Aedes vexans* gives the ability to simulate the behavior of mosquitoes taking into account environmental factors, as well as the control of the movement of animals. The developed model allows us to better understand the relationship between rainfall pause, *Aedes vexans* mosquitoes and mobility of host animals.

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References

1. Mark L Wilson, Louisa E Chapman, David B Hall. Rift Valley fever in rural northern Senegal: Human risk factors and potential vectors. American Journal of Tropical Medicine and Hygiene. 1994; 50(6):663-675.
2. Davies FG, Jacobsen P, Sylla D. Laboratory manual on Rift Valley fever: isolation and identification techniques. In: Report of FAO/WHO group on emergency preparedness for Rift Valley fever control in West Africa. Report no. WHO-VPH/88.77. Geneva: World Health Organization. 1998, 1134.
3. Mondet B, Diaité A, Ndione JA, Fall AG, Chevalier V, Lancelot R *et al*. Rainfall patterns and population dynamics of Aedes (Aedimorphus) vegan's arabiensis, Patton 1905 (Diptera : Culicidae), a potential vector of Rift Valley Fever virus in Senegal. Journal of Vector Ecology. 2005; 30:102-106.
4. Ndione JA, Besancenot JP, Lacaux JP, Sabatier P. Environnement et épidémiologie de la fièvre de la vallée du Rift (FVR) dans le bassin inferieur du fleuve Sénégal. Environnement, Risques et Santé. 2003; 2:176-182.
5. Linde TCK, van der, Hewitt PH, Nel A, Westhuizen MC, van der. Development rates and percentage hatching of Culex (culex) theileri theobald (Diptera: culicidae) eggs at various constant temperatures. Journal of the Entomological Society of Southern Africa. 1990; 53:17-26.
6. Turel MJ, Rossi CA, Bailey CL. Effect of extrinsic incubation temperature on the ability of Aedes taeniorhynchus and Culex pipiens to transmit Rift Valley fever virus. American Journal of Tropical Medicine and Hygiene 1985; 34(6):1211-8.
7. Linthicum KJ, Anyamba A, Tucker CJ, Kelley PW, Myers MF. Climate and satellite indicators to forecast Rift Valley fever epidemics in Kenya. Science. 1999; 285(5426):397-400.
8. Carrie Marie Bradford. Effects of Weather on Mosquito Biology, Behavior, and Potential for West Nile Virus Transmission on the Southern High Plains of Texas. Ph.D. thesis, Texas Tech. University, 2005.
9. Bousquet F, Gautier D. Comparing two ways of modelling spatial dynamics through multi-agents simulation: spatial and actor approaches. CyberGeo. 1999, 89.
10. Bousquet F, Le Page C. Multi-agent simulations and ecosystem management: a review. Ecol. Model. 2004; 176:313-332.
11. Roche B. Multi-agent systems in epidemiology: A first step for computational biology in the study of vector-borne disease transmission. BMC BioInformatics. 2008; 435(9):1471-2105
12. Hoogstraal H, Meegan JM, Khalil GM, Adham FK. The Rift Valley Fever Epizootic in Egypt 1977-1978, Ecological and Entomological Studies. Transactions of the Royal Society of Tropical Medicine and Hygiene. 1979; 73:624-629. http://dx.doi.org/10.1016/00359203(79)90005-1
13. Jupp PG, Kemp A, Grobbelaar A, Leman P, Burt FJ, Alahmed AM *et al*. The 2000 Epidemic of Rift Valley Fever in Saudi Arabia: Mosquito Vector Studies. Medical and Veterinary Entomology. 2002; 16(3):245-52.
14. Sissiko D, Giry C, Gabrié P, Tarantola A, Pettinelli F, Collet, *et al*. Emergence chez l'homme de la fièvre de la vallée du rift à Mayotte. Bulletin Epidémiologique Hebdomadaire Institut de Veille Sanitaire (INVS). 2009; 4:33-36.
15. Ba Y, Diallo D, Kebe CMF, Dia I, Diallo M. Aspects of Bioecology of Two Rift Valley Fever virus Vectors in Senegal (West Africa): Aedes vexans and Culex poicilipes (Diptera: Culicidae). Journal of Medical Entomology. 2005; 42:739-750.
16. Lacaux JP, Tourre YM, Vignolles C, Ndione JA, Lafaye M. Classification of Ponds from High-Spatial Resolution Remote Sensing: Application to Rift Valley Fever Epidemics in Senegal. Remote Sensing of Environment. 2007; 106:66-74.
17. Ndione JA, Lacaux JP, Diop M, Gaye AT. Pluviométrie et émergence de la Fièvre de la Vallée du Rift dans la vallée du fleuve Sénégal : nouvelles considérations. Premier Colloque Francophone en Environnement et Santé Dakar Senegal, 2006.
18. Murray JD. Mathematical Biology. II. Spatial Models and Biomedical Applications. Springer, Berlin. 2003; 17:2-576.
19. Paul P, Bah A, Ndiaye P, Ndione J. An Agent-Based Model for Studying the Impact of Herd Mobility on the Spread of Vector-Borne Diseases: The Case of Rift Valley Fever (Ferlo Senegal). Open Journal of Modelling and Simulation. 2014; (2):97-111. doi: 10.4236/ojmsi.2014.23012.
20. Hare M, Deadman P. Further towards a taxonomy of agent-based simulation models in environmental management. Math. Comput. Simulat. 2004; 64(1):25-40.
21. Parker DC, Manson SM, Janssen MA, Hoffmann MJ, Deadman P. Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann. Assoc. Am. Geogr. 2003; 93(2):314337.
22. Muller G, Grbaut P, Gouteux J. An agent based model of sleeping sickness: simulation trials of a forest focus in southern Cameroon. C. R. Biol. 2004; 327:1-11.
23. Nicholson SE. Revised Rainfall Series for the West African Subtropics. Monthly Weather Review. 1979; 107:620-623.
24. Fontenille D, Traore Lamizana M, Diallo M, Thonnon J, Digoutte JP, Zeller HG. Nouveaux vecteurs de la fièvre de la vallée du Rift en Afrique de l'Ouest. Emerging Infectious Diseases. 1998; 4:289-293.

25. Christophe Le Page, Nicolas Becu, Pierre Bommel. François Bousquet Participatory Agent-Based Simulation for Renewable Resource Management: The Role of the Cormas Simulation Platform to Nurture a Community of Practice. Journal of Artificial Societies and Social Simulation. 2012; 15(1):16.
26. Kalliopi Kravari, Nick Bassiliades. A Survey of Agent Platforms. Journal of Artificial Societies and Social Simulation. 2015; 18(1):11.
27. Jaton JF. Contribution à l'étude des relations pluies-débits dans les petits bassins versants ruraux. Thèse de Doctorat en Sciences Techniques, Ecole Polytechnique Fédérale de Lausanne, 1982.
28. Adams B, Kapan DD. Man bites mosquito: Understanding the contribution of human movement to vector-borne disease dynamics. PLoS ONE. 2009; 4(8):e6763.
29. Acevedo MA, Prosper O, Lopiano K, Ruktanonchai N, Caughlin TT, Martcheva M *et al*. Spatial Heterogeneity, Host Movement and Mosquito-Borne Disease Transmission. PLoSONE. 2015; 10(6):e0127552.