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Investigating the use of wasps *Anagyrus lopezi* as a biological control agent for cassava mealybugs: modeling and simulation

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Abstract

In this paper, a cellular automata model is developed in order to investigate the control of cassava mealybugs in a cassava field when the wasp *Anagyrus lopezi* is used as the biological control agent. The model is constructed based upon farmers' usual practices of cassava planting in Thailand. However, the instructions on how to release the *Anagyrus lopezi* wasps in a cassava field are various. In this study, we developed a cellular automata model based upon farmers' usual practices recommended by many organizations in Thailand such as the Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand, and the Thai Tapioca Development Institute. The effect of the life cycles of cassava mealybugs and the *Anagyrus lopezi* wasps is also taken into account. The available reported data from many sources are utilized so that parameter values in the model are obtained. Computer simulations of different tactics of biological control are carried out so that a guideline for controlling the spread of cassava mealybugs by the *Anagyrus lopezi* wasps is obtained.

Keywords: Cassava; Cassava mealybug; Cellular automata; Wasps *Anagyrus lopezi*

1 Introduction

Nowadays, the crops that could survive hot and dry conditions such as cassava (*Manihot esculenta Crantz*) are getting more attention when the global temperatures increase every year. Cassava is a root crop with high starch content and can be used in many food and non-food industries such as pharmaceutical, material, plywood, paper, textile industries. It can also be used as biomass to produce ethanol fuel [1]. Cassava is considered to be one of the major agriculture crops of Thailand. However, a major loss in crop yield might occur if there is the outbreak of its insect pest. In 2008, cassava mealybugs were first identified in Thailand as one of the most important cassava insect pests. Since then, cassava mealybugs have spread throughout Thailand's cassava fields [2]. In 2010, there was an outbreak of cassava mealybugs in Thailand resulting in a major loss in cassava yield. The total cassava yield reduced from 30 million tons per year to 22 tons per year as recorded by the information from the Office of Agricultural Economics, Thailand.

The controls of the spread of mealybugs in Thailand are practiced in various ways. Farmers might use biological controls, insecticides, or both of biological controls and insecticides. The Thai Tapioca Development Institute and the Department of Agriculture, Ministry of Agriculture and Cooperatives, Thailand, suggest various practices for biological controls. The recommended instructions on the amount of natural enemies to be released and the period between each natural enemies released are diverse and depend on the type of the natural enemies to be released.

One of natural enemies that have been used frequently to control the spread of cassava mealybugs is wasps *Anagyrus lopezi* (*Apoanagyrus lopezi*) [3]. Wasps *Anagyrus lopezi* were first imported to Thailand in the year 2009 in order to control the outbreak of cassava mealybugs in the infested cassava fields because they attack cassava mealybugs specifically. However, there are various instructions on how to release wasps *Anagyrus lopezi* when a spread of cassava mealybugs occurs. Wasps *Anagyrus lopezi* are suggested to be released once or three times every three weeks when cassava mealybugs are first detected in a cassava field where the recommended number of wasps *Anagyrus lopezi* to be released in a cassava field also varies, e.g., 50–100 pairs per rai (0.16 ha), 200 pairs per rai (0.16 ha), and 400 pairs per rai (0.16 ha). In this paper, different tactics of biological control of cassava mealybugs in a cassava field are investigated.

2 Model development

According to the cassava planting instructions recommended by the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand, the suggested distance for planting any two connected cassava plants is 1 meter. Suppose that the total area of cassava field is 4 rai (0.64 ha), the number of cassava plants on the first day of planting is 6400 plants in total. A cellular automata model is constructed as follows to investigate biological control of cassava mealybugs in the cassava field.

A 80×80 lattice will be used to stand for the cassava field. A cassava plant in the field is represented by a cell in the lattice. There are three possible states for each cell. Susceptible cell (S) refers to the non-infested cassava plant (the cassava plant that is free of cassava mealybug). Infested cell (I) refers to the infested cassava plant (the cassava plant that has cassava mealybug on the plant). Empty cell (E) refers to the removed cassava plant.

At first, every cell in the lattice will be assumed to be in the state S. In each time step (1 time step (Δt) = 1 day), the updates for the state of every cell in the lattice will be carried out at random order based upon the following rules.

Rule for updating E

If an empty cell E is randomized, it will remain at the state E.

Rules for updating S

If a susceptible cell S is randomized and it is located on the 1st or 2nd row next to the borders of the lattice, the state of the cell might become I because the cassava plant in the cell might be infested with cassava mealybugs that blown in by the wind from outside of the field with the probability $w = w_1$. On the other hand, if the randomized susceptible cell is not located on the 1st and 2nd row next to the borders of the lattice, it might become an infested cell I with the probability $w = w_2$, where $0 \leq w_2 < w_1 \leq 1$.

Moreover, the randomized susceptible cell might become I with the probability n because it is infested from cassava plants in its neighborhood shown in Fig. 1. The probability that the cassava plant in the randomized cell will be infested from the cassava plants belonging to its immediate neighborhood is higher than from the distant neighborhood. The probability that the cassava plant in the randomized cell will be infested from the cassava plants belonging to its distant neighborhood is higher than from the far distant neighborhood.

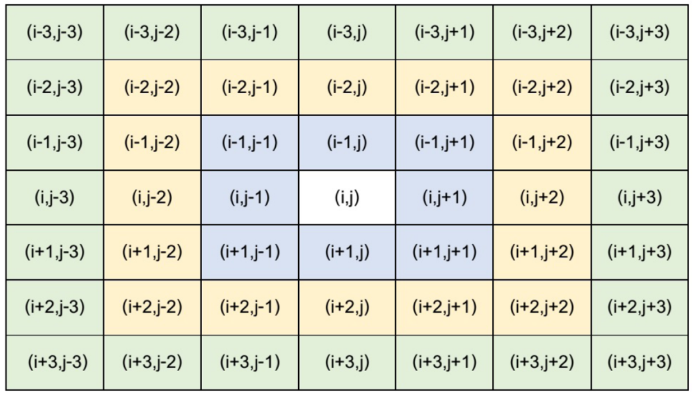

Figure 1 The blue, yellow, and green areas represent immediate neighborhood, distant neighborhood, and far distant neighborhood, respectively, of the cell (i,j)

Rules for updating I

If an infested cell I is randomized, it might return to the susceptible state S in the next time step if wasps *Anagyrus lopezi* successfully eliminate cassava mealybugs on the randomized cell.

On the other hand, when cassava has been planted in the field for a month, a surveyed for cassava mealybugs will be done every two weeks. If the randomized infested cell I is surveyed during the 1st, 120th or 211th, 360th day of planting, the state of the cell will then change to E.

Rule for release of wasps Anagyrus lopezi

Starting from the second month of planting, the survey for cassava mealybugs will be carried out every two weeks. If cassava mealybug is found when the survey is conducted during the 5th and the 7th month of planting, wasps *Anagyrus lopezi* will be released in the field once or every three weeks for three times with the amount of 50–100 pairs per rai, 200 pairs per rai, or 400 pairs per rai.

Rule for updating numbers of cassava mealybug

In addition to the wind effect that might bring cassava mealybugs from inside or outside of the field so that the number of cassava mealybugs on each cassava plant might be changed, the effect of the life-cycle of cassava mealybug is also taken into account. Here, the difference equations (1)–(3) are employed to update the number of cassava mealybugs at each stage on each cell in the lattice due to the effect of the life-cycle of cassava mealybug where C_t^i, C_t^m, and C_t^e are the numbers of cassava mealybugs of the instar stage, adult stage, and egg stage, respectively, at the time step t.

$$\text{Instar stage: } C_{t+\Delta t}^i = C_t^i + r_1\alpha_1 C_t^e - \alpha_2 C_t^i - \beta_1\left(C_t^i, A_t^m\right)A_t^m, \tag{1}$$

$$\text{Adult stage: } C_{t+\Delta t}^m = C_t^m + r_2\alpha_2 C_t^i - \alpha_3 C_t^m - \beta_2\left(C_t^m, A_t^m\right)A_t^m, \tag{2}$$

$$\text{Egg stage: } C_{t+\Delta t}^e = C_t^e + r_3\alpha_4 v_1 C_t^m - \alpha_1 C_t^e - \beta_3\left(C_t^e, A_t^m\right)A_t^m, \tag{3}$$

where $\beta_1(C_t^i, A_t^m)$, $\beta_2(C_t^m, A_t^m)$, and $\beta_3(C_t^e, A_t^m)$ are the average numbers of instar cassava mealybugs, adult cassava mealybugs, and cassava mealybug's eggs, respectively, killed by adult wasps *Anagyrus lopezi* per time step. The definitions of other parameters in equa-

Table 1 Definition and calculated value of parameters in equations (1)–(7)

Parameter	Definition	Value	Unit
• Cassava Mealybug			
α_1	the fraction of cassava mealybug of the egg stage that develop into cassava mealybug of the instar stage in one time step	0.12990	–
α_2	the fraction of cassava mealybug of the instar stage that develop into cassava mealybug of the adult stage in one time step	0.05710	–
α_3	the natural death rate of cassava mealybug of the adult stage	0.04810	day^{-1}
α_4	the fraction of survived female cassava mealybugs of the adult stage in the reproductive period	0.63530	–
r_1	the survival rate of cassava mealybug of the egg stage that develop into cassava mealybug of the instar stage	0.95750	day^{-1}
r_2	the survival rate of cassava mealybug of the instar stage that develop into cassava mealybug of the adult stage	0.96660	day^{-1}
r_3	the fraction of female cassava mealybugs of the adult stage	0.97700	–
v_1	the average number of eggs that are laid by a female cassava mealybug of the adult stage in one time step	16.92500	$\text{eggs} \cdot \text{day}^{-1}$
• Wasps *Anagyrus lopezi*			
γ_1	the fraction of wasps *Anagyrus lopezi* of the egg stage that develop into *Anagyrus lopezi* of the larva stage in one time step	0.50000	–
γ_2	the fraction of wasps *Anagyrus lopezi* of the larva stage that develop into *Anagyrus lopezi* of the pupa stage in one time step	0.16670	–
γ_3	the fraction of wasps *Anagyrus lopezi* of the pupa stage that develop into *Anagyrus lopezi* of the adult stage in one time step	0.16670	–
δ_1	the natural death rate of wasps *Anagyrus lopezi* of the adult stage per a time step	0.06040	day^{-1}
s_1	the survival rate of wasps *Anagyrus lopezi* of the egg stage that develop into *Anagyrus lopezi* of the larva stage	0.78325	day^{-1}
s_2	the survival rate of wasps *Anagyrus lopezi* of the larva stage that develop into *Anagyrus lopezi* of the pupa stage	0.78325	day^{-1}
s_3	the survival rate of wasps *Anagyrus lopezi* of the pupa stage that develop into *Anagyrus lopezi* of the adult stage	0.78325	day^{-1}
s_4	the fraction of female adult wasps *Anagyrus lopezi*	0.39710	–

tions (1)–(3) are provided in Table 1 as well as their approximated values calculated based on the literature [4–8] at $25 \pm 2°\text{C}$.

Rule for updating numbers of wasps Anagyrus lopezi

Apart from the increase in the number of wasps *Anagyrus lopezi* in the field due to the release of wasps *Anagyrus lopezi* when cassava mealybug is first detected, the effect of the life-cycle of wasps *Anagyrus lopezi* is also taken into account. Here, the difference equations (4)–(7) are employed to update the number of wasps *Anagyrus lopezi* at each stage on each cell in the lattice due to the effect of the life-cycle of wasps *Anagyrus lopezi* where A_t^i, A_t^d, A_t^m, and A_t^e are the numbers of wasps *Anagyrus lopezi* of the larva stage, pupa stage, adult stage, and egg stage, respectively, at the time step t.

$$\text{Larva stage: } A_{t+\Delta t}^i = A_t^i + s_1\gamma_1 A_t^e - \gamma_2 A_t^i, \tag{4}$$

$$\text{Pupa stage: } A_{t+\Delta t}^d = A_t^d + s_2\gamma_2 A_t^i - \gamma_3 A_t^d, \tag{5}$$

$$\text{Adult stage: } A_{t+\Delta t}^m = A_t^m + s_3\gamma_3 A_t^d - \delta_1 A_t^m, \tag{6}$$

$$\text{Egg stage: } A_{t+\Delta t}^e = A_t^e + s_4\delta_2\big(C_t^i, C_t^m, C_t^e, A_t^m\big)A_t^m - \gamma_1 A_t^e, \tag{7}$$

where $\delta_2(C_t^i, C_t^m, C_t^e, A_t^m)$ is the efficiency of an adult female wasps *Anagyrus lopezi* on laying eggs per time step depending on the amount of consumed cassava mealybugs. The definitions of parameters in equations (4)–(7) are provided in Table 1 as well as their approximated values calculated from literature [4–8] at $25 \pm 2°C$.

Note that, on each cassava plant, the number of cassava mealybugs at each stage and the number of wasps *Anagyrus Lopezi* at each stage are also monitored. In this study, wasps *Anagyrus Lopezi* at the adult stage on an infested cassava plant might fly to another infested cassava plant in their immediate, distant, or far distant neighborhood. Cassava mealybugs of the instar stage on an infested cassava plant might be blown by the wind to a cassava plant(infested or non-infested) in its immediate, distant, or far distant neighborhood.

In addition, we also monitor the approximated total crop yield. Here, the estimated crop yield is assumed to be α kilograms per cassava plant if the plant has not been infested by cassava mealybugs for longer than two weeks. The crop yield of the plant will be damaged by 100%, 30%, and 10%, approximately, if the cassava plant has been infested during the 1st, 121st, 210th, and 360th day, respectively, by cassava mealybugs for longer than two weeks. At each time step, the total estimated crop yield $Z(t)$ can then be calculated by

$$Z(t) = \alpha \cdot Z_1 + (0.9 \times \alpha) \cdot Z_2 + (0.7 \times \alpha) \cdot Z_3, \tag{8}$$

where Z_1 is the number of cassava plants that have not been infested by cassava mealybugs for longer than two weeks in total at the time step t, Z_2 is the number of cassava plants that have been infested by cassava mealybugs for longer than two weeks in total during the 211th and 360th day at the time step t, and Z_3 is the number of cassava plants that have been infested by cassava mealybugs for longer than two weeks in total during the 121st and 210th day at the time step t.

3 Numerical simulations

In the simulations, the lattice is of the size 80×80, that is, the area of cassava planting is 4 rai (0.64 ha), while the distance between each of the two connected cassava plants is one meter; hence, the initial number of cassava plants in the field is 6400. The planting period is one year. The simulations are carried out step by step as indicated in Fig. 2.

Here, we investigate six different tactics of releasing wasps *Anagyrus lopezi* in a cassava field when the spread of cassava mealybugs is detected. The six tactics are listed as follows.

I: Release wasps *Anagyrus lopezi* only once when the spread of cassava mealybug is first detected in the field at the amount of 50–100 pairs per rai.

II: Release wasps *Anagyrus lopezi* only once when the spread of cassava mealybug is first detected in the field at the amount of 200 pairs per rai.

III: Release wasps *Anagyrus lopezi* only once when the spread of cassava mealybug is first detected in the field at the amount of 400 pairs per rai.

IV: Release wasps *Anagyrus lopezi* three times every three weeks when the spread of cassava mealybug is first detected in the field at the amount of 50–100 pairs per rai.

V: Release wasps *Anagyrus lopezi* three times every three weeks when the spread of cassava mealybug is first detected in the field at the amount of 200 pairs per rai.

VI: Release wasps *Anagyrus lopezi* three times every three weeks when the spread of cassava mealybug is first detected in the field at the amount of 400 pairs per rai.

Computer simulations of the six tactics are carried out by MATLAB software. In the simulations, $n_1 = 0.001$, $n_2 = 0.0001$, $n_3 = 0.00001$, $w_1 = 0.0001$, $w_2 = 0.00001$, and $\alpha = 2.25$.

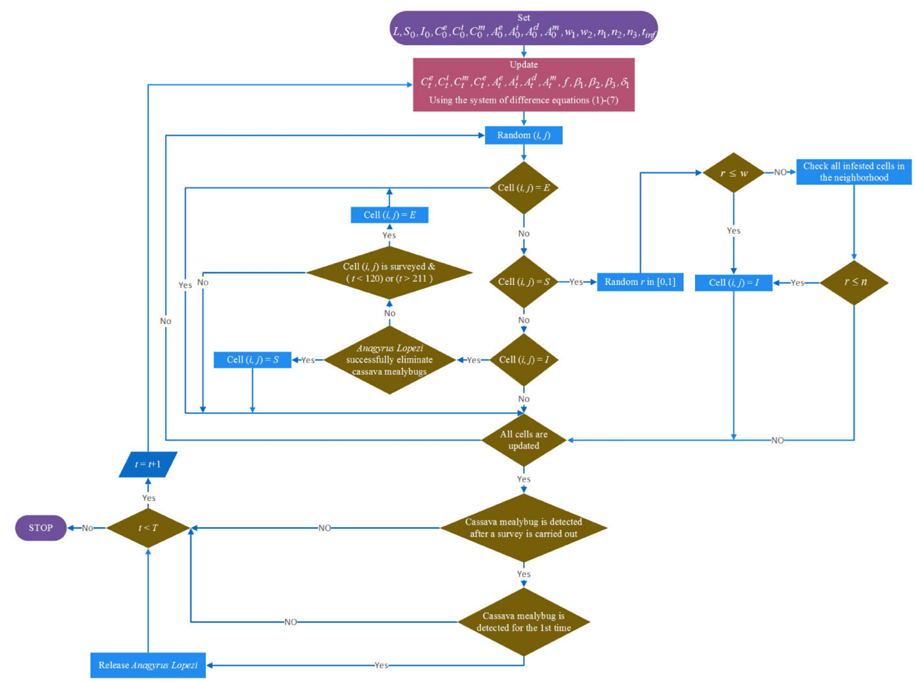

Figure 2 The main loop of cellular automata

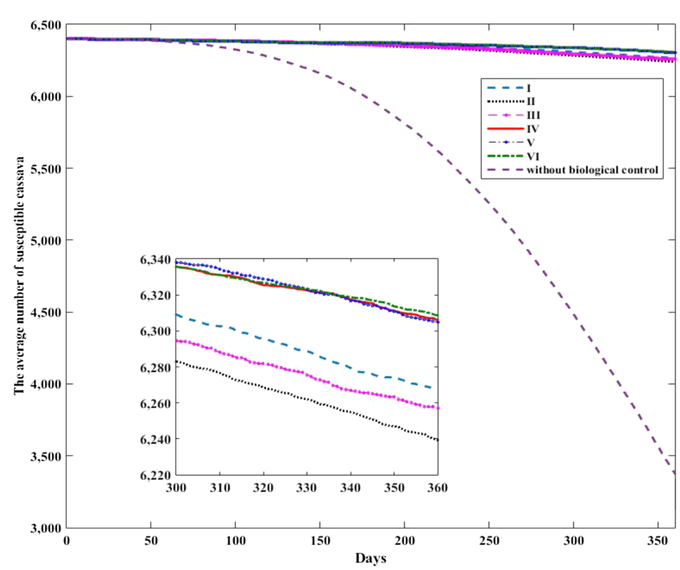

Figure 3 The average number of susceptible cassava plants

The averaged simulation result of the 100 runs is shown in Figs. 3–8. The average of the 100 runs on the estimated crop yield of cassava at the end of planting period and the average of the 100 runs on the total number of wasps *Anagyrus lopezi* released in the field are also given in Table 2.

The results indicate that tactic VI (Release wasps *Anagyrus lopezi* three times every three weeks when the spread of cassava mealybug is first detected in the field with the

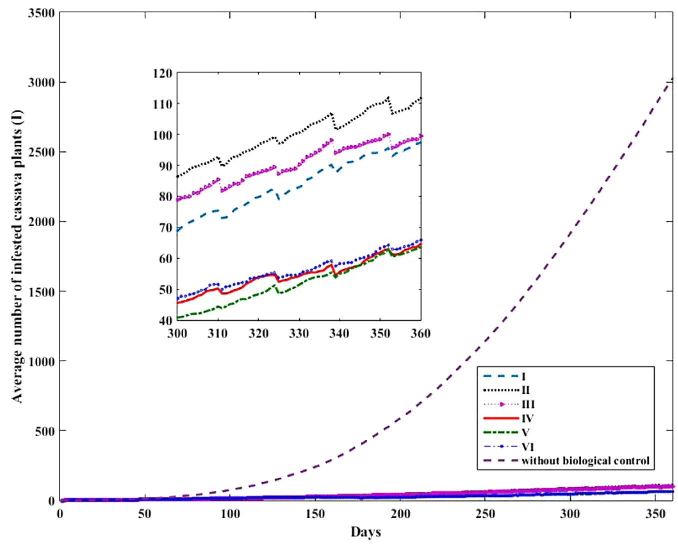

Figure 4 The average number of infested cassava plants

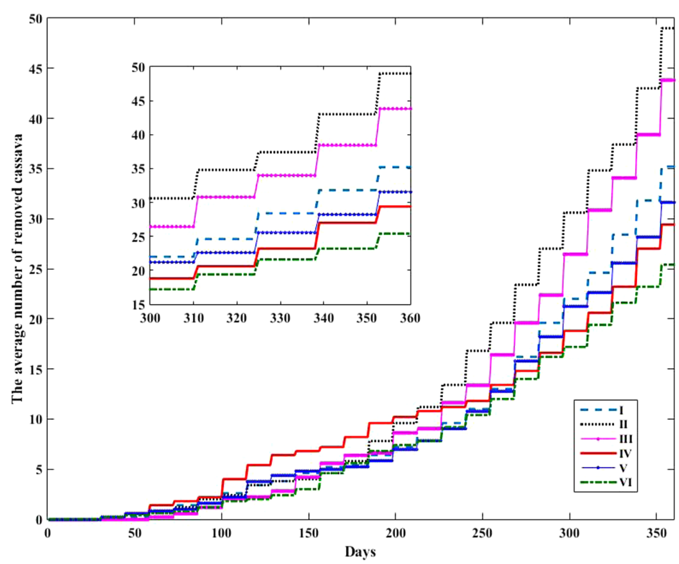

Figure 5 The average number of removed cassava plants

amount of 400 pairs per rai) gives the highest average estimated crop yield of cassava with the lowest number of infested cassava plants compared to the other five tactics.

4 Discussion and conclusion

We investigate the biological control of cassava mealybugs in a cassava field when wasps *Anagyrus lopezi* are used as a biological control agent. The six tactics of the control are considered. Even though the results indicate that tactic VI is the best option for the control of the spread of cassava mealybugs and gives the highest average estimated cassava yield at the end of planting period, the cassava selling price is approximately 2.50 baht (0.072 USD) per kilogram, and the cost for the biological control agent wasps

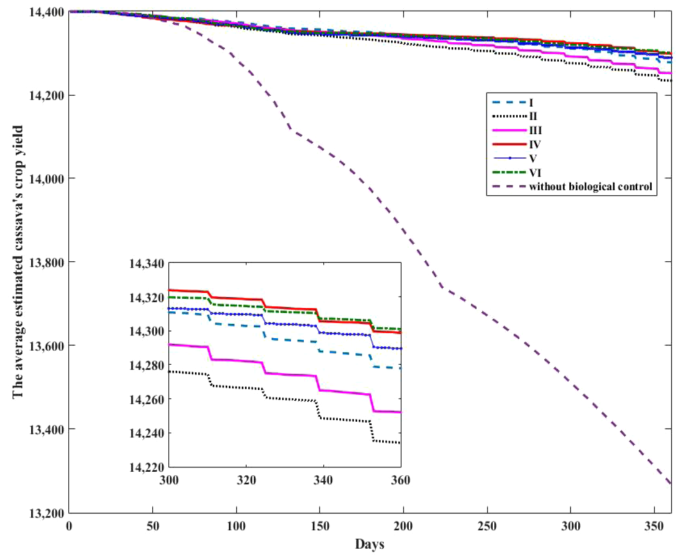

Figure 6 The average estimated cassava crop yield

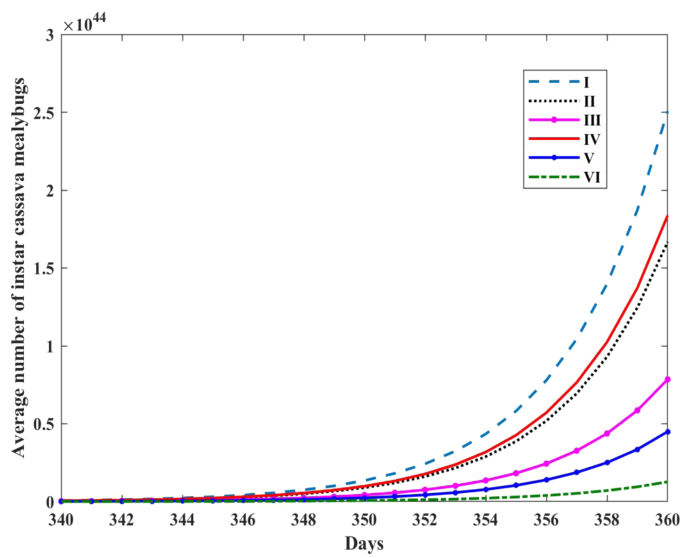

Figure 7 The average number of instar cassava mealybugs

Anagyrus lopezi is approximately 4.50 baht (0.13 USD) per pair. In order that the most efficient biological control in terms of maximum profit for farmers may be obtained, Table 3 shows the average estimated cost of wasps *Anagyrus lopezi* released in the field, the average estimated income from selling cassava yields, and the average estimated (income – cost of biological control agents) at the end of planting period for each tactic.

In Table 3, we can see that even though tactic VI gives the highest average estimated cassava crop yield, the tactic that gives the maximum profit is tactic I (releasing wasps *Anagyrus lopezi* only once when the spread of cassava mealybug is first detected in the field at the amount of 50–100 pairs per rai). Note that the planting area that we considered

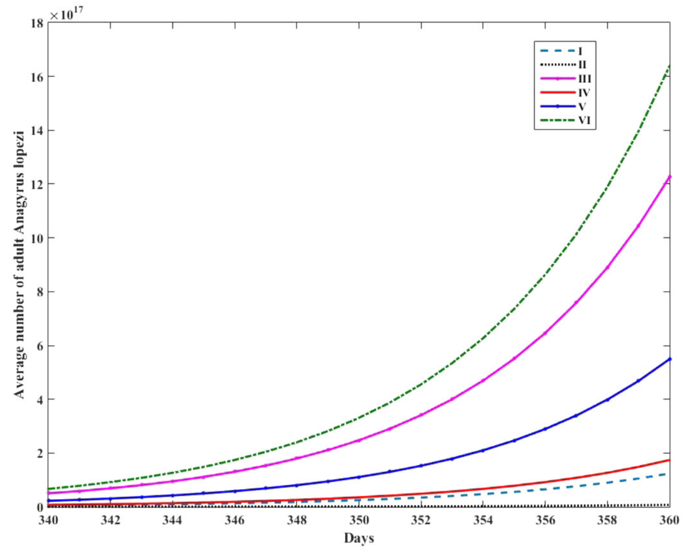

Figure 8 The average number of adult wasps *Anagyrus lopezi*

Table 2 The average estimated crop yield of cassava at the end of planting period and the average total number of wasps *Anagyrus lopezi* released in the field for each tactic

Tactic	Average estimated crop yield of cassava (kgs)	Average total number of wasps *Anagyrus lopezi* released in the cassava field (pairs)
I	14,277.96	60
II	14,234.04	160
III	14,252.09	320
IV	14,298.75	440
V	14,289.57	1760
VI	14,301.05	3520

Table 3 The average estimated cost of wasps *Anagyrus lopezi* released in the field, the average estimated income from selling cassava's crop yields, and the average estimated (income – cost of biological control agents) at the end of planting period for each tactic

Tactic	Average estimated cost of wasps *Anagyrus lopezi* released in the field (baht)	Average estimated income from selling cassava crop yields (baht)	Average estimated (income – cost of wasps *Anagyrus lopezi*) at the end of planting period (baht)
I	270	35,694.90	35,424.90
II	720	35,585.10	34,865.10
III	1440	35,630.23	34,190.25
IV	1980	35,746.88	33,766.88
V	7920	35,723.93	27,803.93
VI	15,840	35,752.63	19,912.63

here is just 4 rai (0.64 ha). When the planting area is a large-scale cassava farm, the results might not be the same as what we have found here. One reason is that the spread of cassava mealybugs might not be detected in the large-scale cassava farm as fast as in a small-scale cassava farm. Hence, further investigations are needed for a large-scale cassava farm.

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Competing interests
The authors declare that they have no competing interests.

Authors' contributions
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