Elimination of Mosquitoes using Genetically Modified Mosquitoes

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***Abstract*—Over the past two decades, the threat for public health is increasing day by day, one among all the vectors considered to be a serious threat to the public is the threat caused by tiny small insect named mosquitoes. These tiny little small creatures carry viruses along and spread it to the whole mankind causing them to suffer from diseases such as zika virus, chikungunya, dengue, etc., Considering all the facts, such as outbursts of zika virus in the USA, Brazil, etc., considered Aedes aegypti commonly know as yellow fever mosquito as a serious public health threat all around the tropics as well as the subtropics. There is no cure, vaccine, or efficient control method still due to their genomic flexibility and reproductive capacity thereby making conventional control methods work inefficiently on terminating this threat by reducing the population of the yellow fever mosquitoes. A type of sterile insect technique, the release of insects carrying the dominant lethal (RIDL) in which genetically modified mosquitoes(GMOs) replace irradiation is an approach that offers greater flexibility compared to other techniques. The RIDL outperforms over all the disadvantages occurred by other conventional approaches all of which have restricted their use in mosquitoes while preserving their usefulness for the environment and species.**

This paper presents the Aedes aegypti mosquito agent-based modelling and focuses mainly on simulating the changes in population over the period of time and control methods. The agents in agent based modelling model has the key components such as characteristics and behavior of mosquitoes. The primary goal of this model will produce the practical implementation and simulation of the RIDL strategy for eradicating or regulating the mosquito population. Verification of the ABM is executed by simulations by varying the parameters and simulation. The use of Netlogo has proven to be a valuable platform for the task of simulating that helps deployment and analysis of reliable and environmentally friendly agent based modelling.

***Index Terms*—Genetically Modified Mosquitoes(GMOs), Release of Insects Carrying the Dominant Lethal(RIDL), Sterile Insect Technique(SIT), Mosquitoes, Zika Virus, Agent Based Modelling(ABM), Netlogo, Aedes Aegypti, Yellow Fever Mosquitoes**

I. Introduction

Mosquitoes mostly being the home of several arboviruses such as zika, malaria and dengue have become one of the concerning issues from the past to the present. The increase in geographic distribution increases the spread of such viruses [1]. According to the World Health Organization (WHO), around 438,000 human deaths have been reported for malaria alone which is attributed to the carrying and spreading of the disease or virus to humans. Today, over 3500 species of mosquitoes are present over the globe out of which approximately 180 of them are in the United States of America (USA) [2]. The ae. aegypti is a life form that acts as a threat to the ecology in the environment and also in recent years has taken benefit to spread all across the globe, and particularly Brazil [3]. The buzzing sound and biting habits of mosquitoes seem to be a nuisance to every individual and even are considered a serious threat for the public after the outbreaks of the viruses and also these mosquitoes are responsible for spreading chikungunya, other viruses for example a significant outburst of Zika fever in Brazil that later infected other parts of America around 2015. After the Zika virus outbreak, the Aedes aegypti mosquitoes have become a serious public threat.

Several reports have been issued by the Centers for Disease Control trying to warn the community that this virus presents in the relatively hot and moist climatic conditions, providing Aedes Aegypti with an excellent breeding ground in particular. Within those respective regions, public health administration departments actively participate in observing, controlling and regulating the population of mosquitoes. Additionally, standard methods of population control, such as breeding ground elimination through community cleanings, DDT/insecticide sprayers, etc. Environmentally friendly and reliable mosquito control strategies are crucial as there is no such vaccine available on which we can rely on. Anyway, the Aedes Aegypti (yellow fever mosquito) population has not been properly regulated by conventional methods of controlling the mosquitoes. To regulate or control the population or substitute a virus-resistant strain for the target population, novel methods involving the use of GMOs are being developed [4], [5]. The method we would use in this project is the Release of Insects Carrying the Dominant Lethal (RIDL) system [4], which is a form of Sterile Insect Technique (SIT) in which genetically modified (GM) mosquitoes replaces irradiation, a strategy that offers higher flexibility compared to other techniques [6]. The RIDL requires the discharge of very huge numbers of GMOs into the wild(affected areas). The RIDL gene is using a 'suicidal' gene which helps prevent the genetically modified mosquito's offspring from evolving into adulthood. There are currently 2 distinct genetics-based strategies, Bi-sex RIDL and fs-RIDL (female-specific). Bi-sex RIDL will cause both male and female offspring to die before adulthood. Repeated releases of GMO mosquitoes into the wild will be needed for this strategy. It could reduce the population significantly, but it is hard to eradicate a mosquito population. On the other hand, the female offspring are targeted by fs-RIDL (female-specific), ensuring they fail to survive until adulthood. Meanwhile, with the lethal gene, the male offspring will mature and continue to mate with other wild females. The modified gene is automatically propagated in favorable circumstances. Because reducing the amount of females in the next generation will further take us to follow and notice the reduction in the total population, this strategy controls and can ultimately eradicate the target population. This model focuses exclusively on the fs-RIDL method, although the Bi-sex RIDL model was iterated by the code. The primary purpose of this model is to help the user choose the ideal locations and quantities of GMO male mosquitoes to release while providing the most effective results for the practice.

Here, Agent-Based Modelling (ABM) is the computational model I would use, that simulates agent actions and interactions, as it is one of the novel approaches based on genetics. The use of ABM varies widely in the field of biology, such as population dynamics, stochastic gene expression and interactions with plant animals. The actors are depicted as independent, heterogeneous agents in agent-based modeling and are identified with features and rules governing their behavior that organize their actions and interactions. Agent-based modeling offers heterogeneity advantages by distinctly varying the characteristics of the agent and their interactions with the environment; spatial structure resulting from exposures across time and space, interactions between people and geographical constraints; and adaptation by allowing multiple correlated factors to affect the outcomes in which adaptation can be in the form of biological or behavioral [7]. Through the use of agent-based modeling to simulate this system has three main benefits. First, mosquitoes are represented by autonomous, heterogeneous agents while preserving individual attributes. All these attributes are variable and specific to the individual in the real wild environment. Second, it will lead to different outcomes by releasing genetically modified mosquitoes at different locations. This encourages an increased level of user interaction that directly influences the resulting behavior observed. At last, in a wild environment, using a model-based solely on equations could not show the actual situation. Therefore the best way to approach us to visualize the most effective way to use novel genetics-based strategies is to design and operate an ABM to simulate this system. In this paper, ABM would enable the user in many areas to select ideal places and volumes of genetically modified male mosquitoes for release and help to provide efficient outcomes. The genetically modified male mosquitoes mate with the female ones who lay eggs that hatch with the early death of the larvae before adulthood. Many experiments conducted in Brazil and other countries in recent years have shown that the discharge of genetically modified mosquitoes(male) is known to decrease yellow fever(ae. aegypti) mosquitoes population by 90% [8]. It would be easy for the researcher to choose and control the location(s) and quantities of genetically modified mosquitoes to be released for an efficient outcome with agent-based modeling. I would consider different parameters, such as changing distribution positions such as grouping or placing the mosquitoes away from each other, changing the survival rate of non-genetically modified mosquitoes. Hence, here the agents will be genetically modified male mosquitoes consisting of the following attributes.

1) Genetically modified mosquitoes - Boolean
2) Carrier of Zika - Boolean
3) Sex is female - Boolean

The context we are going to consider is an open environment for the agents to move freely. An arbitrary number of potentially infected mosquitoes would include the initial state of the model. When the simulation begins, genetically modified male mosquitoes will be released and will begin mating with wild females. When mated with genetically modified males, the females would fail to reproduce but reproduce successfully when mated with wild males. We will assess the ideal quantities and patterns depending on the success and failure of reproduction to reduce the number of genetically modified males to be released. We will use Net-Logo, a multi-agent programming language that is cross-platform and particularly suitable for agent-based modeling [9]. Users can provide instructions for many independent agents to work simultaneously, allowing users to examine "the relationship between people's micro-level behavior and the macro-level patterns that emerge from their interaction(s)" [10].

II. Literature Review

For the evaluation of nature and living creature monitoring problems [11]–[13], simulation models have been used. There's whole variety of techniques in the literature for population dynamics of mosquitoes including analytical models, mathematical models, and agent-based modeling models. Among the most notable works of mosquito populations is CIMSim [14], which uses dynamic life-table modeling of the ae. aegypti gonotrophic cycle life-stage periods, as affected by environmental factors such as temperature and moisture. United Nations Framework Convention on Climate Change recognizes CIMsim as the preferred population dynamics model of mosquito despite lacking in properties related to spatial such as distance, pattern, location, size, etc.,.DyMSim [15], TAENI2 [16] and a model [17] which uses Markov chain are other similar models. Skeeter Buster, another variant of CIMSim, is also frequently used to estimate the population of mosquitoes [18]. Multiple models of mosquitoes and mosquito-related diseases have been developed, starting with the classical Ross-Macdonald models of malaria [19]–[21] and extending to current day vector population models or vector biology aspects, not directly taking disease into account- [22]–[25]. Several approaches incorporate disease models with mosquito population suppressing models. An Agent-Based Modelling model [26] suggested creating a model for the expansion of fever(dengue), of which ae. aegypti is possibly the important vector. In this model, The movement of mosquitoes is defined with a utility function that is impacted by population characteristics, weather and geographical location. Although a granulated spatial discretization is missing from this model and only a tiny proportion of agents have been used.

Agent-Based Modelling models vary greatly from several others by gathering spatial properties between individuals that result from small changes in the agents' characteristics or behavior on a macro scale. In epidemiology, spatial systems research about the change in population over time or for analyzing population suppressing methods. In Aedes aegypti population suppression, a researcher [27] Introduce a spatial system by considering CA to examine the effects of various mosquito launch techniques as well as to simulate the discharged pulses. The model results show the importance of the frequency of the discharged pulse, the quantity of discharging sites and the threshold values for discharging volume.

SimPopMosq [28], Agent-Based Modelling of representative mosquito agents, a few other mammals, and particles found in urban ecosystems, is another spatial strategy to simulating the Aedes aegypti population. SimPopMosq is used as a population control strategy for the research of active traps and does not include sterile insect agents or methodologies. the framework [14] integrates the Agent-Based Modelling with a GIS to include a spatial system for discovering epidemiological changes in the landscape like Allocation of and impact on the allocation of aquatic breeding regions and homes of the spatial mosquito population. Another Researcher [29] had analyzed the impact of spatial characteristics such as the size of the launch area on controlling the population. To study the relationship between location-related variables, the method utilizes a mathematical model. To evaluate the RIDL for the yellow fever mosquito(A. Aegypti) population, the method [30] used the LAIS approach. The Agent-Based Modelling includes mosquitoes with independent decision-making agents and pre-determined rules which were set to the elements, such as oviposition spots, for environmental objects. This same model that being said lacks significant factors, such as an accurate and precise realistic map or effects on temperature. The absence of introducing the structure of mosquitoes(male) as well as about their need to migrate among nutritional plant life, mating is the analysis in most of these research findings.

Focks and colleagues [14], [31], investigating the biology of Aedes aegypti, is considered as one among the samples of modeling the population trends of dengue. It's an extraordinarily comprehensive model, with multiple sorts of larval development containers. Each container type is concretely tracked for levels of water, temporal changes in larval growth, the existence of food, ability to survive. Hydrological and biological functions are driven by detailed weather information. This amount of detail does have benefits and costs; it allows detailed elements of mosquito biology to be taken into account, but it also makes the model's true sensitivity analysis exceedingly difficult. Therefore, for estimated coefficients and validation, it is essential to have substantial data available to create a system with this degree of competence.

The use of ABM to model yellow fever mosquito populations has at best, been rare and extremely expensive. A work by a researcher [26] presents a few interesting ideas for example the use of a utility function for determining the mobility of mosquitoes, taking into consideration factors such as size, weather conditions, category of land use and unevenness of the landscape. Models are useful for assessing various mosquito preventive measures. Techniques such as the release of GMM have recently been regarded as an enhanced SIT for mosquito population reduction, as gene modification of mosquitoes or insects results in sterility or lethal [2], [32]. Although no genetically modified mosquito open field launch has yet been performed, a few mathematical modeling investigations carried for evaluating the model's success [33]–[35]. None of these models include simulation software or a tool for simulating the communication between the individual with mosquitoes, such as mating habits, geographical extent and many more. This tool (ABM) used for simulating help us in evaluating the model.

III. Methodology

Sterile Insect Techniques (SITs) is a technique that is used to suppress or control insects and even mosquitoes. SIT for mosquito suppression is pretty recent in the US. Since 1950, SITs were used to suppress or control insect pests or mosquitoes in the US and other parts of the world. To consider as an example SIT has been used to eradicate or suppress worm flies in the Northern and Central parts of America. Many other sorts of flies and moths have also been handled utilizing SITs. Although it is, pretty recent in the US to use SITs to control insects. SITs for mosquitoes, and not others, target specific types or species of mosquitoes involves 3 stages and they are mass mosquito producers, filtering males from females, then large scale discharge into an area of sterile male mosquitoes.

The male SIT mosquitoes discharged into a neighborhood must mainly exceed the number of wild male mosquitoes to be effective. Sterilized male mosquitoes mate with wild females after they set to release, but no children are produced due to sterility. Over the period, the amount of targeted species of mosquitoes in the region has been lowered. In the wild, SIT mosquitoes can not reproduce. Thus the particular species of mosquito being targeted will start to recover over time once SIT male mosquitoes stop being discharged into a region. Male mosquitoes don't start biting animals or people. They're feeding out of nectar. Furthermore, individuals living in the discharge region will not be bitten more often than regular. SITs for mosquito control can be used as part of an approach associated with regulating the mosquitoes. SIT may well be the favored process of reducing the number of mosquitoes in regions where it would not be possible to use insecticides, where it is not supported by the public, or where the efficacy of insecticides has been decreased by insecticide resistance.

The progress of SITs lead to a technique know to be RIDL, which is put into effect to eliminate or regulate wild populations harming agriculture or mankind for example consider a farm getting affected by pests or humans getting affected by mosquitoes. , This is obtained by the widespread rearing and discharging of homozygous mosquitoes(male) to an inducible dominant deadly genome structure, which when acquired, leads to death in offspring. Overall, genetically modified mosquitoes or insects are released to compete with wild individuals for mates, leading to control or eradication of the population. The RIDL is further comprised of two strategies Bi-Sex RIDL and Female Specific RIDL.

when considering Bi-Sex RIDL, the heterozygous progeny are killed by the lethal inherited whereas when considering female-specific RIDL, The gene which is lethal to be considered as female-specific, so female offspring die but heterozygous male offspring live. The below figure shows the overall description of the RIDL method.

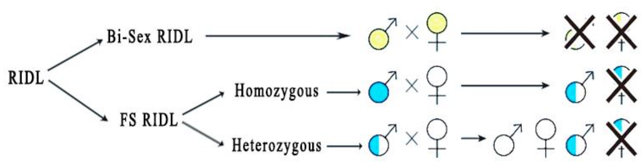

Fig. 1. Methodology of RIDL

In this paper, we considered FS-RIDL over Bi-Sex RIDL because of the limitations of the Bi-sex RIDL such as this method will cause that both male and female offspring die before adulthood. This method requires repeated releases of the GMO mosquitoes into the wild. It could significantly reduce the population but hard to eradicate a mosquito population.

IV. Model Description, Technical Implementation and Operating Instructions

We proposed the components required to design Agent-Based Modelling and all the information necessary to understand the simulation and working of this model.

A. Model Description and Technical Implementation

Eggs have been hatched in the bodies of water which in our model is represented by cyan colour patches. After hatching, the adult mosquitoes then try to mate with the compatible mosquitoes of the opposite gender.The user who controls the release of genetically modified (GMO) male mosquitoes in terms of locations, quantities, and quantity of releases. In the open, unbound environment, the mosquito agents fly around, interacting with others, evaluating compatibility, and attempting to mate.

Successful mating requires a non-pregnant, fertile female and a male within a radius of 3 units of the female. There is a compatibility variable (0-9) that must match for the female and male to mate successfully. This represents the variable frequency used for mosquitoes to find a mate. Once a suitable mate is found, the fertilized female seeks out the nearest water patch within her field of view (180-degree, 10 distance). After waiting a rest period of 5 ticks, she lays 0 to 300 eggs. The eggs laid are of type wild (non-GMO) or GMO depending on the genetic makeup of her male partner. Females can get pregnant a random number of times (1 - 3). After eggs have been laid, the female resumes seeking a mate.

Male mosquitoes have a life span, randomly set, ranging from 3 to 10 ticks. The life span of females same as male mosquitoes life span but with a random multiplier between 2 and 5. This represents the fact that female mosquitoes can live up to 5 times longer than males.

On each tick each water patch, if applicable, hatches 1 egg. If both wild (non-GMO) and GMO eggs exist on said patch, one is chosen at random. A user-controlled survival rate for both wild (non-GMO) and GMO determines the odds that the egg will successfully hatch. Since females produced from GMO eggs do not survive to adulthood, only GMO males are produced. The new generations of mosquitoes then proceed to seek mates, thus continuing the cycle.

The code demonstrates many examples of sprouting turtles from a patch. It also shows the use of the watch, subject, and reset-perspective primitives in conjunction with mouse-down and mouse coordinates to automatically pause model and allow user to select and drag a turtle. The model shows how to leverage the in-cone reporter to create a field of vision then uses max-one-of and face to find the closest water patch.

B. Operating Instructions

Prior to Setup, the initial release locations should be set using the initial-release-locations slider. This sets the number of GMO deployment locations ranging from 0 to 10. These deployment locations are represented by red boxes in the environment.

Next simulation initialization is invoked using the SETUP button. This creates the aforementioned deployment locations as well as three bodies of water represented by cyan colored patches. Within these patches are an initial random (0-49) amount of wild (non-GMO) eggs.

To start the simulation, the GO button is pressed. This button has the forever option selected to keep the simulation running continuously until subsequent pressing of the GO button. Once running, eggs will hatch producing adult mosquitoes. These mosquitoes will attempt to reproduce as detailed in the previous sections.

While the simulation is running the user can position the release locations for the genetically modified mosquitoes by dragging each red box using the mouse to place them anywhere in the environment.

The quantity of genetically modified male mosquitoes to be discharged per region is defined using the GMO-release-per-deployment slider, ranging from 0 to 100. Note, this is per location so multiply this number by the overall number of regions to obtain the overall quantity of genetically modified male mosquitoes that will be deployed each time the Release GMO button is pressed.

Once release settings are configured, press the Release GMO button. This can be pressed any number of times. Each press will release the set number of GMO mosquitoes from the current locations. Locations and gmo-release-per-deployment can be changed through out the simulation run.

Survival rate of wild (non GMO) and GMO mosquitoes are controlled by the wild-survival-rate and gmo-survival-rate respectively. This is the success rate that a hatched egg will produce an adult mosquito. This represents the reality that not all eggs laid result in adult mosquitoes that are able to reproduce in their own rite.

On the bottom left side you will find several counters display the total tally of wild (non-GMO) egg, GMO eggs, uninfected adult mosquitoes, and adult mosquitoes that have been infected with the mutated gene.

On the right side there are two plots that historically track the eggs and mosquito populations. The plot titled Eggs plots wild (non-GMO) egg in blue and GMO eggs in red. The plot titled Mosquitoes plots wild (non-GMO) mosquitoes in blue and GMO mosquitoes in red.

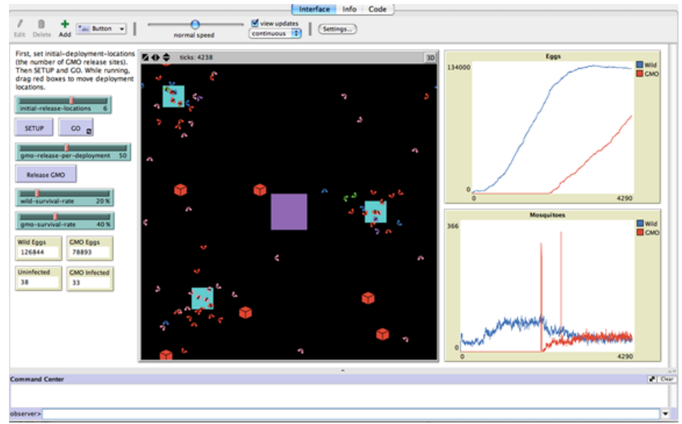

Fig. 2. Violet structure has no affect on agent behavior

C. Model Design

1) Prototypes: The design process was an agile prototype paradigm. This paper began with initial research. Based on that research, we quickly determined the model would need mosquito agents, possibly multiple breeds, and water sources to support the reproductive cycle. The original proposal focused on Zika carrying mosquitoes and the process of reducing the pathogen carrying insects. Once we understood the science of what researchers were targeting, the scope of the model changed to an eradication model of entire populations of mosquitoes.

The prototype process started by creating the water sources similar to the food sources in the ant model explained in class. The major difference is the water patches have eggs, which the patches sprout the mosquito agents. This how the initial mosquito population is established. I like this because it mimics the real world in which researchers would enter an environment with an established random population. Next the mosquito agents received attributes to enable mating, followed by the ability to fly around seeking a mate. This was the basis for the entire system.

the project focused on both the Bi-sex RIDL method and fs-RIDL method of genetic manipulation initially. Later, we found that in Bi-sex RIDL method the GMO impregnated females simply did not lie any eggs to model the fact that none of the offspring survive to adulthood. and the fs-RIDL (female specific) method as discussed early, the female offspring does not survive to adulthood and the males mature thus passing the modified gene to the next generation.

An early prototype experiment was to include structures that might interfere with the reproduction process by allowing a small percentage of mosquitoes to enter the structure. Those that enter would have a hard time getting out but could still mate if the opportunity presented itself. I quickly found this feature had almost no impact on the greater simulation. Mosquitoes rarely entered the structure and those that did, died. Though a valuable investigation, the building did not serve in understanding the real problem at hand. I chose to remove this feature.

2) Assumptions: A number of assumptions were made in interest of time. The developmental stages from egg to adult are not represented. Eggs simply hatch and produce an adult mosquito that is ready to mate. To counter the lack of temporal delay while the mosquito develops through the life cycle, I have up to one egg hatch per patch, per tick. To simplify the code and reduce clutter in the environment, there are no GMO female offspring, since they will not survive to adult hood. The initial wild egg count on water patches is hard coded to a random number from zero to 49. As explained earlier, this is only intended to kick start a preexisting population. A mating compatibility variable exists to add a challenge to the success of mating. Without this in place, the mosquitoes would not need to seek a mate. They would simply spawn and immediately mate with the nearest agent of the opposite sex. The random compatibility forces the agent to move around and actually seek out a mate. In nature the pregnant females rest to allow the eggs to develop after she feeds on the necessary proteins, blood. To mimic this behavior, I added a hard coded rest period of 5 ticks that must elapse before eggs can be laid. This period can elapse while the female is seeking a water patch. Another assumption is pregnant females head straight for water. In reality they need to feed to develop the eggs so they would not go straight to water. In seeking water they were given a vision cone of 180 degrees and distance of 10. In addition to these assumptions, there are a number of random values generated to maintain variability in the model.

Random Values:

- Life expectancy – Males 3-10, Females 3-50
- Compatibility value – 0-9
- Max pregnancies in a lifetime – 0-3
- Number of eggs laid per pregnancy – 0-299

3) Agent Identification: The identification of the agents are done with the color that is changed and their characteristics such as reproductive events and genetically modified(GMO) status. The below table 1 illustrates the color and other characteristics of the agents.

TABLE I
AGENT IDENTIFICATION BASED ON COLOR

Color	Sex	GMO Infected	Pregnant
	Female	Wild(Non-GMO)	No
	Female	Wild(Non-GMO)	Yes
	Female	GMO	Yes
	Male	Wild(Non-GMO)	NA
	Male	GMO	NA

4) Agent Relationships: There are three types of agent-self interactions:

- If not pregnant, female mosquitoes look for a male to mate
- If pregnant, female mosquitoes find water to lay eggs
- If life time decrease to zero, agents die.

There are two types of agent-agent interactions:

- Wild male mate with wild female
- GMO male mate with wild female

There are three types of agent- environment interactions:

- Release GMO male at one or several release locations.
- Female laid eggs at water patches.
- Hatch eggs from water patches.

There is one type of environment-environment interaction:

- Select a release location and move the location to another patch.

5) Verification and Validation: The primary methods of verification employed were inspection. Debug statements using show and show word were used to confirm correct values were produced and procedures were utilized correctly. Iterative development was used in coding and testing small features and procedures before incorporating them into the main code base. Verification in the environment was performed by watching and following agents and patches to confirm the correct behavior and values.

The validation methods performed for this model include of requirements validation, data validation, face validation, process validation, agent validation, and theory validation.

- Requirements validation addressed that the primary problem of determining the most efficient method of releasing GMO mosquitoes for eradication purposes is correct problem to solve.
- Data validation confirmed all data used in model include survival rate, life span, number of eggs laid, and number pregnancies in a lifetime, are set to the correspond numbers observed natural environment.
- Face validation established all assumptions are based on the real world, and the model results are reasonable.
- Process validation confirmed the model does not represent all the steps in real-world process, but it captured the most important steps of reproduction process of mosquitoes.
- Agent validation determined agent behaviors and interaction mechanisms such as mating and laying eggs at water sources correspond to agents in the real world.
- Theory validation is represented by experimental simulation runs of the model. The fs-RIDL (female specific) strategy indicated that, through using genetically modified (GMO) male mosquitoes, the entire population would be reduced and ultimately eradicated. The results of the simulation are consistent with this theory.

V. EXPERIMENTS, RESULTS, AND DISCUSSION

There are a number of interesting aspects to notice and explore in this model which are listed below.

1) The extinction process will occur rapidly if the survival rate of GMO mosquitoes is greater than the survival rate of wild (non-GMO) mosquitoes. On the other hand, extinction will take a much if GMO mosquitoes and wild (non-GMO) mosquitoes have the same survival rate, with the same release number. The survival rate of wild mosquitoes in a wild environment is about 20%.
2) The result would not be significantly affected by changing the position of deployment points, such as grouping them together or positioning them far from each other. Putting deployment points near the water sources, however could speed up the eradication time particularly when the number of deployment points is low.
3) The initial population can be controlled prior to GMO release by adjusting the survival rate of the wild mosquitoes and letting the model run, allowing the population to increase or decrease to the desired number.

Overall, 13 test experiments were carried out. The main concept of experiments was to choose one variable to alter, while keeping the others constant. After that, we observed how the results would be affected by these alterations. All the results of these experiments were shown in table 1.

1) Tests 1 through 3 held the initial release location at one. GMO release number and GMO deploy times were constant. The release locations were moved or the GMO survival rate was changed.
2) Tests 4 through 6 increased initial release location to five and held the GMO release number and GMO deploy times constant. Again, the release locations were moved or the GMO survival rate was changed.
3) Tests 7 through 9 increased initial release location to ten, held GMO release number and GMO deploy times constant, moved the release locations or change the GMO survival rate..
4) Tests 10 and 11 held initial release location at ten, held GMO release number constant, and reduced release times to one.
5) Tests 12 and 13 held initial release location at ten, resume GMO deploy times to ten, increase GMO release number to 10000, and change the GMO survival rate.

From Table 2 and Figure 3 shown below, the test result shows that, the top three of “wild mosquitoes survival time”

TABLE II
TESTING RESULTS OF MOSQUITO MODEL

Test No	Initial Release Location	GMO Release Per Deploy	Wild Survival Rate	GMO Survival Rate	GMO Release Number	GMO Release Ticks	GMO Deploy Times	Release Location	Extinction at Ticks
T1	1	100	20%	40%	1000	1496	10	Near Water	60925
T2	1	100	20%	40%	1000	1563	10	Far From Water	119258
T3	1	100	20%	20%	1000	1465	10	Near Water	167893
T4	5	20	20%	40%	1000	1460	10	Randomly	50237
T5	5	20	20%	40%	1000	1491	10	Near Water	74846
T6	5	20	20%	20%	1000	1504	10	Randomly	241024
T7	10	10	20%	40%	1000	1495	10	Randomly	79211
T8	10	10	20%	40%	1000	1438	10	Near Water	53408
T9	10	10	20%	20%	1000	1480	10	Randomly	167397
T10	10	100	20%	40%	1000	1608	1	Randomly	50877
T11	10	100	20%	20%	1000	1508	1	Randomly	NA
T12	10	100	20%	40%	10000	1470	10	Randomly	46721
T13	10	100	20%	20%	10000	1473	10	Randomly	88609

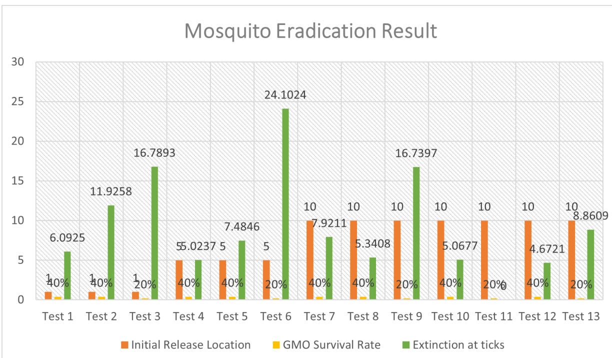

Fig. 3. Histogram of Mosquito Model

were test6, test 3 and test 9. All three tests have set that both GMO and wild survival rate were equal to 20%. Furthermore, test 11 released GMO only for one time, and the GMO and wild survival rate still be kept at 20%. This setting resulted in that none of the GMO mosquito survived and failed to mate with wild female. In result, the eradication was also failed.

A. *Test Screenshots*

Some of the test screenshots have been captured and shown in the below figures.

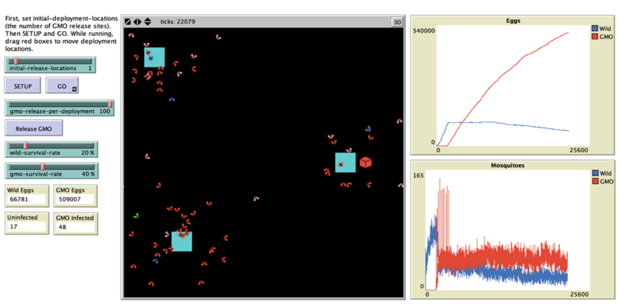

Fig. 4. One "near water" release location GMO survival rate: 40%

VI. CONCLUSION AND FUTURE WORK

To conclude, the same settings do not always lead to the same results.The eradication process may not be speeded up by increasing the GMO input. Increasing the input of GMOs,

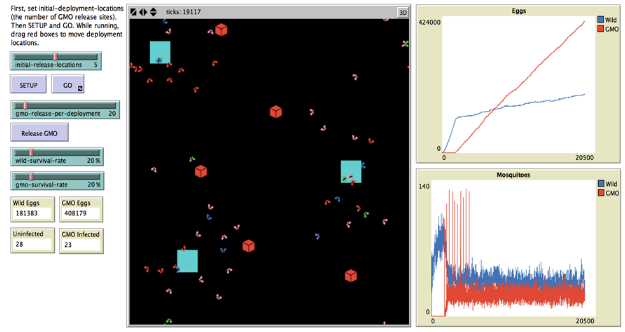

Fig. 5. Five randomly release locations GMO survival rate: 20%

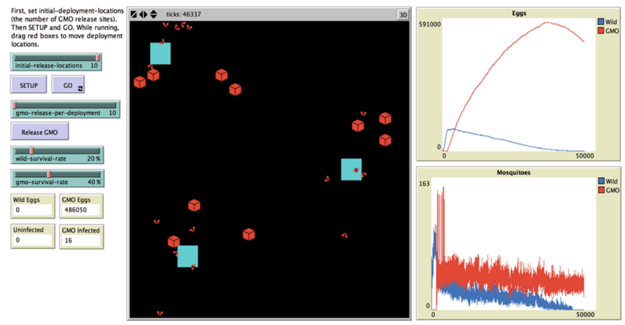

Fig. 6. Ten randomly release locations GMO survival rate: 40%

however could increase the chance of success and will lead to shorter average total eradication times. The outcome is closer to the real world and demonstrates Agent Based Modelling Systems advantage. From all the tests conducted, we found several phenomena:

1) With the same GMO release number, the eradication time was accelerated by putting deployment points near the water, particularly when the number of deployment points is low.
2) With several release locations, the eradication efficiency was not significantly influenced by increased location numbers.
3) When the survival rate of GMO mosquitoes is above the survival rate of wild (non-GMO) mosquitoes, the eradication speed is faster.
4) Increasing the release times increased the possibility of eradication with the same GMO release number, but did not significantly affect the efficiency of eradication.
5) Releasing only one time may cause none of the GMO mosquitoes to survive and the mission will fail
6) Increasing the GMO release number from 1000 to 10000 would give us a decrease return to scale but it is not efficient at these high numbers.

Therefore, the most efficient way to release the GMO mosquitoes is to use 5 release locations. The locations can be randomly placed, but not too far from the water sources. They are most effective when close to or on the actual water sources. The total GMO release number should be 10%-20% of wild mosquitoes, and release GMO mosquitoes about 10 times. Considering that in a wild environment, the survival rate of wild mosquitoes is about 20%, and we could not expect that the GMO survival rate would higher in wild, so set both survival rate at 20% is closer to reality. There are a number of ways to alter the model, so it will make the model much more precise to the reality.

According to the changes in the environment there might be scope of adding new elements or changing the behaviours of the existing elements. Adding more user control of multiple species of mosquitoes would implied by the compatibility variable but could be expanded upon. To closer resemble the development stages of the mosquito, from egg to adulthood one must add hatch time. In reality, female mosquitoes need feeding on blood, which they need to mature their eggs. By adding agent predation behaviour embeds a full life cycle in the model and could incorporate additional factors that decrease population of mosquitoes such as bats and spray treatments.

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APPENDIX A-CODE

Below is the code attached and it has been completely created and simulated by me taking some of the references from YouTube tutorials and the highlighted code below is inspired by mouse drag one example(http://modelingcommons.org/) and it is replicated as per the requirement in our code.

```
breed [ females female ]                ;; Female mosquito breed of turtles
breed [ males male ]                    ;; Male mosquito breed of turtles
breed [ deployments deployment ]        ;; GMO mosquito release sites breed of turtles

;;;;;;;;;;;;;;;;;;;;;;;;;
;;; Female variables ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;

females-own [
  compatibility  ;; Random number that must match for mosquitoes to mate (integer)
  life-time      ;; Remaining life in number of ticks (integer)
  pregnant?      ;; Boolean flag to track if female is pregnant (boolean)
  preg-count     ;; Counter to track number of pregnancies (integer)
  target         ;; Patch where female will lay eggs (patch)
  rest-count     ;; Counter for length of time between pregnancies (integer)
]

;;;;;;;;;;;;;;;;;;;;;;;
;;; Male variables ;;;
;;;;;;;;;;;;;;;;;;;;;;;

males-own [
  compatibility  ;; Random number that must match for mosquitoes to mate (integer)
  life-time      ;; Remaining life in number of ticks (integer)
  gmo?           ;; Boolean flag to track if mosquito is GMO (boolean)
]

;;;;;;;;;;;;;;;;;;;;;;;;
;;; Patch variables ;;;
;;;;;;;;;;;;;;;;;;;;;;;;

patches-own [
  water?         ;; Flag to track if patch represents water (boolean)
  wild-eggs      ;; Counter for number of wild eggs on a patch (integer)
  gmo-eggs       ;; Counter for number of GMO eggs on a patch (integer)
]

;;;;;;;;;;;;;;;;;;;;;;;;;
;;; Global variables ;;;
;;;;;;;;;;;;;;;;;;;;;;;;;

globals [
  total-wild-eggs  ;; Counter for wild eggs laid (integer)
  total-gmo-eggs   ;; Counter for GMO eggs laid (integer)
]

;;;;;;;;;;;;;
;;; Setup ;;;
;;;;;;;;;;;;;

to setup                    ;; Observer procedure
```

```
  clear-all                  ;; Initialize environment by clearing all agents
  reset-ticks                ;; Reset tick count to 0
  set total-wild-eggs 0      ;; Initialize global total wild eggs counter to 0
  set total-gmo-eggs 0       ;; Initialize global total GMO eggs counter to 0
  set-default-shapes         ;; Apply default shapes to turtle breeds
  setup-patches              ;; Setup initial patches
  setup-deployments          ;; Setup initial GMO release locations
end

to set-default-shapes        ;; Turtle procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Define shapes to represent each turtle breed;;
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  set-default-shape females "butterfly"
  set-default-shape males "butterfly"
  set-default-shape deployments "box"
end

to setup-patches                        ;; Patch procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Initialize all patches;;
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ask patches [
    set water? false                    ;; Not water
    set wild-eggs 0                     ;; Patch has 0 wild eggs
    set gmo-eggs 0                      ;; Patch has 0 GMO eggs
  ]
  setup-water                           ;; Call sub procedure
end

to setup-water                          ;; Patch procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Create three water sources;;
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ask patches [
    if (distancexy (0.6 * max-pxcor) 0) < 2
    [ setup-water-patch ]
    if (distancexy (-0.6 * max-pxcor) (-0.6 * max-pycor)) < 2
    [ setup-water-patch ]
    if (distancexy (-0.8 * max-pxcor) (0.8 * max-pycor)) < 2
    [ setup-water-patch ]
  ]
end

to setup-water-patch         ;; Patch procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Initialize water patches;;
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  set water? true            ;; Is water
  set wild-eggs random 50    ;; Each water patch starts with 0-49 wild eggs
  set pcolor cyan            ;; Color water patches light blue

  ;; Update global total wild egg counter
  set total-wild-eggs total-wild-eggs + wild-eggs
end
```

```
to setup-deployments                    ;; Patch procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Create one deployment location on n-number of random patches,;;
  ;; where n is initial-release-locations set from interface;;;;;;;;
  ask n-of initial-release-locations patches [ ;; create a deployment turtle on
     random patches
    sprout-deployments 1 [
      set color red                     ;; Color deployments red
      set size 2                        ;; Lager size, easier to see
    ]
  ]
end

;;;;;;;;;;
;;; Go ;;;
;;;;;;;;;;

to go               ;; Observer procedure, forever button
  if (total-wild-eggs = 0 and total-gmo-eggs = 0 and count females = 0 and count
     males = 0) [
    stop            ;; Stop simulation when there are no more mosquitoes and eggs
  ]

  gmo-release-location  ;; Monitor for deployment location movements
  hatch-eggs            ;; Hatch eggs, 1 per patch (where applicable)

  ask females [
    if not pregnant? [ find-mate ]    ;; Female mosquitoes look for a male mate
    if pregnant? [ find-water-to-lay-eggs ]  ;; When pregnant find water to lay eggs
    if not pregnant? [ mingle ]       ;; If not pregnant, continue looking for mate
    advance-life          ;; Call sub procedure to keep track of life time remaining
  ]
  ask males [
    mingle          ;; Call sub procedure to
    advance-life    ;; Call sub procedure to keep track of life time remaining
  ]

  tick                                  ;; Advance ticks
end

to release-gmo      ;; Observer procedure, Button
  ;; This button triggered procedure creates n-number of GMO male mosquitoes at the
     patch where each deployment
  ;; box is positioned, where n is the gmo-release-per-deployment set from slider in
     interface. This runs every
  ;; the button is pressed
  ask deployments [
    ask patch-here [
      release-gmo-males gmo-release-per-deployment
    ]
  ]
end

to release-gmo-males [ num ]    ;; Patch procedure
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  ;; Create n-number of GMO male mosquitoes, where n is the parameter num;;;;
```

```
  ;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
  sprout-males num [
    sprout-gmo-male      ;; Call sub procedure to create a GMO male
  ]
end

to gmo-release-location    ;; Deployment breed turtle procedure
                           ;; While Go procedure is running, this procedure
                           ;; monitors if user mouse drags a deployment turtle
  if mouse-down? [
    let candidate min-one-of deployments [distancexy mouse-xcor mouse-ycor]
    if [distancexy mouse-xcor mouse-ycor] of candidate < 1 [
      ;; The WATCH primitive puts a "halo" around the watched turtle.
      watch candidate
      while [mouse-down?] [
        ;; If we don't force the view to update, the user won't
        ;; be able to see the turtle moving around.
        display
        ;; The SUBJECT primitive reports the turtle being watched.
        ask subject [ setxy mouse-xcor mouse-ycor ]
      ]
      ;; Undoes the effects of WATCH.  Can be abbreviated RP.
      reset-perspective
    ]
  ]
end
}

to hatch-eggs                          ;; Patch procedure
  ;; This procedure hatches an egg on each water patch where an egg exists
  ask patches with [ water? = true and (wild-eggs > 0 or gmo-eggs > 0) ] [
    ;; If both wild and GMO eggs exist, one is chose randomly
    ifelse (wild-eggs > 0 and gmo-eggs > 0) [
      ifelse one-of [ true false ] [
        ;; hatch wild eggs
        hatch-wild-egg
      ]
      [
        ;; hatch gmo eggs
        hatch-gmo-egg
      ]
    ]
    [
      ifelse wild-eggs > 0 [
        ;; Only wild eggs exist
        ;; hatch wild eggs
        hatch-wild-egg
      ]
      [
        ;; Only gmo eggs exist
        ;; hatch gmo eggs
        hatch-gmo-egg
      ]
    ]
  ]
end
```

```
to hatch-wild-egg                    ;; Patch procedure
  ;; This procedure creates a non GMO mosquito if a random number between 0 and 100
  ;; is less than or equal to the wild-survival-rate set on the interface slider
  if random 101 <= wild-survival-rate [
    ;; Randomly choose to create a wild male or wild female
    ifelse one-of [ true false ] [
      sprout-females 1 [
        set color pink  ;; Color pink to indicate wild (non GMO), fertile female
        set compatibility random 10   ;; Random compatibility number between 0 and 9
        ;; This represents the fact that female mosquitoes can live up to 5 times
           longer than males
        set life-time (3 + random 8) * (2 + random 4)
        set pregnant? false           ;; Female specific variables, indicates non GMO
        ;; Female specific variables, counter for random maximum number of
           pregnancies in the
        ;; females life time. Random number between 1 and 3
        set preg-count 1 + random 3
      ]
    ]
    [
      sprout-males 1 [
        set color blue  ;; Color blue to indicate wild (non GMO) male
        set compatibility random 10 ;; Random compatibility number between 0 and 9
        set life-time 3 + random 8 ;; Life span will be a random number between 3
           and 10
        set gmo? false  ;; Male specific variables, indicates non GMO
      ]
    ]
  ]
  set wild-eggs wild-eggs - 1  ;; Decrement wild egg counter for this patch
  set total-wild-eggs total-wild-eggs - 1 ;; Decrement global total wild egg counter
end

to hatch-gmo-egg         ;; Patch procedure
  ;; This procedure creates an GMO mosquito if a random number between 0 and 100
  ;; is less than or equal to the gmo-survival-rate set on the interface slider
  if random 101 <= gmo-survival-rate [
    ;; Since females produced from GMO eggs do not survive to adulthood, we only
       produce GMO males
    sprout-males 1 [
      sprout-gmo-male
    ]
  ]
  set gmo-eggs gmo-eggs - 1 ;; Decrement GMO egg counter for this patch
  set total-gmo-eggs total-gmo-eggs - 1 ;; Decrement global total GMO egg counter
end

to sprout-gmo-male       ;; Patch procedure
  set color red          ;; Color red to indicate GMO male
  set compatibility random 10   ;; Random compatibility number between 0 and 9
  set life-time 3 + random 8  ;; Life span will be a random number between 3 and 10
  set gmo? true          ;; Male specific variables, indicates GMO
end

to find-mate             ;; Female breed turtle procedure
```

```
  if color = pink and preg-count > 0 [ ;; Double check only fertile female
    ;; Randomly select a male with in a radius of 3
    let mate min-one-of males in-radius 3 [distance myself]
    ;; Error handler against no male getting selected
    if mate != nobody [
      ;; Check compatibility matches
      if [compatibility] of mate = [compatibility] of self [
        fertilize [gmo?] of mate      ;; Fertilize this female based passing GMO flag male mate
      ]
    ]
  ]
end

to fertilize [gmo-flag?] ;; Female breed turtle procedure
  ;; This procedure fertilizes the female given the gmo? flag parameter
  set pregnant? true      ;; Flag indicates this female is now pregnant
  set rest-count 5        ;; Females must rest at least 5 ticks between pregnancies
  set preg-count preg-count - 1 ;; Decrement pregnancy counter
  ifelse gmo-flag? [    ;; If fertilized by a GMO male
    set color green     ;; Color green to identify carrying GMO eggs
  ]
  [
    set color violet ;; Color violet to identify carrying wild eggs
  ]
end

to find-water-to-lay-eggs   ;; Female breed turtle procedure
  if pregnant? [            ;; Double check only pregnant female
    find-water              ;; Look for water patch
    ;; Error handler against no patch getting selected
    ifelse target = nobody [
      ;; If no water patch is found, keep looking
      mingle
    ]
    [
      ifelse patch-here = target [
        ;; If current patch is the targeted water patch and rested long enough, lay eggs
        if rest-count <= 0 [
          lay-eggs
        ]
      ]
      [
        ;; If current patch is not the targeted water patch, change heading to the target
        face target
        forward 1                     ;; Move forward 1
      ]
    ]
    set rest-count rest-count - 1     ;; Decrement rest counter
  ]
end

to find-water               ;; Female breed turtle procedure
  ;; Look for water patches with in a 180 degree view, distance of 10, and colored
```

```
    cyan
  let targets (patches in-cone 10 180 ) with [pcolor = cyan]
  ;; Choose the closest water patch and set the female member variable
  set target min-one-of targets [ distance myself ]
end

to lay-eggs                    ;; Female breed turtle procedure
  ;; This procedure lays random number of eggs (0 to 299), either wild (non GMO) or
  ;; GMO depending on which type of male she mated
  let new-eggs random 300
  if color = violet [  ;; Lay wild eggs on current patch
    set wild-eggs wild-eggs + new-eggs
    set total-wild-eggs total-wild-eggs + new-eggs ;; Update global total wild egg
      counter
  ]
  if color = green [     ;; Lay GMO eggs on current patch
    set gmo-eggs gmo-eggs + new-eggs
    set total-gmo-eggs total-gmo-eggs + new-eggs ;; Update global total GMO egg
      counter
  ]
  set pregnant? false     ;; Reset pregnancy flag to false
  set color pink          ;; Reset color to pink to indicate fertile
  set rest-count 0        ;; Reset rest counter to 0
end

to mingle                      ;; Female and male breed turtle procedure
  right flutter-amount 45    ;; Turn right random amount
  left flutter-amount 45     ;; Turn left random amount
  forward 1                  ;; Move forward 1
end

to-report flutter-amount [limit] ;; Female and male breed turtle procedure
  report random-float (2*limit) - limit
end

to advance-life      ;; Female and male breed turtle procedure
  set life-time life-time - 1   ;; Decrements life counter
  if life-time < 0 [ die ]      ;; If life expired, turtle die
end
```