Optimization of Insect Management Strategy Using Green Insecticide and Mating Disruption

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Abstract

Many losses in the agriculture sector all around the world are caused by insects. Pest insect is one kind of pests that damages crop by feeding directly to crop or being a vector of crop diseases. To avoid loss from crop failures caused by an insect, an environmentally friendly pest insect management becomes important. This paper provides the illustrations of pest insect management strategies using an optimal control approach. A model of insect life stages was used to describe the process of the insect life cycle and 2 control methods were introduced namely green insecticide intervention and mating disruption. A set of differential equations consisting of the state system and adjoin system were derived and used to solve the control problem. This paper discusses four possible scenarios that describe the possible control cost possibilities and examine three types of strategies based on the combination of controls used. Illustrative examples are provided to assess the effectiveness of each strategy in each scenario.

Keywords
Green insecticide, mating disruption, optimal control

1. Introduction

Many types of insects are considered major pests in the agriculture sector. This problem exists along with the additional problem caused by the agriculture production intensification. Crop losses around the world in 2001-2003 are said to be at around 10.9% for potatoes, 15.1% for rice, and 12.3% for cotton while the losses caused by the pathogen are said to be at 14.5% for potatoes, 10.8% for rice, and 8.5% for cotton (Oerke 2006). The use of agrochemicals along with the use of dwarf and high yielding crops resulted in the increasing number of crop losses caused by pests (Dhaliwal *et al.* 2010). The reduction of pest natural predator and organism diversity caused by the intensification of the agricultural sector also contribute the pest outbreaks around the world, including pest insect outbreaks (Dent 2000).

Chemical indiscriminate pesticide application is one of the most common ways to control the population of pests including insects. However, it is also commonly known that the long term application of this kind of pesticide impacts negatively to agriculture itself. The use of indiscriminate pesticide creates an environmental and health problem. The use of conventional pesticides poses a great threat to the environment such as the contamination of soil, surface water, and groundwater that are also threats to the consumer of agricultural products and the workers in that sector (Mourato *et al.* 2000), A good example would be Brazil with the indication of 46% of active substance used comes with a medium to high risk to human (Dasgupta *et al.* 2001).

Several alternative substances and methods to control the population of pest insects are being developed to deal with this dilemma. Two of them are the development of mating disruption method and bisacylhydrazine insecticide that is considered as a green insecticide. Mating disruption is a non-insecticide method of insect population control using synthetic sex pheromone (Foster and Harris 1997). There are several ways to apply mating disruption. Combining it with a trap is one of the most common ways to apply mating disruption (Evenden *et al.* 1998). Aerial dispersal is also one way to apply mating disruption (Brockerhoff *et al.* 2012). However, it is suggested to apply mating disruption along with the application of other complementary control methods (Cocco *et al.* 2014). Therefore, we also consider bisacylhydrazine insecticide. Bisacylhydrazine is a class of chemistry that affects the larva stage of insect and results in desiccation and death (Dhadialla *et al.* 1998). This type of insecticide is also called a development disrupting insecticide since it disrupts the development process of insect which was firstly inspired by the research to find an insecticide from insect moulting hormone (Watkinson and Clarke 1973). The effects of bisacylhydrazine application include feeding inhibition within three to four hours, and making larva mouthparts remain soft, thus preventing it from feeding on crops and die (Dhadialla *et al.* 2010). These two methods are considered in this paper since both of them are selective pest control methods as an alternative to indiscriminate conventional pesticides.

To ensure the effectiveness of the control application, not only the development of the substances and methods that are important. The strategies of control implementation are also an important part of pest management. The strategies expected to be used are the strategies that give the most benefit with the lowest cost spent in the process of control implementation. The optimal control approach is one of many approaches to find optimal strategies to control the pest population.

2. Mathematical model

2.1. Model

In this paper, the model introduced in Anguelov *et al.* (2017) is examined to evaluate the effectiveness of control strategies. This model explains the life stages of an insect. To do that, the model uses four compartments namely larva (I), unfertilized female (Y), fertilized female (F), and male insect (M). There are several modification of interpretation made from this model. First, mating disruption method in Anguelov *et al.* (2017) is modified and interpreted as the proportion of natural sex pheromone is targeted to be repelled by the synthetic sex pheromone. Second, the rate of mortality that is caused by the implementation of green insecticide is also added. These controls are interpreted as dynamic variables instead of constant variables. In the framework of optimal control, this interpretation enables us to apply control differently at different points of time and find the optimal application strategy. The compartment model is provided by Figure 1.

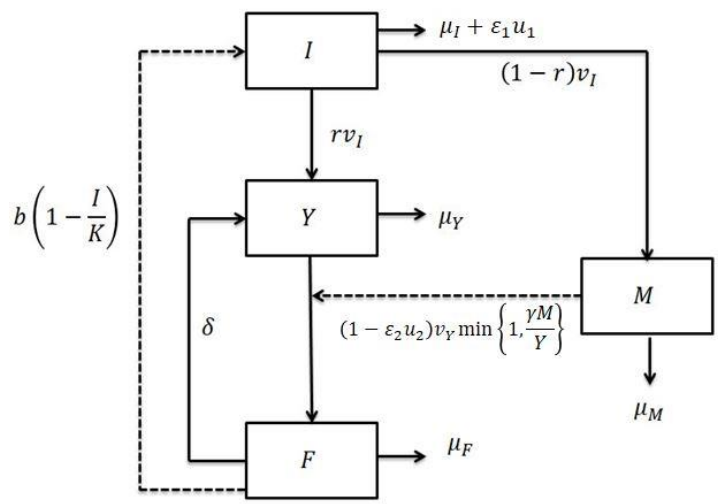

Figure 1. Insect life stages compartment model

Larva is produced by the fertilized female with the intrinsic egg laying number of b and it is assumed to follow logistic growth with the carrying capacity of K. Larva will grow to be a mature insect with the growth rate of v_I. Larva will grow to be either unfertilized female insect or male insect with the proportion of female to male of r. Unfertilized female insect will mate with male insect with the rate of v_Y for the possibility of a single female to be mated expressed as $\min\left\{1, \frac{\gamma M}{Y}\right\}$ for γ is the number of female that can be mated by a single male. It is important to note that the system is divided into two cases. First is the male abundance case where the number male is large enough to mate every unfertilized female. This case will happen if $\xi = \gamma M - Y \geq 0$. Second case is male scarcity where the number of male is not large enough to mate every unfertilized female. This case will happen if the expression $\xi = \gamma M - Y < 0$ is met. Fertilized female will be unfertilized female again at the rate of δ. In every stage of insect life, there will be natural rate of mortality. These natural rates of mortality are expressed as μ_I, μ_Y, μ_F, and μ_M that represented the natural mortality rate of larva, unfertilized female, fertilized female, and male population.

The controls introduced in this paper namely green insecticide using bisacylhydrazine and mating disruption is represented a time dependent dynamic variables u_1 and u_2. As the interpretation of controls in this paper, these controls are also bounded and have the values that follow the expression of $0 \leq u_i \leq 1$ for $i = 1,2$. Each control has the affectivity of ε_i for $i = 1,2$. The control variables are attached to the model based on their respective role in controlling the insect population. The algebraic form of the model is provided by equations (1)-(4) and the initial values for each differential equation are $I(0) = I_0 > 0, Y(0) = Y_0 > 0, F(0) = F_0 > 0$, and $F(0) = F_0 > 0$.

$$\frac{dI(t)}{dt} = b\left(1 - \frac{I(t)}{K}\right)F(t) - \left(v_I + \mu_I + \varepsilon_1 u_1(t)\right)I(t) \tag{1}$$

$$\frac{dY(t)}{dt} = rv_I I(t) + \delta F(t) - \left(\left(1 - \varepsilon_2 u_2(t)\right)v_Y \min\left\{1, \frac{\gamma M(t)}{Y(t)}\right\} + \mu_Y\right)Y(t) \tag{2}$$

$$\frac{dF(t)}{dt} = \left(1 - \varepsilon_2 u_2(t)\right)v_Y \min\left\{1, \frac{\gamma M(t)}{Y(t)}\right\}Y(t) - (\delta + \mu_F)F(t) \tag{3}$$

$$\frac{dM(t)}{dt} = (1 - r)v_I I(t) - \mu_M M(t). \tag{4}$$

2.2. Control problem

In the framework of optimal control, the dynamic control variables are going to be determined optimally with respect to a performance index that will be the objective functional. The objectives of controls application is to minimize the total insect population and minimize the controls application cost. Considering these objectives, the objective functional (5) was constructed.

$$\min J = \int_0^{t_f} C_0 N(t) + C_1 u_1^2(t) + C_2 u_2^2(t)\, dt \tag{5}$$

for $C_k; k = 0,1,2$ are the balancing cost weights that represent the relative cost of each parts of the objective functional and $N(t) = I(t) + Y(t) + F(t) + M(t)$ is the total insect population. The minimization process of the control problem is subject to equations (1)-(4) that are referred as state system. The values of each state function are a response to the application of controls (Tu 1984).

3. Optimality conditions

In order to solve the control problem, Pontryagin's maximum principle (Tu 1984) was exploited. Pontryagin's maximum principle expresses the control problem as the solutions for the optimal controls, state system, and adjoin system. To derive the optimality conditions, a Hamiltonian function (6) was constructed.

$$\begin{aligned} H = {} & C_0 N(t) + C_1 u_1^2(t) + C_2 u_2^2(t) + p_1(t)\left[b\left(1 - \frac{I(t)}{K}\right)F(t) - \left(v_I + \mu_I + \varepsilon_1 u_1(t)\right)I(t)\right] \\ & + p_2(t)\left[rv_I I(t) + \delta F(t) - \left(\left(1 - \varepsilon_2 u_2(t)\right)v_Y \min\left\{1, \frac{\gamma M(t)}{Y(t)}\right\} + \mu_Y\right)Y(t)\right] \\ & + p_3(t)\left[\left(1 - \varepsilon_2 u_2(t)\right)v_Y \min\left\{1, \frac{\gamma M(t)}{Y(t)}\right\}Y(t) - (\delta + \mu_F)F(t)\right] \\ & + p_4(t)\left[(1 - r)v_I I(t) - \mu_M M(t)\right] \end{aligned} \tag{6}$$

for $p_j(t); j = 1,2,3,4$ are adjoin functions. Following the state system, the Hamiltonian function is also piecewise. The optimality conditions provided by Pontryagin's maximum principles are given by equations (7)-(9).

$$\frac{\partial H}{\partial u_i} = 0; i = 1,2 \tag{7}$$

$$\frac{dx_j}{dt} = \frac{\partial H}{\partial p_j}; j = 1,2,3,4 \tag{8}$$

$$\frac{dp_j}{dt} = -\frac{\partial H}{\partial x_j}; j = 1,2,3,4. \tag{9}$$

for $x_j \in \{I, Y, F, M\}$. The optimality conditions also include transversality conditions and control boundaries. The transversality condition in general is given by equation (10).

$$(S_x - p)\delta x|_{t_f} + (H + S_t)\delta t|_{t_f} = 0. \tag{10}$$

From condition (7), we derived the solution for optimal control variables for the control problem. Since the Hamiltonian function is piecewise, the control that is attached to the piecewise part of the system is also piecewise. The solution for the first control is provided by equation (11).

$$u_1^*(t) = \frac{p_1(t)\varepsilon_1 I(t)}{2C_1}. \tag{11}$$

The solution for the second control $u_2^*(t)$ is piecewise since it is attached to the piecewise part of the system. The first part is when $\xi \geq 0$ and the system enters male abundance case. The solution for control u_2 is given by equation (12).

$$u_2^*(t) = \frac{\big(p_3(t) - p_2(t)\big)\varepsilon_2 v_Y Y(t)}{2C_2}. \tag{12}$$

If $\xi < 0$, the system enters male scarcity case. The solution for control u_2 is given by the equation (13).

$$u_2^*(t) = \frac{\big(p_3(t) - p_2(t)\big)\varepsilon_2 v_Y \gamma M(t)}{2C_2}. \tag{13}$$

Since the controls are bounded, the solution for the optimal controls can be written as equation (14)-(15).

$$u_1(t) = \min(1, \max(u_1^*(t), 0)) \tag{14}$$

$$u_2(t) = \min(1, \max(u_2^*(t), 0)) \tag{15}$$

Condition (8) gives back the state system (1)-(4). Condition (9) provides the adjoin system for the control problem. Since the Hamiltonian function is piecewise, the adjoin system is also going to be piecewise. The first equation is $\frac{dp_1(t)}{dt}$ is provided by equation (16).

$$\frac{dp_1(t)}{dt} = -C_0 - p_1(t)\left[-\frac{bF(t)}{K} - \big(v_I + \mu_I + \varepsilon_1 u_1(t)\big)\right] - p_2(t)[rv_I] - p_4(t)[(1-r)v_I]. \tag{16}$$

For the piecewise equation $\frac{dp_2(t)}{dt}$ and $\frac{dp_4(t)}{dt}$, the expressions are depending on the case of the system. If $\xi \geq 0$, the system enters male abundance. The expressions for $\frac{dp_2(t)}{dt}$ and $\frac{dp_4(t)}{dt}$ are provided by equation (17) and (18).

$$\frac{dp_2(t)}{dt} = -C_0 - p_2(t)\left[-\Big(\big(1 - \varepsilon_2 u_2(t)\big)v_Y + \mu_Y\Big)\right] - p_3(t)\big[\big(1 - \varepsilon_2 u_2(t)\big)v_Y\big] \tag{17}$$

$$\frac{dp_4(t)}{dt} = -C_0 - p_4(t)[-\mu_M]. \tag{18}$$

If $\xi < 0$, the system enters male scarcity case. The expressions for $\frac{dp_2(t)}{dt}$ and $\frac{dp_4(t)}{dt}$ are provided by equation (19) and (20).

$$\frac{dp_2(t)}{dt} = -C_0 - p_2(t)[-\mu_Y] \tag{19}$$

$$\frac{dp_4(t)}{dt} = -C_0 - p_2(t)\left[-\Big(\big(1 - \varepsilon_2 u_2(t)\big)v_Y\gamma\Big)\right] - p_3(t)\big[\big(1 - \varepsilon_2 u_2(t)\big)v_Y\gamma\big] - p_4(t)[-\mu_M]. \tag{20}$$

The last equation in adjoin system $\frac{dp_3(t)}{dt}$ is provided by equation (21).

$$\frac{dp_3(t)}{dt} = -C_0 - p_1(t)\left[b\left(1 - \frac{I(t)}{K}\right)\right] - p_2(t)[\delta] - p_3(t)[-(\delta + \mu_F)]. \tag{21}$$

It is assumed that the terminal time is set at t_f and the terminal values for state functions are free. Based on the objective functional (5), the scrap function $S\big(x_j(t), t\big) = 0$ for $j = 1,2,3,4$, and $x_j \in \{I, Y, F, M\}$. Thus, the transversality condition (10) can be rewritten as equation (22).

$$p_j\big(t_f\big) = 0; j = 1,2,3,4. \tag{22}$$

4. Numerical solutions

To solve the control problem, state system (1)-(9), adjoin system (17)-(21), and the solutions for the optimal control (14)-(15) need to be solved simultaneously. Numerical method was exploited in solving the problem. The 4th order Runge-Kutta method (Matthews and Fink 2004) combined with forward-backward sweep method (Lenhart and Workman 2007) were used. The algorithm solved the state system forward in time with given initial values. The adjoin system was solved backward in time with the terminal values were given by (22). The solutions for the controls were calculated using (14)-(15). This algorithm was repeated until the control solutions converge.

Three strategies were introduced in this paper. These strategies depend on the combination of control methods used. First strategy is the combination of the use of green insecticide and mating disruption and it is referred as Strategy A. Second strategy is the use of green insecticide only and it is referred as Strategy B. the third strategy is the use of mating disruption only and it is referred as Strategy C. For the purpose of the simulation, four scenarios were introduced. Scenario 1 is the condition where the costs of applying both controls are relatively low ($C_1 = 100, C_2 = 100$). Scenario 2 is the condition where the costs of applying controls are relatively high ($C_1 = 200, C_2 = 200$). The third scenario is the condition where the cost to apply green insecticide is relatively low and the cost to apply mating disruption is relatively high ($C_1 = 100, C_2 = 200$) and it is referred as Scenario 3. The fourth scenario is the condition where the cost to apply green insecticide is relatively high and the cost to apply mating disruption is relatively low ($C_1 = 200, C_2 = 100$) and it is referred as Scenario 4. The parameters used in this paper is the same as the parameters used in (Anguelov *et al.* 2017). The initial values for the state system are given as the following values: $I_0 = 100, Y_0 = 400, F_0 = 120$, and $M_0 = 100$. The terminal values for the adjoin system are given by (22). We set the effectiveness of controls application to be $\varepsilon_i = 0.9$ for $i = 1,2$ and the cost weight $C_0 = 1$.

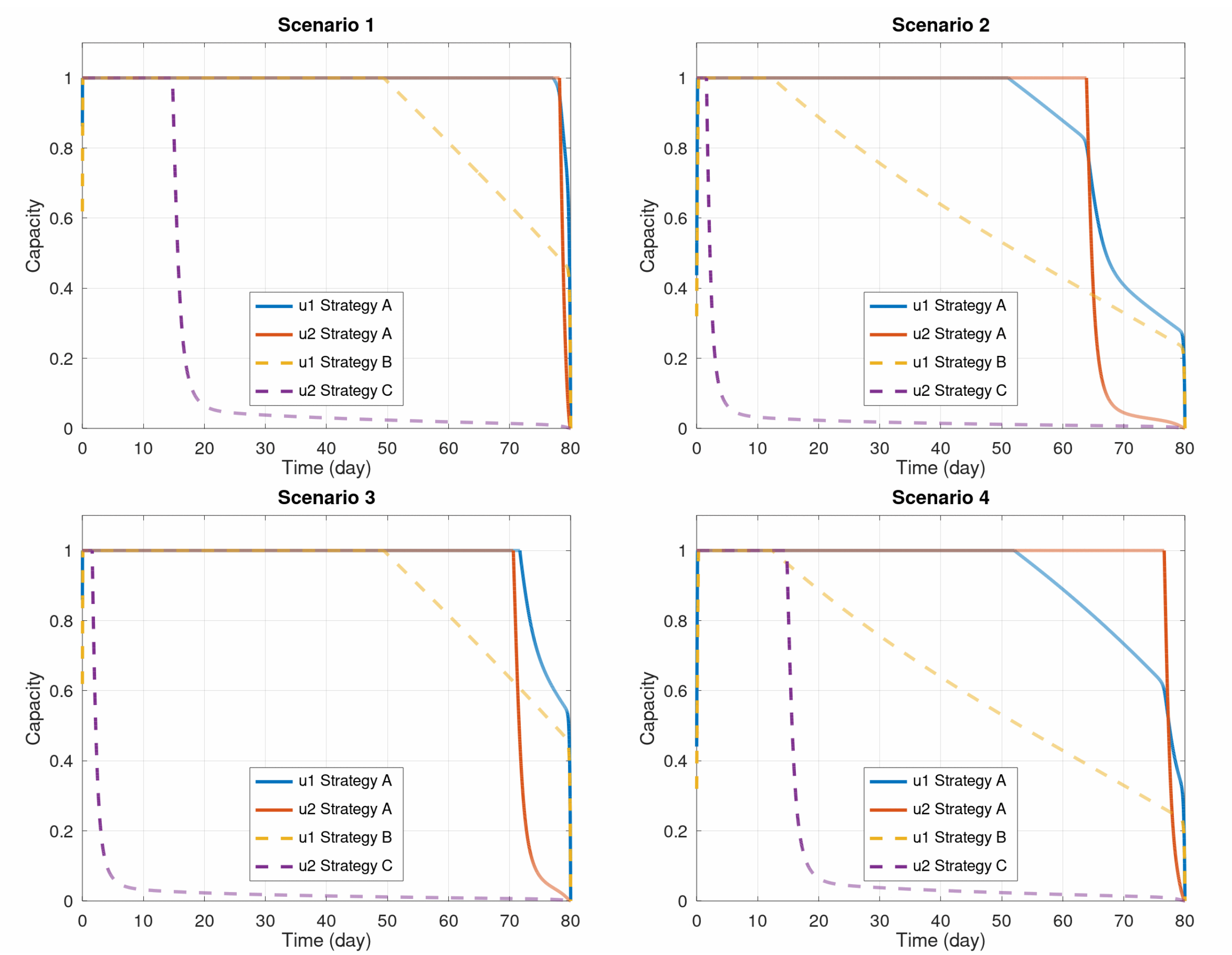

Figure 2. Control profile in all scenarios

Figure 2 provides the control profile for all scenarios. Strategy A in Scenario 1 used both controls excessively. Green insecticide was given at full capacity for around 77 days and mating disruption was given at full capacity in slightly slower amount of time. The decrease of green insecticide is also slower compared to mating disruption which decreased immediately on around day 77. For Strategy B, green insecticide was applied at full capacity for around 49 days of control period while mating disruption for Strategy C was applied at full capacity for around 15 days. In scenario 2, green insecticide and mating disruption for Strategy A were given at full capacity for a shorter amount of time compared to Strategy A in Scenario 1. Green insecticide was given at full capacity for around 52 days of control period while mating disruption was applied for around 64 days. For Strategy B, green insecticide was given at full capacity for around 12 days while mating disruption in Strategy C was given at full capacity on the first few days of control period. In scenario 3, the application of Strategy B was the same with the Strategy B in Scenario 1 while the Strategy C was the same with the Strategy C in Scenario 2. For Strategy A in Scenario 3, green insecticide was given at full capacity for 72 days and mating disruption was given at full capacity for a shorter amount of time. In Scenario 4, Strategy B was the same with Strategy B in Scenario 2 while Strategy C was the same with Strategy C in Scenario 1. Green insecticide for Strategy A in this scenario was given at full capacity for around 52 days with slight different pattern of application with green insecticide application for Strategy A in Scenario 2. Mating disruption for Strategy A in Scenario 4 was given at full capacity for around 76 days of control period.

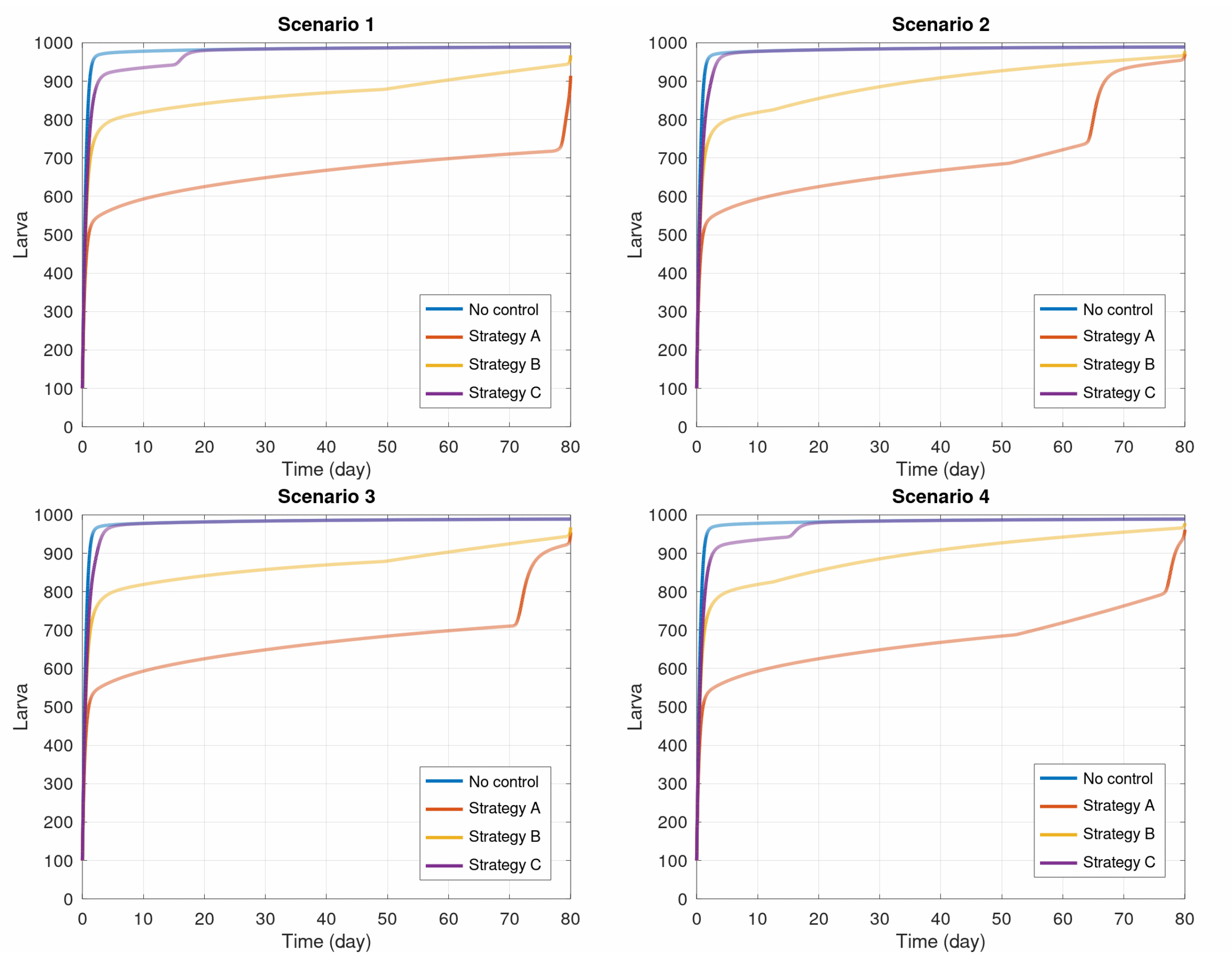

Figure 3. Dynamics of larva population

Figure 3 provides the dynamics of larva population in all scenarios. In all scenarios, it is found that Strategy A is the most effective strategy by decreasing the larva population the most followed by Strategy B, and the least effective strategy is Strategy C. This is expected because Strategy A is the combination of the use of green insecticide and mating disruption while the other two strategies are the use of individual control methods. It is also found that in Scenario 1, Strategy A gave the most benefit compared to the other three scenarios. This is because the cost weights applied in Scenario 1 are the cheapest among all scenarios. In Strategy A in all scenarios, there was sudden increase of larva population near the last 20 days of control period. The same thing also happened in Strategy C on the first

20 days of control period. This happened because of the sudden drop of mating disruption application, resulting in more larva produced.

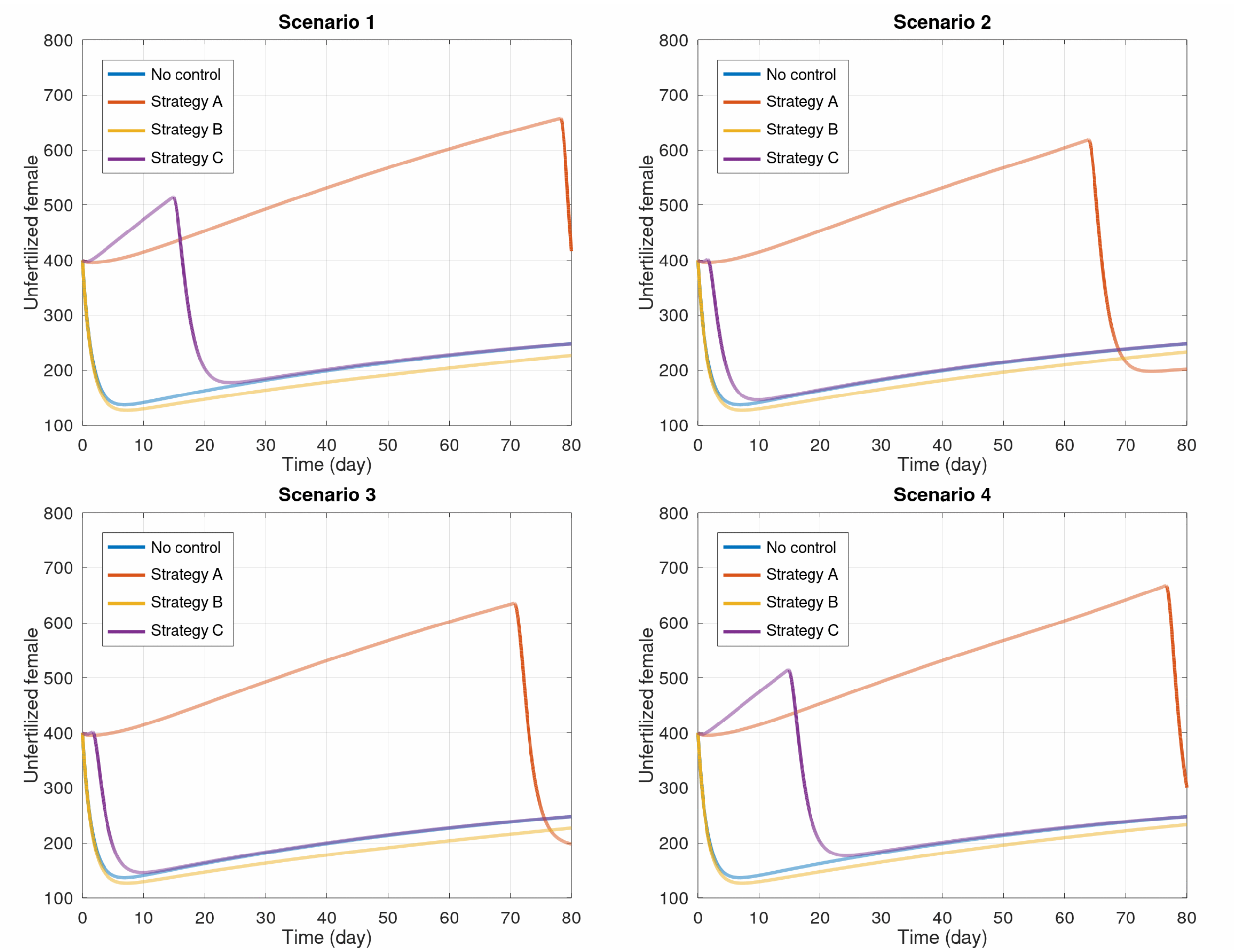

Figure 4. Dynamics of unfertilized female population

Figure 4 provides the dynamics of unfertilized female insect population. It is found that Strategy A increased the number of unfertilized female in all scenarios. Strategy D also increased the population within the first 20 days of control period. This happened because of the use of mating disruption. Mating disruption prevents the transfer from unfertilized female to fertilized female. The increased number of insect that is unfertilized indicated the success of mating disruption. To take a closer look, in Scenario 1 and Scenario 4, the unfertilized female population resulted by Strategy D is the highest number of population compared to other strategies within the first 20 days of control period before the population decreased due to sudden drop of mating disruption application. This happened because Strategy D only applies mating disruption while the other two strategies use green insecticide. Strategy B decreased the number of female insect population since there was less larva to grow. Thus the line became below the line of no control condition.

Comparing each scenario, the results generated in Scenario 1 were generally more significant compared to the other three scenarios. This happened because the cost weights applied in Scenario 1 are the cheapest compared to other scenarios. Scenario B is comparison provided the least difference compared to the other three scenarios since the cost weights in this scenario are the most expensive. Scenario 3 and Scenario 4 are the scenarios between the cheapest and the most expensive scenarios. While Strategy B and Strategy C in Scenario 3 and Scenario 4 are the same with the strategies in Scenario 1 and Scenario 2, Strategy A in both Scenario 3 and Scenario 4 differed with the Strategy A in Scenario 1 and Strategy 2. In Scenario 3, green insecticide was applied at full capacity for a longer period of time than the application of mating disruption. In Scenario 4, the application of mating disruption at full capacity was conducted for a longer period of time than the application of green insecticide in the same scenario for the same strategy. The results generated by Strategy A for both scenarios are consistent with the application of controls that the female insects that stayed unfertilized in Scenario 4 were more in number compared to Scenario 3.

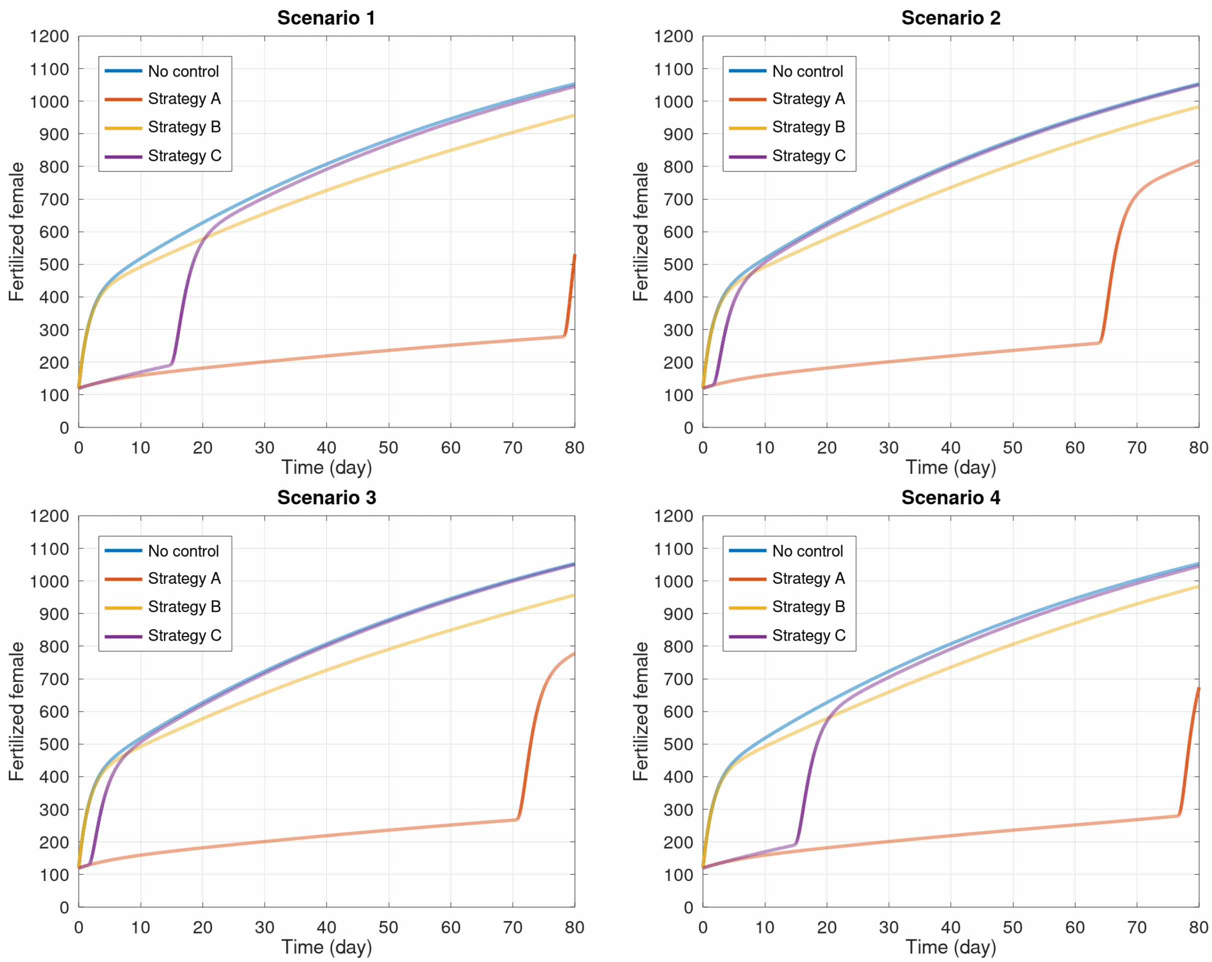

Figure 5. Dynamics of fertilized female population

Figure 5 provides the dynamics of fertilized female population. This population is from the female population that are successfully mated by male. The results generated are consistent with the results shown in Figure 4. The results in Scenario 1 are the most significant results compared to the other scenarios. In this scenarios, Strategy A generated the lowest number of population for the whole period of time. Strategy B grew consistently and became the second lowest number of population after day 20 of control period while for the first 20 days, Strategy C generated the second lowest number of population. The results generated in Scenario 2 are the least significant results compared to the results in other scenarios. The sudden increase from Strategy A and Strategy C in Scenario 2 happened sooner than in Scenario 1 because the drop of control capacity happened sooner. The result of Strategy B in Scenario 1 was also less in population number compared to the result of Strategy B in Scenario 2. This results are expected and consistent with the results in Figure 4 and this happened because of the difference of cost weights applied for bith scenarios.

Comparing Scenario 3 and Scenario 4, the focus would be the results generated by Strategy A since the results from Strategy B and Strategy C can be seen easily in Scenario 1 and Scenario 2 by matching the cost weights applied to the individual control. For Strategy A, in Scenario 3, t8he sudden increase of population happened sooner because the drop of the mating disruption capacity happened sooner in Scenario 3 due to higher cost weight applied to the control. This means, the number of larva that would be produced in Scenario 4 is less because the number of fertilized female also less compared to Scenario 3 potentially.

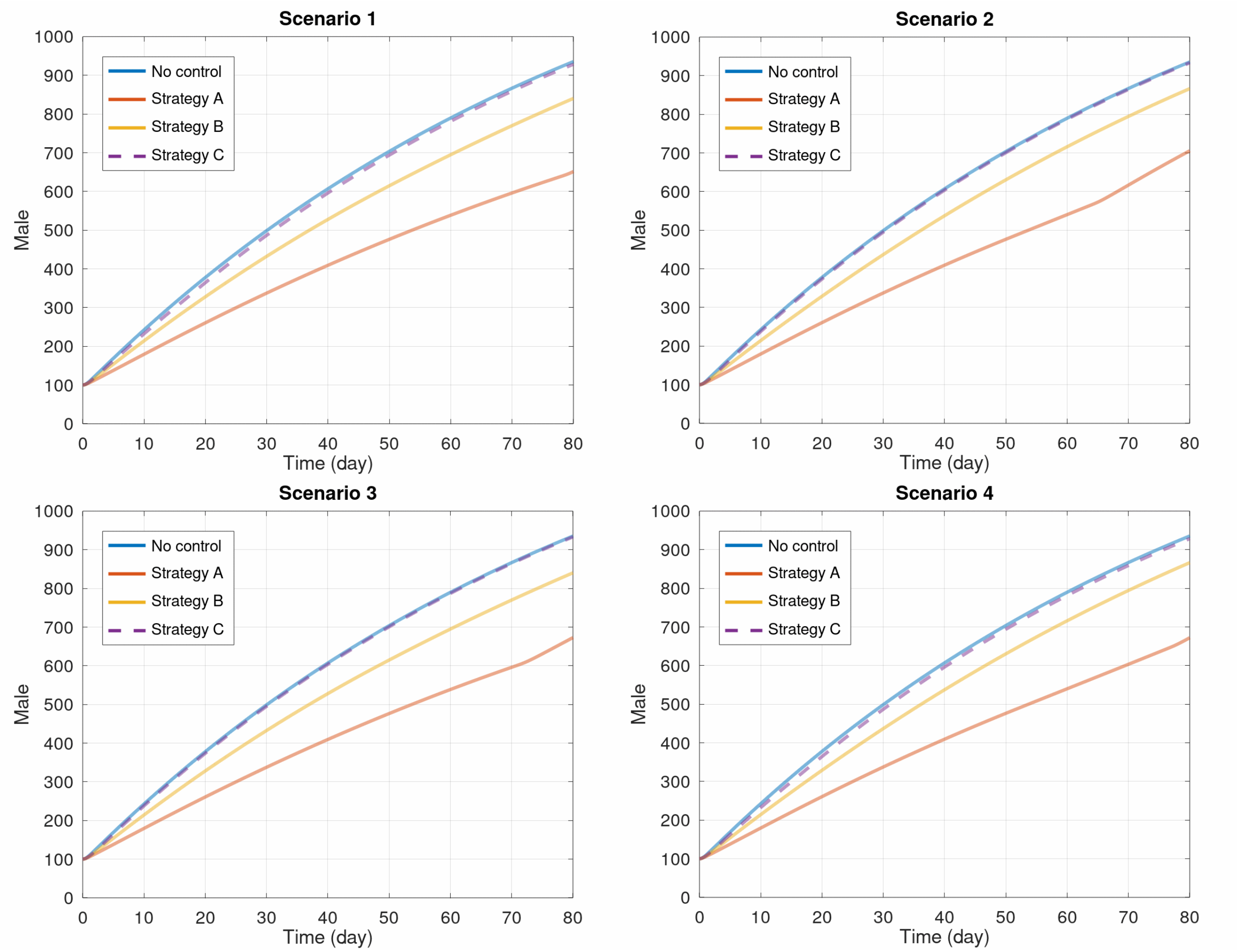

Figure 6. Dynamics of male population

Figure 6 provides the dynamics of male population. This population is not directly influenced by any of the control methods, thus any sudden drop of control capacity will affect this population immediately. The pattern of the solutions in each scenario is relatively the same. However, it is found that there is a more increase of male population on between day 60 to 70 in Scenario 2 and between day 70 to 80 in Scenario 3 generated by Strategy A while in Scenario 1 and Scenario 4, the lines seem to be smooth. The slight more increase in Scenario 2 happened sooner than in Scenario 3 because the drop of both controls happened sooner in Scenario 2. The lines generated by Strategy A in Scenario 1 and Scenario 4 seem to be smooth because the drop of both controls happened near the end of control period.

The differences between Strategy B and Strategy C generated in each scenario also differed slightly. The population of male resulted from Strategy B in Scenario 1 and Scenario 3 is less in number compared to the results in Scenario 2 and Scenario 4. The same comparison also happened for Strategy C that the results generated in Scenario 1 and Scenario 4 is less in number compared to the results in Scenario 2 and Scenario 3. These results also depend on the cost weight applied to the respective strategies where the scenarios with lower cost weight will result a longer period of time for the controls to be given at full capacity.

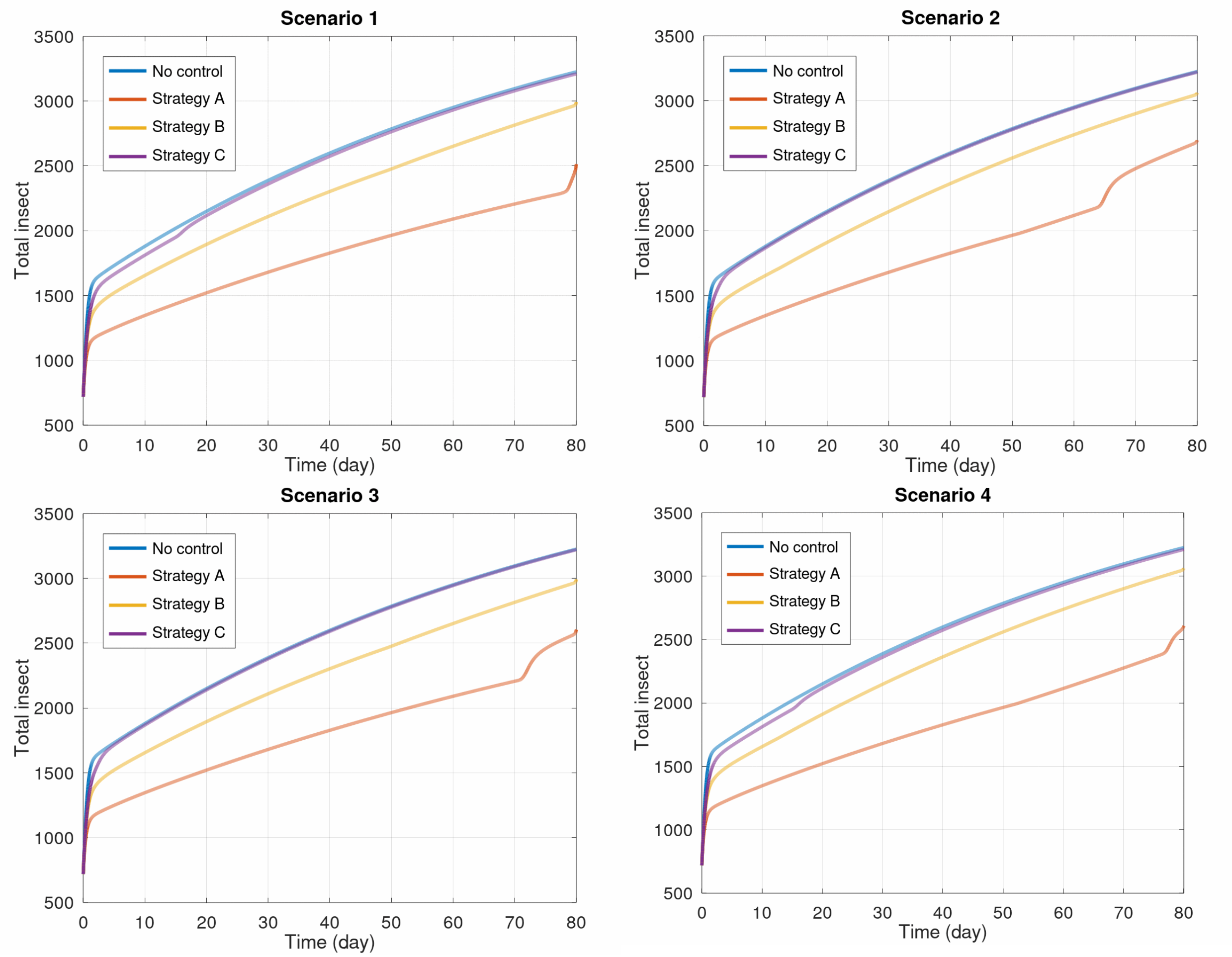

Figure 7. Dynamics of total insect population

Figure 7 provides the dynamics of total insect population that includes larva, unfertilized female, fertilized female, and male insect population. The ultimate goal of control application is to minimize the total insect population. In doing so, Strategy A generated the most significant benefit in all four scenarios. This is expected since Strategy A combines the use of green insecticide and mating disruption and both controls are applied with a relatively high capacity in all four scenarios based on Figure 2. The second most significant strategy is Strategy B and the least is Strategy C. The difference between no control situation and the results of Strategy C in all scenarios are not big. The significant difference occurred within the first few days of control period before the drop of control capacity.

5. Cost-effectiveness analysis

In the previous section, this paper discusses about the effectiveness of optimal controls application strategies. However, the cost needed to perform the strategies in each scenario is not included. In this section, the paper discusses the cost-effectiveness analysis to compare the benefit and the cost of every strategy in every scenario. Two analysis tools were used in this section which are average cost-effectiveness ratio (ACER) and incremental cost-effectiveness ratio (ICER). ACER is the value of strategy comparison to the condition of no intervention while ICER is the value of strategy comparison to another strategy (Okusun *et al.* 2013).

In order to calculate both ACER and ICER, the strategies were ranked based on the effectiveness of a strategy in generating benefit. Then, the values of ACER and ICER were calculated. There are also two ICER calculations since there are three strategies for each scenario. The values of cost, benefit, ACER, and ICER are presented in Table 1. The total cost was defined as the sum of spending accumulatively during the whole control period, while total benefit was defined as the sum of number of insect that were successfully killed and the number of insects that were successfully prevented from potentially be added to the insect population during the whole control period. The calculation for the cost and benefit are given by (23) and (24) for strategy $p \in \{\mathrm{A,B,C}\}$ and scenario $r \in \{1,2,3,4\}$.

$$\mathrm{Cost}(p,r) = \int_0^{t_f} C_1 u_{1,p,r}^2(t) + C_2 u_{2,p,r}^2(t)\, dt \tag{23}$$

$$\mathrm{Benefit}(p,r) = \int_0^{t_f} B\big(I_{p,r}(t) + M_{p,r}(t) + Y_{p,r}(t) + F_{p,r}(t)\big)\, dt. \tag{24}$$

ACER is calculated by dividing the total cost spent for a strategy by the total benefit generated from a strategy. This means that ACER is the cost that needs to be spent for a single benefit. The calculation is expressed by equation (25) for strategy $p \in \{\mathrm{A,B,C}\}$ and scenario $r \in \{1,2,3,4\}$.

$$\mathrm{ACER}(p,r) = \frac{\mathrm{Cost}(p,r)}{\mathrm{Benefit}(p,r)}. \tag{25}$$

Since the most cost effective strategy is the strategy that generates benefit with cheap cost, the smaller the ACER value, the more cost-effective a strategy is. While ACER compares strategy to a condition of no intervention, ICER calculates the difference of cost per difference of benefit between two alternatives. ICER calculation is expressed by equation (26) for strategy $p, q \in \{\mathrm{A,B,C}\}$ and scenario $r \in \{1,2,3,4\}$.

$$\mathrm{ICER}(p,q,r) = \frac{\mathrm{Cost}(p,r) - \mathrm{Cost}(q,r)}{\mathrm{Benefit}(p,r) - \mathrm{Benefit}(q,r)}. \tag{26}$$

In the case of more than two control strategies available, the comparison will always be conducted between the least effective to the second least effective in generating benefit.

Table 1. ACER and ICER values

Scenario	Strategy	Cost	Benefit	ACER	ICER	ICER
1	C	1547.5	2685.4	0.576264	0.576264	0.576264
	B	13282.01	21705.63	0.611915	0.616949	
	A	23695.94	58515.37	0.404952	0.282912	0.396712
2	C	207.55	959	0.216423	0.216423	0.216423
	B	7719.9	17592.2	0.438825	0.451648	
	A	19393.53	54001.85	0.359127	0.320619	0.361707
3	C	207.55	959	0.216423	0.216423	0.216423
	B	13282.01	21705.63	0.611915	0.630197	
	A	22267.55	57018.26	0.390534	0.254457	0.393512
4	C	1547.5	2685.4	0.576264	0.576264	
	B	7719.9	17592.2	0.438825	0.414066	0.438825
	A	21586.66	56824.53	0.379883	0.353452	0.353452

The cost, benefit, ACER, and ICER are provided by Table 1. Strategy A generated the most benefit for all scenarios and Strategy C generated the least benefit in all scenarios. However, the number of benefit is not the only parameter in analyzing a strategy. Based on the ACER values, Strategy A was the most cost-effective strategy in Scenario 1 and Scenario 4 with ACER 0.404952 and 0.379883. Surprisingly, Strategy C was the most cost-effective strategy in Scenario 2 and Scenario 3 with ACER values of 0.216423 for both scenario 2 and scenario 3 despite of the number of benefit it generated.

The result of ICER calculation generated the same conclusion with ACER. The first ICER calculation was to compare Strategy B and Strategy C in all scenarios. In Scenario 1, Scenario 2, and Scenario 3, ICER of Strategy C was lower compared to Strategy B. This means that Strategy B was dominated by Strategy C. Thus, Strategy B for Scenario 1, Scenario 2, and Scenario 3 was excluded. In Scenario 4, ICER of Strategy B was lower compared to Strategy C. This means Strategy C was dominated by Strategy B. Thus, for Scenario 4, Strategy C was excluded.

For the second ICER calculation, Strategy A and Strategy C was compared in Scenario 1, Scenario 2, and Scenario 3, while in Scenario 4, Strategy A was compared with Strategy B. In Scenario 1, the ICER of Strategy A was lower compared to Strategy C, thus making Strategy A dominated Strategy C and became the most cost-effective strategy in Scenario 1. In Scenario 2 and Scenario 3, the ICER of Strategy C was lower than Strategy A, making Strategy C dominated Strategy A and becomes the most cost-effective strategy in Scenario 2 and Scenario 3. In Scenario 4, the ICER of Strategy A was lower than Strategy B, making Strategy A dominated Strategy B and becomes the most cost-effective strategy in Scenario 4.

6. Conclusion

This paper has presented a model representing the life stages of insect population. Two control methods were introduced and attached to the model namely green insecticide intervention using bisacylhydrazine and mating disruption that deal with larva population control and affect the total insect population. Three control strategies were introduced namely the use of both control methods and the use of individual control. These strategies were assessed in four scenarios representing the possible cost weights combination. With the effectiveness of controls at 90%, strategy that uses both control methods generated the least insect population in all scenarios and strategy that uses mating disruption only generated the most insect population after the controls application. However, based on ACER and ICER, Strategy A was not always the most cost effective strategy. Strategy A was the most cost-effective strategy in scenarios where the cost of applying mating disruption is relatively low. Surprisingly, Strategy C was the most cost-effective strategy in scenarios where the cost of mating disruption application is relatively high.

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