Kasetsart J. (Nat. Sci.) 49 : 963 - 970 (2015)

Simulation Study of the Spread of Mealybugs in a Cassava Field: Effect of Release Frequency of a Biological Control Agent

Jairaj Promrak[1,2] and Chontita Rattanakul[1,2,*]

ABSTRACT

Cellular automata and Monte Carlo simulation techniques were employed to study the spread of mealybugs (a major cassava insect pest) in a cassava field. There are various recommended instructions on how often farmers should release green lacewings (a biological control agent) to control the spread of mealybugs. In this study, the effects of different release frequencies of green lacewings in controlling the spread of mealybugs were investigated.
Keyword: Cellular automata, cassava, mealybugs, green lacewings, biological control

INTRODUCTION

Cassava is one of Thailand's agriculture crops of importance and its share on the world's export market has been reported as approximately 61% (Office of Agricultural Economics, 2007). The spread of mealybugs in cassava fields in Thailand might cause a dramatic loss in crop yields as was recorded in 2009 when the total cassava yield was reduced from 30 million tonnes per year to 22 million tonnes per year (Boonseang, 2010). Therefore, the efficient control of the spread of mealybugs is essential.

The spread of mealybugs might be controlled by using insecticide, biological control or a mixed approach incorporating both insecticide and biological control. With biological control, green lacewing is considered as one of the major natural enemies of mealybugs and hence, it is often used as a biological control agent and there are various recommended release frequencies of green lacewings such as every two weeks, every month and every two months until there are no mealybugs on the surveyed cassava plants in the field (Centre for Pest Management, 2014). This study investigated the effect of different release frequencies on estimated crop yields.

CELLULAR AUTOMATA MODEL DEVELOPMENT

We assume that planting of cassava follows the recommended instructions of the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand (Field Crops Research Institute, 2014). In the simulations, a 40 × 40 lattice will be considered to represent a cassava field, so that the planting area is 0.16 ha (40 × 40 m). The planting distance between two cassava plants is 1 m and hence the total number of cassava plants in the field is 1,600 plants.

The states of every cell in the lattice will be updated in parallel at each time step (1 time step (Δt) = 1 day). Each cell in the lattice represents a

[1] Department of Mathematics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand.
[2] Centre of Excellence in Mathematics, Commission on Higher Education, Bangkok 10400, Thailand.
[*] Corresponding author, e-mail: chontita.rat@mahidol.ac.th

Received date : 26/04/15 Accepted date : 10/09/15

state of the cassava planted in the cell which will be updated at each time step according to given rules. There are three possible states for each cell in the lattice. S, I and E representing susceptible cassava, infected cassava and removed cassava, respectively.

A number r, $0 \leq r \leq 1$ will be randomized at each time step and each cell will be updated at random according to the following rules:

Updating rule for removal cassava

If the randomized cell is a removed cassava (E), then no change occurs.

Updating rules for susceptible cassava

If the randomized cell is a susceptible cassava (S), the following rules will be applied.

(a) The cell might become an infected cassava with the probability w due to the infection of instar mealybugs from outside of the cassava field through wind transfer. Note that if the randomized cell belongs to the first two rows next to each of the four borders of the lattice then $w = w_1$, or else $w = w_2$, $0 \leq w_2 < w_1 \leq 1$.

(b) The cell might become an infected cassava with the probabilities n_1, $n_2$and n_3 if at least one of the cells in the immediate neighborhood, distant neighborhood and far distant neighborhood of the randomized cell is an infected cassava, respectively, where n_3, $0 \leq n_3 < n_2 < n_1 \leq 1$.

Updating rules for infected cassava

If the randomized cell is an infected cassava (I), the following rules will be applied.

(a) The cell might become a susceptible cassava if green lacewings successfully feed on mealybugs and there are no mealybugs on the cassava plant in the randomized cell.

(b) One month after cassava planting, a survey will be done every two weeks. We assume that each of the cassava plants might be surveyed with the probability f. We also assume further that the planting period is 12 months. If the cell is surveyed during the first 4 months or the last 5 months after planting then the cell will become a removed cassava. On the other hand, if the cell is surveyed during the 5th month and the 7th month and the number of mealybugs on the cassava plant in the cell is greater than m_1, then the cell will become a removed cassava.

The flowchart of the main loop is given in Figure 1.

The cassava field will be surveyed every 2 weeks starting from the 2nd month of planting. If mealybugs are found on the surveyed cassava plants, green lacewings at the larva stage will be released randomly on the infected cassava plants every two months until there are no mealybugs on the surveyed cassava plants. The number of green lacewings to be released depends on the severity of the spread of mealybugs. If over 50% of surveyed cassava plants are infected then the number of green lacewings to be released is G_1 or else the number of green lacewings to be released is G_2.

Apart from the wind effect, the numbers of mealybugs and green lacewings at all stages on the cassava plant in each cell of the lattice are also updated according to their life-cycle as given in Equations 1–7:

$$P_{t+\Delta t}^{i} = P_t^{i} + r_1\alpha_1 P_t^{e} - \alpha_2 P_t^{i} - \beta_1\left(P_t^{i}, M_t^{i}\right)M_t^{i} \quad (1)$$

$$P_{t+\Delta t}^{m} = P_t^{m} + r_2\alpha_2 P_t^{i} - \alpha_3 P_t^{m} - \beta_2\left(P_t^{m}, M_t^{i}\right)M_t^{i} \quad (2)$$

$$P_{t+\Delta t}^{e} = P_t^{e} + r_3\alpha_4 v_1 P_t^{m} - \alpha_1 P_t^{e} - \beta_3\left(P_t^{e}, M_t^{i}\right)M_t^{i} \quad (3)$$

$$M_{t+\Delta t}^{i} = M_t^{i} + s_1\gamma_1 M_t^{e} - \gamma_2 M_t^{i} \quad (4)$$

$$M_{t+\Delta t}^{d} = M_t^{d} + s_2\gamma_2\delta_1\left(P_t^{i}, P_t^{m}, P_t^{e}, M_t^{i}\right)M_t^{i} - \gamma_3 M_t^{d} \quad (5)$$

$$M_{t+\Delta t}^{m} = M_t^{m} + s_3\gamma_3 M_t^{d} - \delta_2 M_t^{m} \quad (6)$$

$$M_{t+\Delta t}^{e} = M_t^{e} + s_4 v_2 M_t^{m} - \gamma_1 M_t^{e} \quad (7)$$

where P_t^i, P_t^m and P_t^e represent the numbers of instar mealybugs, adult mealybugs and mealybug eggs, respectively, at the time step t; M_t^i, M_t^d, M_t^m and M_t^e represent the numbers of larva green lacewings, pupa green lacewings, adult green lacewings and green lacewing eggs, respectively, at the time step t; α_1 and α_2 are the fractions of mealybug eggs and instar mealybugs that develop into instar mealybugs and adult mealybugs, respectively, in one time step; r_1 and r_2 are the probabilities that mealybug eggs and instar mealybugs survive this time step and develop into instar mealybugs and adult mealybugs, respectively, in the next time step; α_3 is the natural death rate of adult mealybugs in one time step; r_3 is the fraction of female adult mealybugs. α_4 is the fraction of female adult mealybugs in the reproductive period; ν_1 is the average number of eggs laid by a female adult mealybug in one time step; $\beta_1\left(P_t^i, M_t^i\right), \beta_2\left(P_t^m, M_t^i\right)$ and $\beta_3\left(P_t^e, M_t^i\right)$ are the average numbers of instar mealybugs, adult mealybugs and mealybug eggs, respectively, eaten by a green lacewings of the larva stage in one time step; γ_1, γ_2 and γ_3 are the fractions of green lacewing eggs, larva green lacewings and pupa green lacewings, respectively, that develop into green lacewing larva, green lacewing pupa and adult green lacewings, respectively, in one time

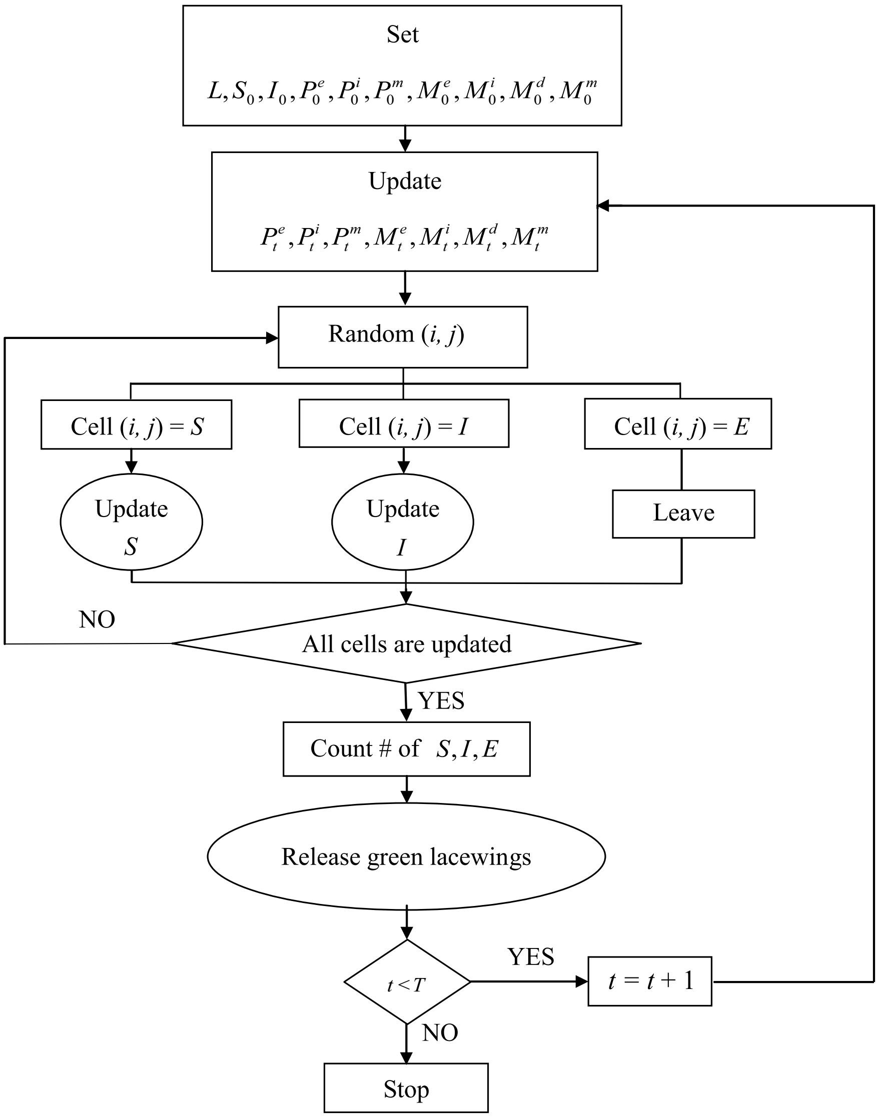

Figure 1 Main loop of Cellular Automata Model.

step; s_1, s_2 and s_3 are the probabilities of green lacewing eggs, green lacewing larva and green lacewing pupa that survive this time step and develop into green lacewing larva, green lacewing pupa and adult green lacewings, respectively, in the next time step; $\delta_1\left(P_t^i, P_t^m, P_t^e, M_t^i\right)$ is the efficiency of converting green lacewing larva to green lacewing pupa in one time step; δ_2 is the natural death rate of adult green lacewings in one time step; s_4 is the fraction of female adult green lacewings; and v_2 is the average number of eggs laid by a female adult green lacewings in one time step.

Moreover, the estimated crop yield at the end of the planting period is also monitored at each time step. By assuming that the estimated crop yield per cassava plant is c kilograms if the plant has never been infected with mealybugs longer than 2 weeks during the planting period, whereas the estimated crop yields will be reduced by 100%, 30% and 10% if the plant is infected for longer than 2 weeks during the first 4 months, during the period between the 5th and the 7th months, and during the period between the 8th and the 12th months, respectively, the estimated crop yields at each time step can be calculated using Equation 8:

$$P(t) = c \cdot C_S(t) + (0.9 \times c) \cdot C_{I_1}(t) + (0.7 \times c) \cdot C_{I_2}(t) \quad (8)$$

where $P(t)$ represents the estimated crop yields at the time step t; $C_S(t)$ represents the total number of cassava plants that have never been infected at the time step t; $C_{I_1}(t)$ represents the total number of cassava plants that have been infected longer than 2 weeks during the period between the 8th and the 12th months of planting at the time step; and $C_{I_2}(t)$ represents the total number of cassava plants that have been infected longer than 2 weeks during the period between the 5th and the 7th months of planting at the time step t.

SIMULATION RESULTS

The simulations of the spread of mealybugs were carried out using parametric values that were estimated from the available reported data at 30°C (Office of Agricultural Economics, 2007; Chong *et al.*, 2008; Pappas *et al.*, 2009; Pappas and Koveos, 2011).

The results shown in Figures 2–4 are the averaged values of the 10 runs using the MATLAB software (Version 7.11.0.584 (R2010b); MathWorks Inc.; Natick, MA, USA) with α_1 = 0.1493 per day, α_2 = 0.0388 per day, α_3 = 0.0596 per capita per day, α_4 = 0.4468 per day, r_1 = 0.9120, r_2 = 0.6589, r_3 = 0.8500 per day, γ_1 = 0.2703 per day, γ_2 = 0.0625 per day, γ_3 = 0.1053 per day, s_1 = 0.8170, s_2 = 0.7938, s_3 = 0.7402, s_4 = 0.4850, v_1 = 2.9126 per capita per day, v_2 = 2.3876 per capita per day, δ_2 = 0.0206 per capita per day, n_1 = 0.05, n_2 = 0.005, n_3 = 0.0005, w_1 = 0.01, w_2 = 0.001, c = 2.25 kg, G_1 = 1,000 green lacewings, G_2 = 800 green lacewings,

$$\beta_1\left(P_t^i, M_t^i\right) = \min\left\{20, \frac{P_t^i(i,j)}{M_t^i(i,j)}\right\}$$ mealybugs per larva green lacewings per day,

$$\beta_2\left(P_t^m, M_t^i\right) = \min\left\{20, \frac{P_t^m(i,j)}{M_t^i(i,j)}\right\}$$ mealybugs per larva green lacewings per day,

$$\beta_3\left(P_t^e, M_t^i\right) = \min\left\{20, \frac{P_t^e(i,j)}{M_t^i(i,j)}\right\}$$ mealybugs per larva green lacewings per day,

$$f = \left\{\frac{\text{the number of surveyed cassava plants in the field}}{\text{the total number of cassava plants that have not been removed from the cassava field}}\right\}$$

and $\delta_1 = 0.0521 \times \min\left\{1, \frac{P_t^i(i,j) + P_t^m(i,j) + P_t^e(i,j)}{M_t^i(i,j)} \div 60\right\}$

where min is the minimum and other terms are as previously defined.

DISCUSSION

From the simulation results shown in Figures 2–4, we can see that the release frequency of 2 weeks gives the best result as the estimated crop yield in this case is higher than in the other cases. However, the cumulative numbers of released green lacewings every 2 weeks and every 2 months are at about the same level while they is a little higher when they are released every month. Moreover, the spread of mealybugs seems to be controllable in all three cases.

Since the cumulative numbers of released green lacewings every 2 weeks and every 2 months are at about the same level, the costs for the release of green lacewings every 2 weeks and every 2 months are then different only with regard to the wage costs. The wages in the case of a 2 week release frequency will be four times those of the case of a 2 month release frequency. In Figure 2a, the estimated crop yields for the release frequency of 2 weeks is approximately 50 kg higher than the release frequency of 2 months at the end of

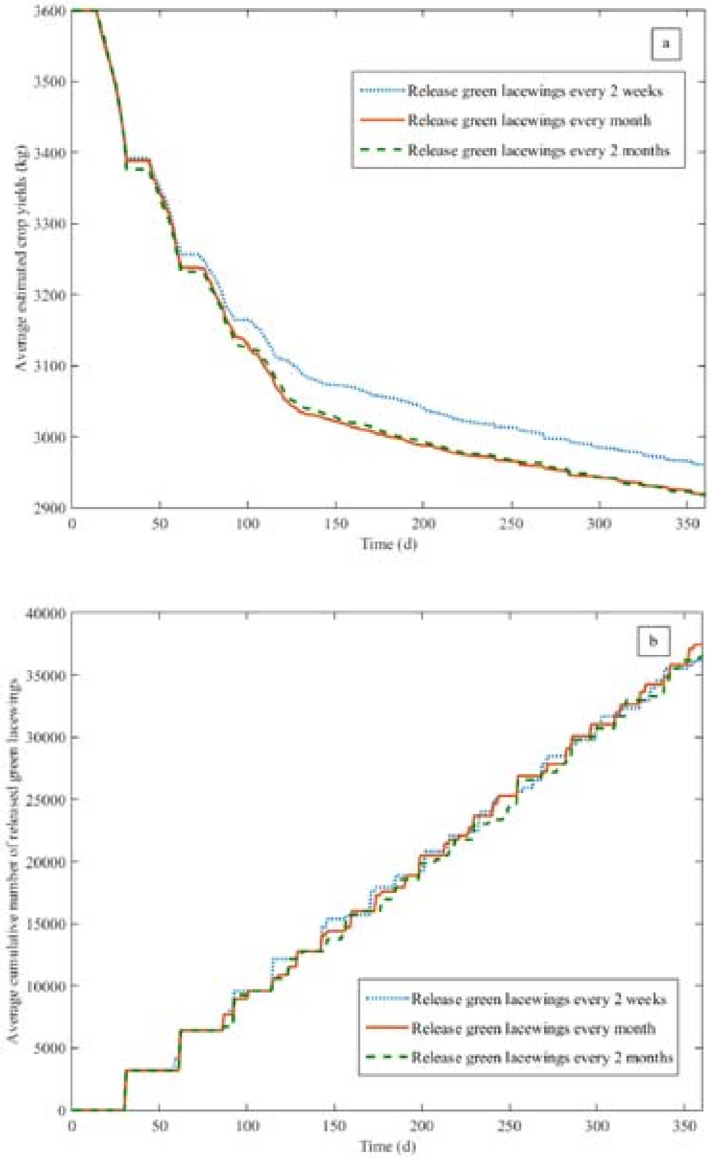

Figure 2 Simulation results of the spread of mealybugs in a cassava field: (a) Average estimated crop yields; (b) Average cumulative number of released green lacewings.

the planting period. Suppose that the market price of cassava is 0.08 USD per kilogram, the release frequency of 2 weeks will give 4.17 USD or 1.67% more on the total crop sale income and hence, the increase in wages will not be covered by the increased income in this case. Therefore, the release frequency of 2 months seems to be the better option. However, in this study, the cassava field of interest is just 0.16 ha and hence the infected probability through wind might be higher compared to a larger field whereas more labor may be necessary. It also depends on how high the wage level is and how long it takes to finish the task. On the other hand, the increased income from the yields would be higher for a larger field. Therefore, further study is needed before any general conclusion can be drawn.

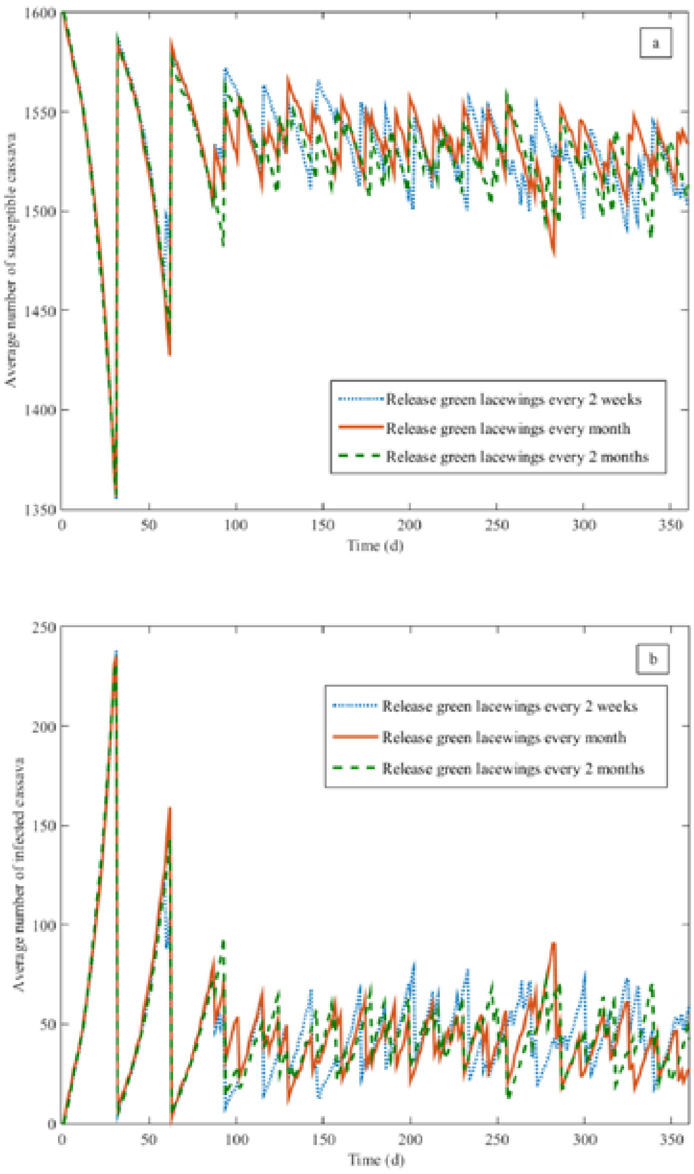

Figure 3 Simulation results of the spread of mealybugs in a cassava field: (a) Average number of susceptible cassava; (b) Average number of infected cassava.

CONCLUSION

The release frequency of green lacewings is one of the factors that must be taken into account to achieve the most efficient control of mealybugs. The cost of biological control for each of the different release frequencies of green lacewings such as wages and the reproduction cost of green lacewings, will be investigated further in comparison to the increased crop yields so that the optimal frequency that maximizes profit can be obtained.

ACKNOWLEDGEMENT

This work was supported by the Centre of Excellence in Mathematics, Commission on Higher Education, Thailand and the Thailand Research Fund (contract number RSA5880004).

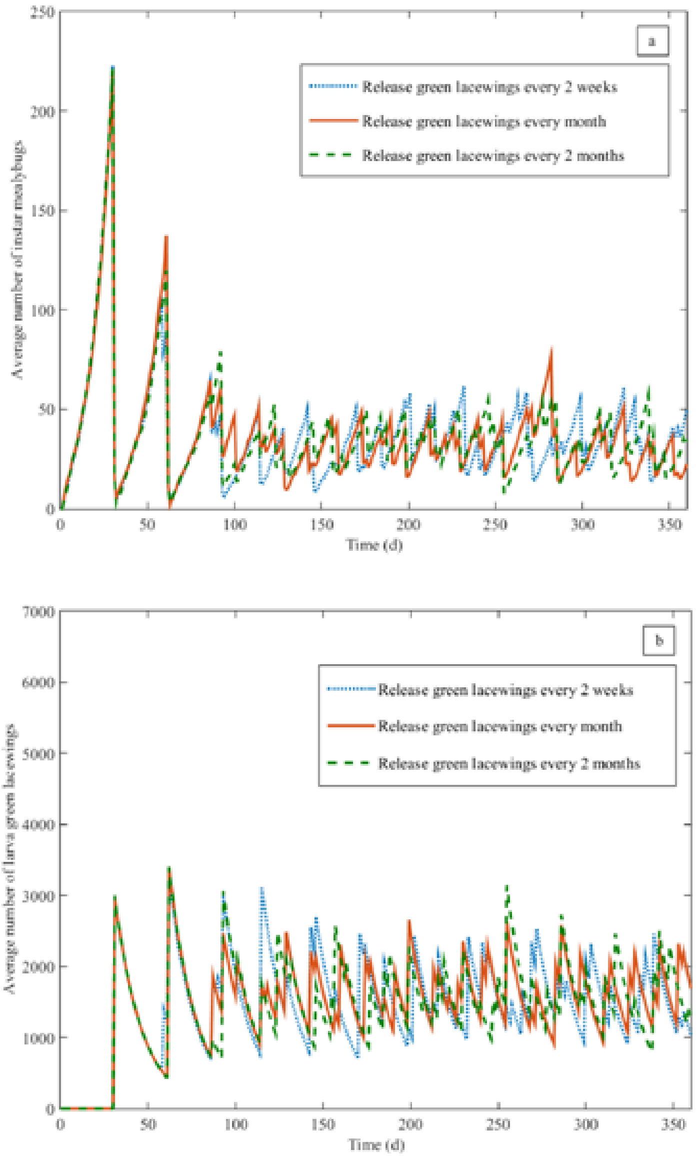

Figure 4 Simulation results of the spread of mealybugs in a cassava field: (a) Average number of instar mealybugs; (b) Average number of larva green lacewings.

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