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MALARIA DISEASE MODEL TRANSMISSION WITH MOSQUITOES CONTROL NON-PROLIFERATION

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Abstract

In [1], we have constructed a model which describes transmission of malaria disease by considering mosquitoes bed net as human population control; this model was derived from Kagunda model [6]. In this paper, we study a malaria disease model transmission using mosquitoes proliferation control. We determine the disease free equilibrium state of the model and compute the basic reproduction number. Numerical simulations are performed to show the impact of using mosquitoes proliferation control in malaria disease model transmission.

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1. Introduction

The COVID-19 pandemic has defied all diseases responses throughout the world in general and particularly for malaria disease responses in 2020, and is expected to continue to do so in the upcoming years. All countries and partners have had to adjust programming to safely serve communities with malaria prevention and case management, in line with COVID-19 health measures [2]. According to the Framework for Policy Decision on RTS, S/AS01 endorsed by the Strategic Advisory Group of Experts on Immunization (SAGE) and MPAC in 2019, a WHO policy recommendation on the use of that vaccine beyond the pilot countries could be made if and when:

- the safety signals observed in the Phase 3 trial (i.e. those related to meningitis, cerebral malaria and sex-specific mortality) have been satisfactorily resolved, and
- severe malaria and mortality data trends have been assessed as being consistent with a beneficial impact of the vaccine [3].

As it is every year organized on April 25th, international malaria day, World Health Organization (WHO) announces on this 25th April 2021, that the laboratory of Oxford University of England in collaboration with Burkina Faso researchers has produced a vaccine which is tested on many children and the efficacity is about 77%.

Malaria is a disease which affects millions of people in this world, specially in non-developed countries and make several deaths [7-9]. These countries and the World Health Organization (WHO) spent every year billions of dollars for the eradication of this disease, but their effort is insufficient due to the number of registered deaths. This is why we try to give our contribution by formulating models in order to help the politics in making decision for fighting this calamity [1]. In this model, we make a control on mosquitoes for their non-proliferation.

We have organized our work as follows: Second 2 is devoted to the model formulation. Section 3 treats about the disease free equilibrium state and Section 4 computes the basic reproduction number. Numerical simulations are presented in Section 5 in order to see the impact of using mosquitoes proliferation control within the vectors population for this malaria disease model transmission. A conclusion and some perspectives will end this work.

2. Model Formulation

We consider the same model constructed in [1] with its variables and parameters. The only novelty in the use of a control which we denote by θ_m and means "*the mosquitoes control non-proliferation*"; this is one of our perspective formulated on [1]. The diagram is presented as follows:

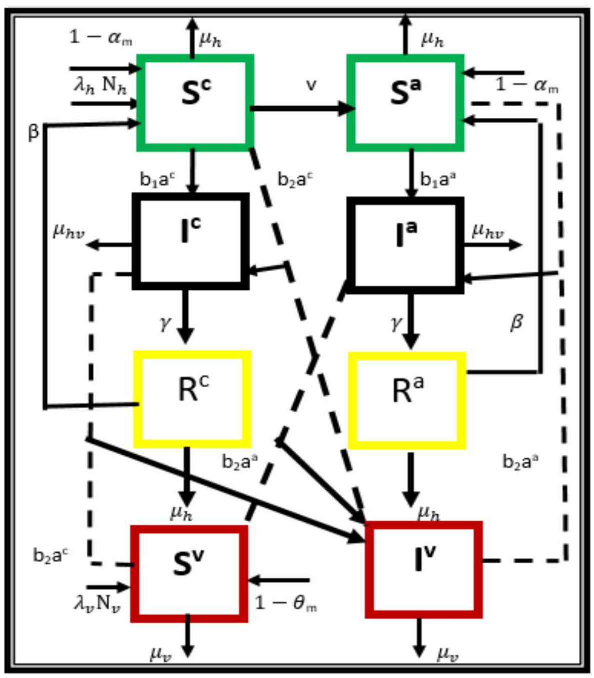

Figure 1. Diagram of the model.

$$\begin{cases} \frac{dS^c}{dt} = \lambda_h N_h + (1-\alpha_m)S^c + \beta R^c - b_2 a^c \frac{I^v}{N_v} S^c - b_1 a^c S^c - (\mu_h + v)S^c, & (1) \\ \frac{dS^a}{dt} = vS^c + (1-\alpha_m)S^a + \beta R^a - b_2 a^a \frac{I^v}{N_v} S^a - b_1 a^a S^a - \mu_h S^a, & (2) \\ \frac{dI^c}{dt} = b_1 a^c S^c + b_2 a^c \frac{I^v}{N_v} S^c - (\mu_{hv} + \gamma) I^c, & (3) \\ \frac{dI^a}{dt} = b_1 a^a S^a + b_2 a^a \frac{I^v}{N_v} S^a - (\mu_{hv} + \gamma) I^a, & (4) \\ \frac{dR^c}{dt} = \gamma I^c - R^c(\mu_h + \beta), & (5) \\ \frac{dR^a}{dt} = \gamma I^a - R^a(\mu_h + \beta), & (6) \\ \frac{dS^v}{dt} = \lambda_v N_v - b_2 a^c \frac{I^c}{N_h} S^v - b_2 a^a \frac{I^a}{N_h} S^v - S^v \mu_v + (1-\theta_m)S^v, & (7) \\ \frac{dI^v}{dt} = b_2 a^c \frac{I^c}{N_h} S^v + b_2 a^a \frac{I^a}{N_h} S^v - \mu_v I^v & (8) \end{cases}$$

with initial conditions:

$$\begin{cases} S^c(0) = S_0^c,\ S^a(0) = S_0^a,\ S^v(0) = S_0^v; \\ I^c(0) = I_0^c,\ I^a(0) = I_0^a,\ I^v(0) = I_0^v; \\ R^c(0) = R_0^c,\ R^a(0) = R_0^a, \end{cases} \quad (9)$$

where:

α_m is the probability of mosquito bed net use;

μ_{hv} is the human death rate related to the disease;

γ is the rate recovery from the disease;

λ_h is the human natality rate;

λ_v is the mosquito natality rate;

N_h, N_v are, respectively, the total number of human population and the vector population;

β is the rate of recovered human who became sensitive;

S^c, S^a, I^c, I^a are, respectively, the susceptible population (children and adults) and the infected population (children and adults);

S^v and I^v are, respectively, the vector susceptible and infected population;

a^c and a^a are, respectively, the mosquito blood rate on children and adults;

b_1 is the probability that a sensitive human becomes infected after infected mosquito biting;

b_2 is the probability that a sensitive mosquito becomes infected after a meal on infected human;

μ_h, μ_v are the natural death rates, respectively, of humans and vectors;

v is the proportion children becoming adults;

Exponents "*c*", "*a*" design, respectively, "children" and "adults";

θ_m designs the mosquitoes control non-proliferation.

Applying the same rules and methods of calculation as in [1], we obtain the following normalized model:

$$\begin{cases} \dfrac{ds^c}{dt} = -s^c[\lambda_h + v + (\alpha_m - 1)(i^c + i^a + r^c + r^a) + (\mu_h - \mu_{hv})(i^c + i^a) \\ \qquad + a^c(b_2 i^v + b_1)] + (\lambda_h + \beta r^c), & (10) \\ \dfrac{ds^a}{dt} = -s^a[\lambda_h + (\alpha_m - 1)(i^c + i^a + r^c + r^a) + (\mu_h - \mu_{hv})(i^c + i^a) \\ \qquad + a^a(b_2 i^v + b_1)] + (\beta r^a + vs^c), & (11) \\ \dfrac{di^c}{dt} = a^c s^c(b_2 i^v + b_1) - i^c[(\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1 - \alpha_m)(s^c + s^a) \\ \qquad + (\mu_h - \mu_{hv})(i^c + i^a)], & (12) \\ \dfrac{di^a}{dt} = a^a s^a(b_2 i^v + b_1) - i^a[(\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1 - \alpha_m)(s^c + s^a) \\ \qquad + (\mu_h - \mu_{hv})(i^c + i^a)], & (13) \\ \dfrac{dr^c}{dt} = \gamma i^c - r^c[(\lambda_h + \beta) + (1 - \alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)], & (14) \\ \dfrac{dr^a}{dt} = \gamma i^a - r^a[(\lambda_h + \beta) + (1 - \alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)], & (15) \\ \dfrac{ds^v}{dt} = \lambda_v - s^v[b_2(a^c i^c + a^a i^a) + \lambda_v - i^v(1 - \theta_m)], & (16) \\ \dfrac{di^v}{dt} = s^v[b_2(i^c a^c + a^a i^a) - i^v(1 - \theta_m)] - \lambda_v i^v, & (17) \end{cases}$$

where

$$s^c = \frac{S^c}{N_h}, \quad s^a = \frac{S^a}{N_h}, \quad i^c = \frac{I^c}{N_h}, \quad i^a = \frac{I^a}{N_h}, \quad r^c = \frac{R^c}{N_h}, \quad r^a = \frac{R^a}{N_h},$$

with

$$s^c + s^a + i^c + i^a + r^c + r^a = 1,$$

$$s^v = \frac{S^v}{N_v}, \quad i^v = \frac{I^v}{N_v} \text{ with } s^v + i^v = 1.$$

From equations (1)-(6), we obtain the variational human population as follows:

$$\frac{dN_h}{dt} = N_h(\lambda_h - \mu_h) + (1 - \alpha_m)(S^c + S^a) + (\mu_h - \mu_{hv})(I^c + I^a). \quad (18)$$

From equations (7) and (8), we obtain the variational mosquito population as follows:

$$\frac{dN_v}{dt} = N_v(\lambda_v - \mu_v) + (1 - \theta_m)S^v. \qquad (19)$$

The resolution of equations (18) and (19) leads to determine the effective total human population (N_h) and the effective mosquito population (N_v), respectively, at time *t*:

$$N_h(t) = N_h^0 e^{[(\lambda_h - \mu_h) + (1-\alpha_m)(S^c + S^a) + (\mu_h - \mu_{hv})(I^c + I^a)]t}$$

and

$$N_v(t) = N_v^0 e^{[(\lambda_v - \mu_v) + (1-\theta_m)S^v]t},$$

where $N_h^0 = N_h(0)$ and $N_v^0 = N_v(0)$.

3. The Disease Free Equilibrium (DFE) State

The Disease Free Equilibrium (DFE) designs the state where the disease does not exist in the whole population. It is defined through its components $x_{dfe}(s^c, s^a, i^c, i^a, r^c, r^a, s^v, i^v)$, where

$$i^a = i^c = i^v = r^a = r^c = 0. \qquad (20)$$

To obtain this, we solve the following problem:

$$\begin{cases} -s^c[\lambda_h + v + (\alpha_m - 1)(i^c + i^a + r^c + r^a) + (\mu_h - \mu_{hv})(i^c + i^a) \\ + a^c(b_2 i^v + b_1)] + (\lambda_h + \beta r^c) = 0, \\ -s^a[\lambda_h + (\alpha_m - 1)(i^c + i^a + r^c + r^a) + (\mu_h - \mu_{hv})(i^c + i^a) \\ + a^a(b_2 i^v + b_1)] + (\beta r^a + v s^c) = 0, \\ a^c s^c(b_2 i^v + b_1) - i^c[(\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1 - \alpha_m)(s^c + s^a) \\ + (\mu_h - \mu_{hv})(i^c + i^a)] = 0, \\ a^a s^a(b_2 i^v + b_1) - i^a[(\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1 - \alpha_m)(s^c + s^a) \\ + (\mu_h - \mu_{hv})(i^c + i^a)] = 0, \\ \gamma i^c - r^c[(\lambda_h + \beta) + (1 - \alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)] = 0, \\ \gamma i^a - r^a[(\lambda_h + \beta) + (1 - \alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)] = 0, \\ \lambda_v - s^v[b_2(a^c i^c + a^a i^a) + \lambda_v - i^v(1 - \theta_m)] = 0, \\ s^v[b_2(i^c a^c + a^a i^a) - i^v(1 - \theta_m)] - \lambda_v i^v = 0. \end{cases} \tag{21}$$

Applying equation (20) to the above system, we obtain:

$$\begin{cases} \lambda_h = s^c(\lambda_h + v), \\ v s^c = s^a \lambda_h, \\ \lambda_v = s^v \lambda_v. \end{cases} \tag{22}$$

We deduce $s_h^c = \dfrac{\lambda_h}{\lambda_h + v}$; $s_h^A = \dfrac{v}{\lambda_h + v}$; $s_v = 1$ and

$$x_{dfe}\left(\frac{\lambda_h}{\lambda_h + v}, \frac{v}{\lambda_h + v}, 0, 0, 0, 0, 1, 0\right).$$

4. Basic Reproduction Number Computation

We use the next generation matrix method to compute the basic reproduction number R_0' [5]. This method consists to solve the infected equations (11), (12) and (16):

$$\begin{cases} \dfrac{di^c}{dt} = a^c s^c (b_2 i^v + b_1) - i^c[(\lambda_h + \mu_{hv} + \gamma - \mu_h) \\ \qquad + (1-\alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)], \\ \dfrac{di^a}{dt} = a^a s^a (b_2 i^v + b_1) - i^a[(\lambda_h + \mu_{hv} + \gamma - \mu_h) \\ \qquad + (1-\alpha_m)(s^c + s^a) + (\mu_h - \mu_{hv})(i^c + i^a)], \\ \dfrac{di^v}{dt} = s^v[b_2(i^c a^c + a^a i^a) - i^v(1-\theta_m)] - \lambda_v i^v. \end{cases} \tag{23}$$

Let

$$K_1 = (\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1-\alpha_m)(s^c + s^a);$$

$$K_2 = (\mu_h - \mu_{hv})(i^c + i^a);$$

$$K_3 = (\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1-\alpha_m)(s^c + s^a);$$

$$K_4 = (\mu_h - \mu_{hv})(i^c + i^a);$$

$$K_5 = \lambda_v + s^v(1-\theta_m);$$

$$F_1 = \begin{pmatrix} a^c s^c b_2 i^v \\ a^a s^a b_2 i^v \\ s^v[b_2(i^c a^c + a^a i^a)] \end{pmatrix}; \quad V_1 = \begin{pmatrix} K_1 i^c + K_2 i^c \\ K_3 i^a + K_4 i^a \\ i^v K_5 \end{pmatrix},$$

where:

- F_1 the vector of new infections and;
- $V_1 = V_- - V_+$, where V_- and V_+ design, respectively, the entry vector and the outer vector for a given compartment.

The partial derivatives of F_1 and V_1 relative to i^c, i^a and i^v lead to the Jacobian matrixes F and V as follows:

$$F = \begin{pmatrix} 0 & 0 & a^c s^c b_2 \\ 0 & 0 & a^a s^a b_2 \\ a^c s^v b_2 & a^a s^v b_2 & 0 \end{pmatrix};$$

$$V = \begin{pmatrix} K_1 + (2i^c + i^a)(\mu_h - \mu_{hv}) & i^c(\mu_h - \mu_{hv}) & 0 \\ i^a(\mu_h - \mu_{hv}) & K_3 + (2i^a + i^c)(\mu_h - \mu_{hv}) & 0 \\ 0 & 0 & K_5 \end{pmatrix}.$$

The Jacobian matrix V applied to the Disease Free Equilibrium (DFE) gives:

$$V = \begin{pmatrix} K_1 & 0 & 0 \\ 0 & K_3 & 0 \\ 0 & 0 & K_5 \end{pmatrix}; \quad V^{-1} = \begin{pmatrix} \frac{1}{K_1} & 0 & 0 \\ 0 & \frac{1}{K_3} & 0 \\ 0 & 0 & \frac{1}{K_5} \end{pmatrix};$$

$$-FV^{-1} = \begin{pmatrix} 0 & 0 & -\frac{a^c s^c b_2}{K_5} \\ 0 & 0 & -\frac{a^a s^a b_2}{K_5} \\ \frac{-a^c s^v b_2}{K_1} & \frac{-a^a s^v b_2}{K_3} & 0 \end{pmatrix}.$$

The spectral radius of $-FV^{-1}$ corresponding to the basic reproduction number R_0' is given by:

$$R_0' = \sqrt{\frac{s^c(a^c b_2)^2 + s^a(a^a b_2)^2}{[(\lambda_h + \mu_{hv} + \gamma - \mu_h) + (1 - \alpha_m)](\lambda_v + 1 - \theta_m)}}.$$

Considering that the mosquito blood meal on children a^c is equal to its equivalent on adult $a^a (a^c = a^a)$, we can rewrite:

$$R_0' = \frac{(a^a b_2)}{\sqrt{(\lambda_h + \mu_{hv} + \gamma - \mu_h + 1 - \alpha_m)(\lambda_v + 1 - \theta_m)}}.$$

5. Numerical Results

In this section, we present some numerical results. We compare the basic reproduction number R_0 obtained in [1] with control on human population (mosquitoes bed net use, α_m) and the basic reproduction number R_0' obtained in this document with two controls, mosquitoes bed net use (α_m) and mosquitoes non-proliferation (θ_m):

$$R_0 = \frac{(a^a b_2)}{\sqrt{\lambda_v(\lambda_h + \mu_{hv} + \gamma - \mu_h + 1 - \alpha_m)}}$$

and

$$R_0' = \frac{(a^a b_2)}{\sqrt{(\lambda_h + \mu_{hv} + \gamma - \mu_h + 1 - \alpha_m)(\lambda_v + 1 - \theta_m)}}.$$

To show the impact of mosquitoes control, we consider the following cases:

(1) First case

We chose the following parameters as fixed in [6] $(\mu_h = 0.033,$ $\lambda_v = 0.07,$ $a^c = 0.42,$ $b_2 = 0.24,$ $\mu_{hv} = 0.033,$ $\gamma = 0.035,$ $\lambda_h = 0.04,$ $b_1 = 0.08,$ $\beta = 0.005,$ $v = 0.000283).$

Table 1. Parameters involved in the computation of the basic reproduction number

	First case		
α_m	0.3	0.4	0.5
θ_m	0.3	0.4	0.5
R_0	0.5994	0.6403	0.6910
R_0'	0.0373	0.0428	0.0503

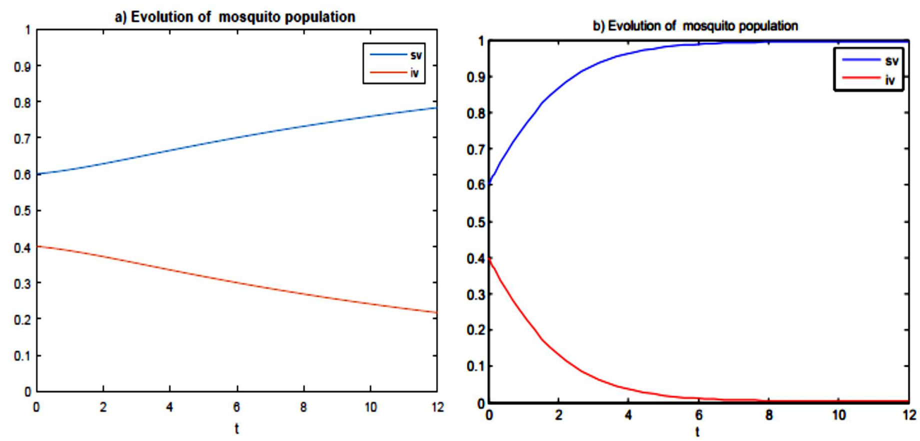

Figure 2. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

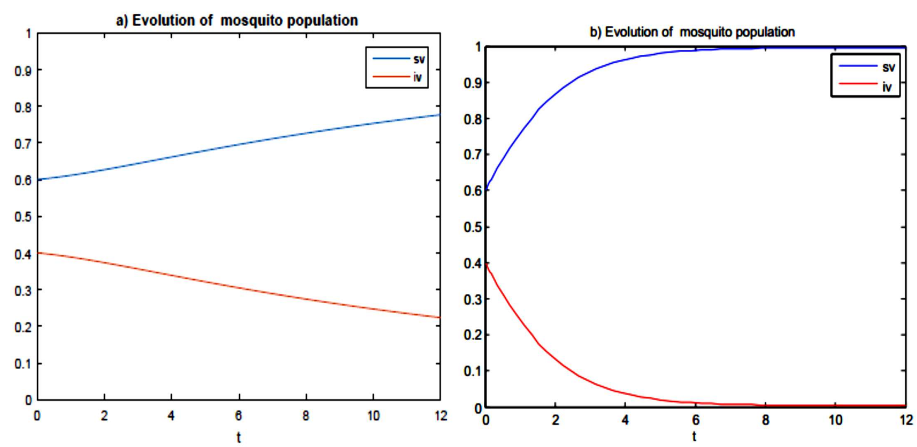

Figure 3. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

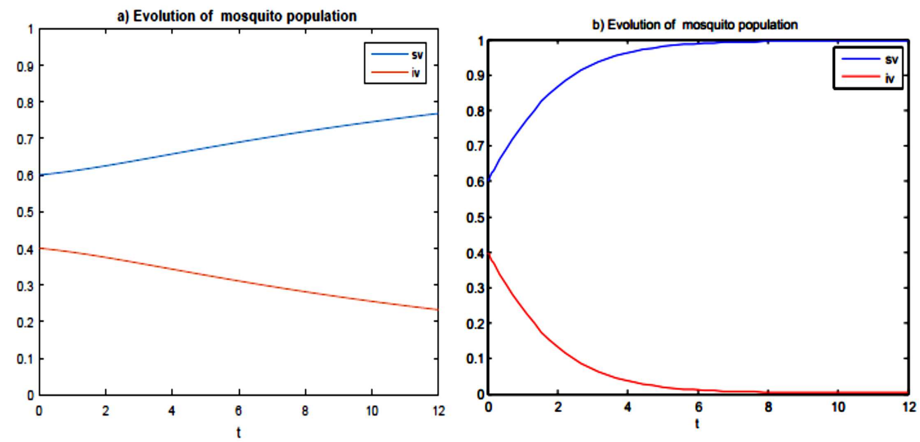

Figure 4. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

(2) Second case

In this case, we change all the variables ($\mu_h = 0.07$, $\lambda_v = 0.07$, $a^c = 0.52$, $b_1 = 0.15$, $b_2 = 0.45$, $\mu_{hv} = 0.05$, $\gamma = 0.05$, $\lambda_h = 0.07$, $v = 0.0004$, $\beta = 0.005$).

Table 2. Parameters involved in the computation of the basic reproduction number

	Second case		
α_m	0.3	0.4	0.5
θ_m	0.3	0.4	0.5
R_0	0.9508	1.0164	1.0979
R'_0	0.2867	0.3285	0.3847

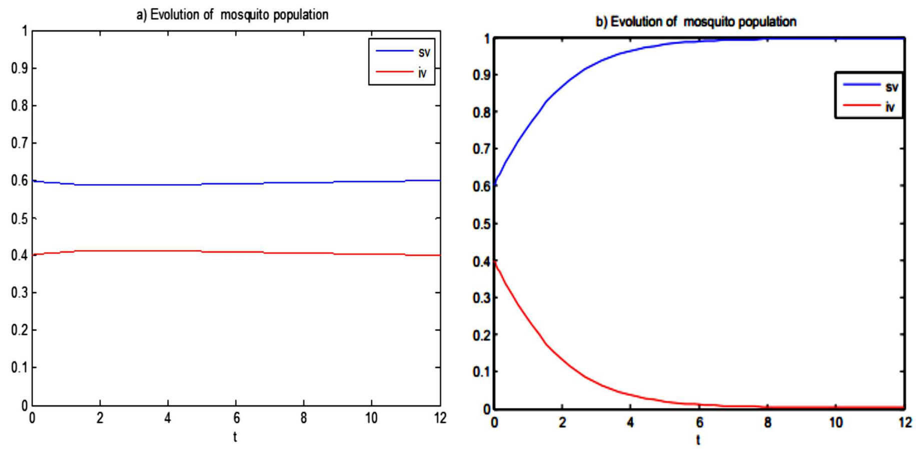

Figure 5. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

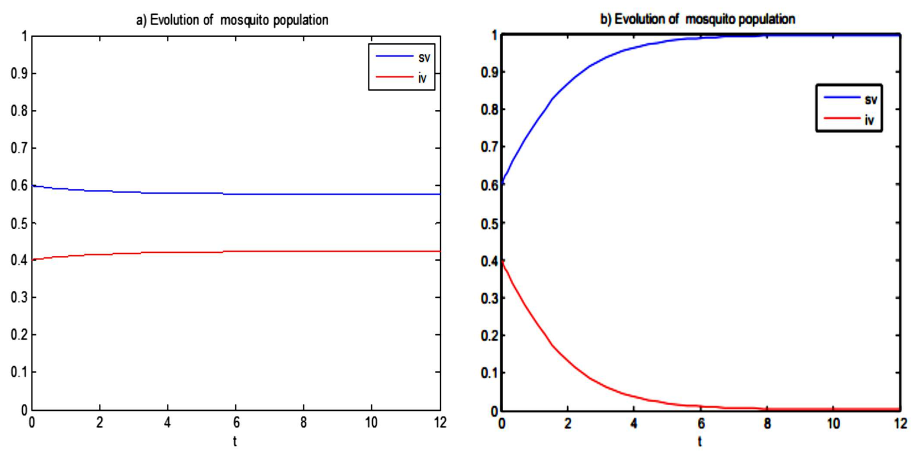

Figure 6. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

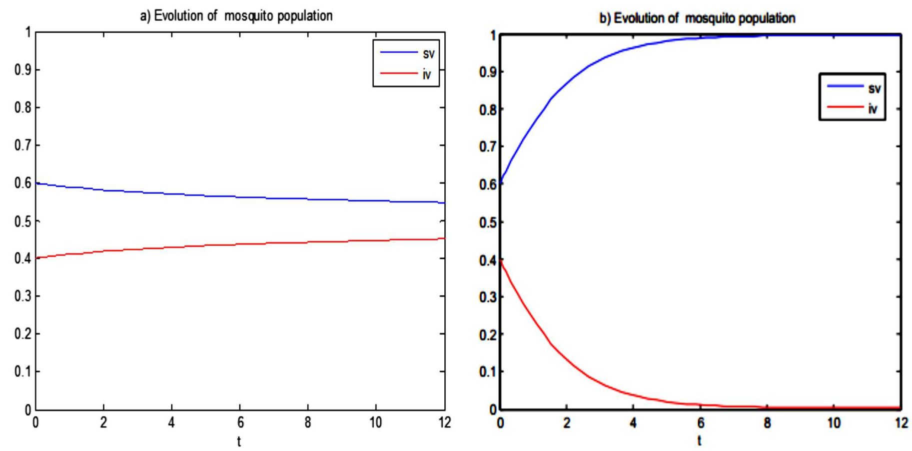

Figure 7. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

(3) Third case

$(\mu_h = 0.07,\ \lambda_v = 0.07,\ a^c = 0.52,\ b_1 = 0.15,\ b_2 = 0.45,\ \mu_{hv} = 0.05,$ $\gamma = 0.05,\ \lambda_h = 0.07,\ v = 0.0004,\ \beta = 0.005).$

Table 3. Parameters involved in the computation of the basic reproduction number

	Third case		
α_m	0.3	0.4	0.5
θ_m	0.2	0.3	0.4
R_0	0.9508	1.0164	1.0979
R_0'	0.2697	0.3065	0.3549

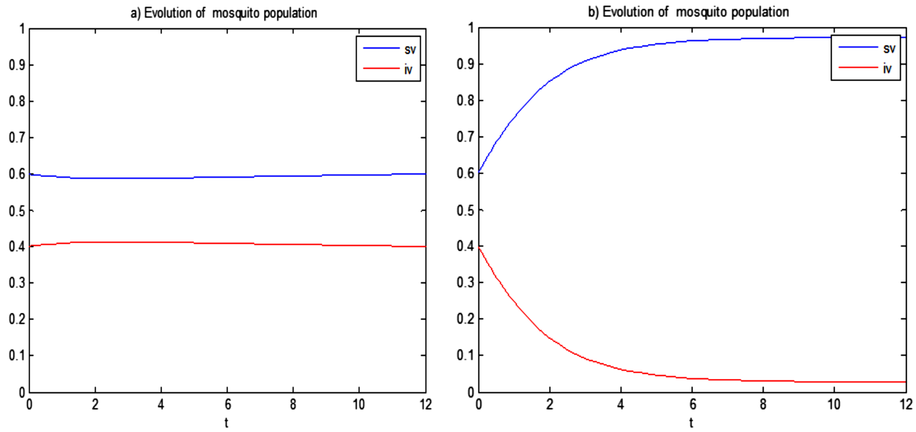

Figure 8. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

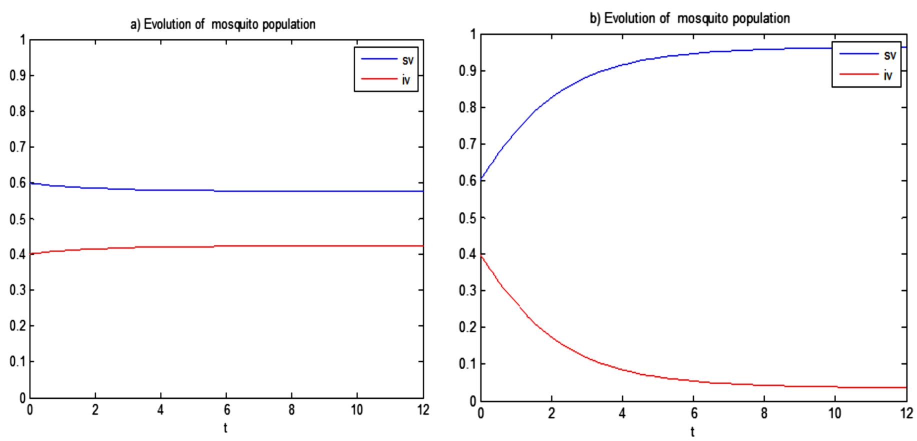

Figure 9. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

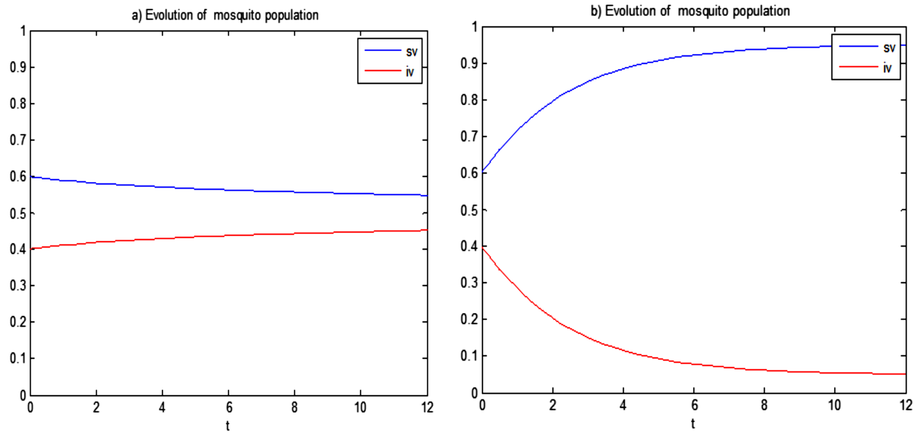

Figure 10. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

(4) Fourth case

($\mu_h = 0.07$, $\lambda_v = 0.07$, $a^c = 0.52$, $b_1 = 0.15$, $b_2 = 0.45$, $\mu_{hv} = 0.05$, $\gamma = 0.05$, $\lambda_h = 0.07$, $v = 0.0004$, $\beta = 0.005$).

Table 4. Parameters involved in the computation of the basic reproduction number

	Fourth case		
α_m	0.3	0.4	0.5
θ_m	0.4	0.5	0.6
R_0	0.9508	1.0164	1.0979
R_0'	0.3073	0.3562	0.4237

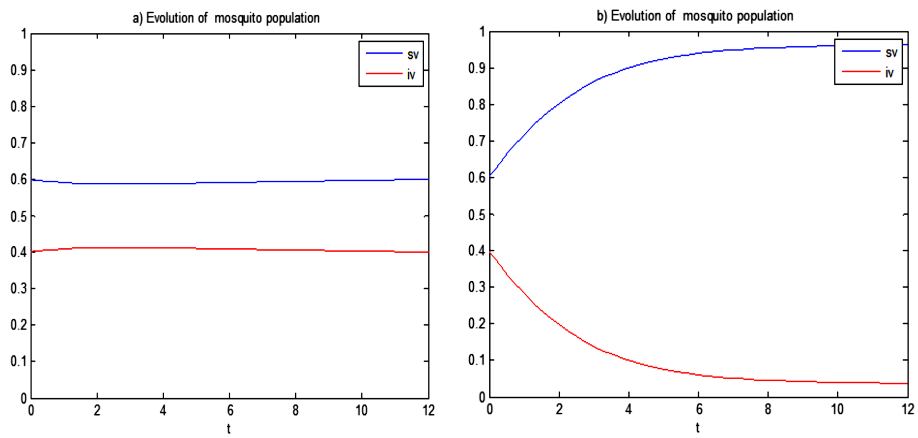

Figure 11. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

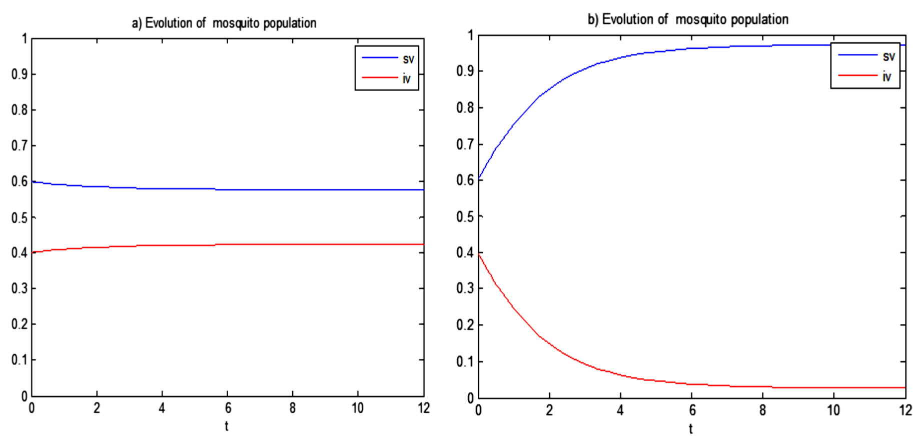

Figure 12. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

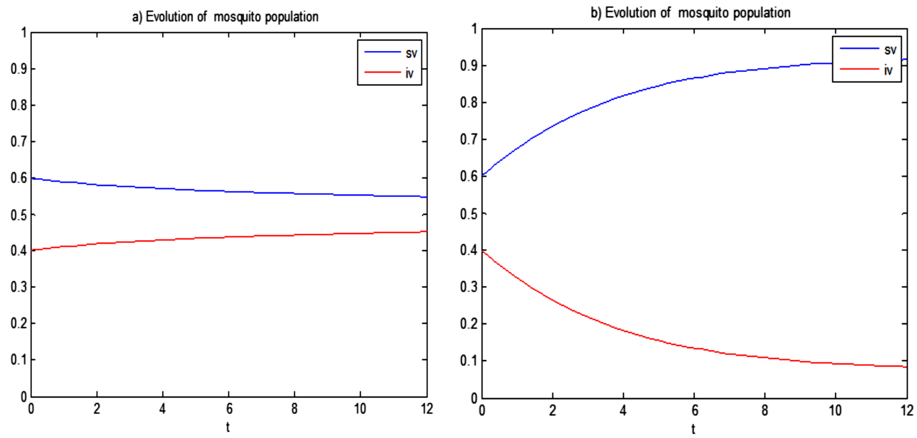

Figure 13. Evolution of mosquitoes population with mosquitoes bed net use only (a), and with both controls (mosquitoes bed net and mosquitoes proliferation control) (b).

Table 1 shows that both values of the basic reproduction number $(R_0$ and $R'_0)$ are less than one, which means that the disease is over to disappear among the whole population by either using the mosquito bed net or mosquito control non-proliferation. This aspect is translated on Figures 2 to 4 by the decrease of the curves representative of the infected mosquito population (i^v) which is nearly to zero (0).

Tables 2 to 4 show that the value of R'_0 in these three last cases (second, third and fourth cases) is tiny less than 1, which effect is the completely disappearance of the disease. This can also be read on Figures 5 to 13, where the curve of infected vector is nearly to zero (0).

The comparison of R_0 and R'_0 shows a significant diminution of its value: 90% to 91% for Table 1, 65% to 70% for Table 2, 68% to 72% for Table 3 and 62% to 67% for Table 4. This large diminution is the impact of using both controls, the mosquitoes bed net and mosquitoes control non-proliferation.

Tables 3 and 4 show that the value of R_0' is the smallest when the mosquitoes control is less than the control on human population (the use of mosquitoes bed net).

Malaria as a disease which affects millions of people in the world, bereaved thousands of families by causing more than 400000 deaths each year. This calamity can be controlled by simultaneously applying a double control. This can be traduced as follows:

(1) if the disease is less represented among the human population, that is when there is no more infected people, by applying a control on human population such as the use of mosquito bed net (α_m);

(2) by applying a simple control on mosquitoes, such as the use of insecticide to control their proliferation (θ_m);

(3) and the use of vaccine for the vulnerable populations (children and old men).

6. Conclusion

In this paper, we have formulated a malaria model disease transmission with a double control (mosquitoes bed net use and mosquitoes non-proliferation). The analysis of our model shows a considerable decrease of the basic reproduction number obtained under two controls (mosquitoes bed net use and mosquitoes non-proliferation) $R_0' < 1$ (Tables 1 to 4) driving out the disease among the populations.

As perspectives according to our model, we intend to introduce a delay in order to better realistic for further studies.

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