Studies on Population Ecology of *Thrips palmi* KARNY

XV. Evaluation of Effectiveness of Control Methods Using a Simulation Model

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(Received November 17, 1986)

The effectiveness of various control methods was simulated using a population model of *Thrips palmi* on cucumber cultivated in a plastic greenhouse, and an effective control system was sought. Since the required frequency of spraying lessens as the control threshold (CT) lowers because of the low density effect, CT must be set as low as possible. The "pursuit" spraying method (insecticide is sprayed when the population exceeds the control threshold level and several days after the spraying regardless of population density) is effective to reduce the frequency of spraying. The frequency of periodical spraying started at very low density is almost the same as that using CT, making it an effective means. From the standpoint of safe use of agricultural chemicals, it is difficult to control *T. palmi* using insecticides alone. Prevention of greenhouse invasion, reduction of density on seedlings and mass trapping using sticky traps are other effective means of *T. palmi* control.

INTRODUCTION

Thrips palmi KARNY is the most serious pest of fruit vegetables in western Japan. The insect has a high reproductive rate (KAWAI, 1985) and low sensitivity to many commercially available insecticides (MATSUZAKI, 1982). The eggs are deposited into plant tissue and the last instar larvae pupate in the soil, making insecticides ineffective on these two stages. These properties make it difficult to control this thrips only with chemicals unless they are sprayed many times. From the standpoint of safe use of insecticides and the possible development of resistance, insecticide applications must be kept at a minimum. Therefore, the most effective spraying method must be developed.

In addition to pesticides, several control methods have been devised, but their effectiveness on the control of the population is not clear. Development of an effective control system requires evaluation of various methods from the viewpoint of integrated control and their best combined use.

In this paper, we attempt to construct a population model of *T. palmi* on cucumber in a plastic greenhouse and use it to evaluate the effectiveness of control methods and to develop a control system for this pest.

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POPULATION MODEL

The population model was constructed according to the matrix model proposed by LESLIE (1945), and a population of *T. palmi* on cucumber plants cultivated in a plastic greenhouse in which the temperature was maintained constantly at 25°C was assumed. Only female insects were dealt with in the model and the population was expressed as their number per leaf. The parametric values used are shown in Table 1.

Because the intrinsic rate of natural increase calculated from the population data in a plastic greenhouse was nearly equal to that obtained from a laboratory reared population (KAWAI, 1985), the population parameter taken by laboratory rearing (Table 1) was used in the model.

The population was shown as a vector which has 47 rows, since the duration of incubation, larval stage, pupal stage and the period from emergence to death of all adults was 6, 5, 4 and 34 days respectively, i.e., the total period from oviposition to death of all adults was 47.

The high density effect on reproduction was not considered in the model, because the population increased exponentially in the field until the density reached 100 adults per leaf (KAWAI, 1983, 1984) and we did not consider such a high density population. On the contrary, KAWAI (1987) showed a low density effect in a field population of *T. palmi* and proposed an equation for this of: $y = 1 - e^{-20.93x}$ (x : number of adult females per leaf, y : percentage of mated females). This equation was used in the model.

The economic injury level (EIL) was considered as the density when yield loss of uninjured fruit was 5%, namely, 4.4 adults per leaf (KAWAI, 1986). As the female

Table 1. Parametric values used in the model^a

		Reference
Developmental period:		KAWAI (1985)
Egg	6 days	
Larva	5 days	
Prepupa and pupa	4 days	
Survival rate:		KAWAI (1985)
Egg	0.997/day	
Larva	0.95/day	
Prepupa and pupa	0.97/day	
Adult	Variable with aging	
No. of eggs layed/day:		KAWAI (1985)
1-2 days after emergence	0	
thereafter	4	
Sex ratio of progeny:		
Not inseminated female	0	YOSHIHARA and KAWAI (1982)
Inseminated female	0.71	KAWAI (1985)
Density effect	Not operated	KAWAI (1985)
Low density effect	$y = 1 - e^{-20.93x}$	KAWAI (1987)
	y : rate of copulation	
	x : no. of adult female/leaf	
Economic injury level	3.1 adult females/leaf	KAWAI (1986)

^a In this model, the population of *Thrips palmi* on the cucumber in a plastic house under the constant temperature (25°C) is assumed.

ratio of *T. palmi* was 0.71 (KAWAI, 1985), EIL was expressed as 3.1 adult females per leaf.

Simulated population growth of the adult females is shown in Fig. 1, assuming that initial density was 0.005 adult female per leaf and there occurred no additional invasion after planting. The intrinsic rate of natural increase and the age structure of the simulated population were very similar to those of field populations except at very low density, because no population data was available for very low density in the field.

EVALUATION OF EFFECTIVENESS OF CONTROL METHOD

The following four control methods were evaluated using the population model described above: spraying of insecticides, prevention of invasion by physical materials, reduction of initial density on seedlings and mass trapping using attractive sticky traps (Table 2). The population was simulated for 180 days in each method. As a rule,

Fig. 1. Simulated population growth of adult females of *Thrips palmi* on cucumber without any control based on the matrix model. For the parameters used in this model, see Tables 1 and 2. It is assumed that initial density is 0.005 adult female per leaf and that no adults invade after planting.

Fig. 2. An example of simulated fluctuation of the population of *Thrips palmi* assuming that an insecticide is sprayed when the population exceeds control threshold (CT) level (conventional spraying method). In this case, CT level is considered as 2 adult females per leaf, initial density is 0.01 female per leaf and no adults invade after planting. The ordinate is represented in log scale.

Table 2. Control methods used in the model

1. Insecticide spraying	90% for larva and adult
Mortality	0% for egg and pupa
2. Prevention of invasion	To vary the number of immigrant
3. Reduction of density of seedling	To vary the number of initial density
4. Mass trapping using sticky trap	a. 1 trap/2.0 m ²
Trapping rate	2.00% 1-2 days after emergence
	6.00% thereafter
	b. 1 trap/3.3 m ²
	0.67% 1-2 days after emergence
	2.00% thereafter

it was assumed that initial density was 0.01 female per leaf, and the number of adult females invading every day after planting was 0 or 0.0001 female per leaf.

Spraying insecticides

Since eggs of *T. palmi* are oviposited into the plant tissue and last instar larvae pupate in the soil, insecticides are ineffective on eggs or pupae. Therefore, insecticide used in the model was assumed to kill 90% of larvae and adults but 0% of eggs and pupae, and not to have a residual effect.

The population fluctuation was examined in the case that an insecticide was sprayed when the population exceeded the control threshold (CT) ("conventional" spraying method). An example of simulated fluctuation when this method was used is shown in Fig. 2; in this case CT was considered as 2 adult females per leaf. With the conventional spraying method, population fluctuation was irregular and insecticide was often sprayed on 3–4 successive days regardless of the value of CT. Since the insecticide was ineffective on eggs and pupae, the population increased rapidly when the number of eggs or pupae was high.

The population fluctuation was simulated when an insecticide was sprayed when the population exceeded CT level and several days after that regardless of population density ("pursuit" spraying method). Though the most effective interval between first and second spraying should be selected, in this paper the interval was tentatively fixed at three days after the first spraying. One example of the pursuit spraying method is shown in Fig. 3; in this case CT level is regarded as 2 adult females per leaf. In the pursuit method, the population fluctuated regularly regardless of CT level. The second spraying was applied when most eggs and pupae which had escaped the first spraying hatched or emerged, so that most stages of the population were exposed to the insecticide.

Fig. 3. An example of simulated fluctuation of the population of *Thrips palmi* assuming that insecticide is sprayed when the population exceeds control threshold (CT) level and several days after that ("pursuit" spraying method). In this case, the second spraying is conducted three days after the first spraying and CT level is considered as 2 adult females per leaf, initial density is 0.01 female adult per leaf and no adults invade after planting. The ordinate is represented in log scale.

Fig. 4. Relationship between the control threshold (CT) level and the frequency of spraying per 180 days assuming that initial density is 0.01 adult female per leaf and no adults invade after planting. ○: "conventional" spraying method, ●: "pursuit" spraying method. The abscissa is represented in log scale.

Using these two spraying methods, the relationship between CT level and the frequency of spray applications were computed for 180 days. The result in the case of no invasion after planting is shown in Fig. 4. In both methods, the frequency rose as CT level exceeded 0.5 female per leaf, but declined when CT level was below 0.5 female per leaf; thus the frequency lowered as CT level lowered. Using the pursuit spraying method with CT set as 0.015 adult female per leaf, the population was extinguished by 6 sprayings. In the case of no invasion, the population could be extinguished by several successive sprayings at low density. The result in the case that 0.0001 female per leaf was assumed to invade every day after planting is shown in Fig. 5. Here, the relationship between CT level and the frequency of spraying time was the same as in the case of no invasion, but the spraying frequency did not fluctuate as much with the change of CT level. Since the frequency of spraying time using the pursuit method was lower in most cases than that using the conventional method, the former was regarded as effective to control *T. palmi*. With no invasion, the differences in frequency of spraying times between the two methods were great.

In the second experiment, the population fluctuation was examined when an insecticide was sprayed at regular intervals regardless of population density ("periodical" spraying). The relationship between the interval and the frequency of spraying time is shown in Fig. 6 in the case of no invasion and in Fig. 7 in the case that 0.0001 female

Fig. 5. Relationship between the control threshold (CT) level and the frequency of spraying time on the assumption that initial density is 0.01 adult female per leaf, and 0.0001 adult female per leaf invades every day after planting. ○: "conventional" spraying method, ●: "pursuit" spraying method. The abscissa is represented in log scale.

Fig. 6. Relationship between the interval and frequency of spraying time when an insecticide is sprayed at regular intervals assuming that initial density is 0.01 adult female per leaf and no adults invade after planting. When the population of adult females does not exceed the economic injury level within 180 days, the control is regarded as effective and the interval and frequency of effective control are shown in the figure. ○: spraying is started at 14 days after planting (0.005 adult/leaf), ●: 21 days (0.021), □: 28 days (0.027), ■: 42 days (0.099), △: 56 (0.331), ▲: 63 (1.275).

Fig. 7. Relationship between the interval and frequency of spraying time when an insecticide is sprayed at regular intervals assuming that initial density is 0.01 adult female per leaf, and 0.0001 adult female per leaf invades every day after planting. When the population of adult females does not exceed the economic injury level within 180 days, the control is regarded as effective and the interval and frequency of effective control are shown in the figure. ○: spraying is started at 14 days after planting (0.006 adult/leaf), ●: 21 (0.023), □: 28 (0.032), ■: 42 (0.125), △: 56 (0.473), ▲: 63 (1.742).

Fig. 8. Effect of the prevention of invasion after planting on the delay of population growth assuming that initial density is 0 adult female per leaf. ○: population does not exceed economic injury level. The abscissa is represented in log scale.

per leaf invaded every day after planting. In both figures, only the intervals for effective control, that is, when the population did not exceed EIL for 180 days, are shown. Therefore, the right end of each line shows the longest interval for effective control. When spraying was started early, namely, at low insect density, effective control could be achieved even by sprayings at long intervals, and the frequency of spraying lessened. On the other hand, when spraying was started late, namely, at high insect density, the insecticide had to be sprayed at shorter intervals for effective control, and the spraying frequency increased. Even when invasion occurred every day, when the spraying was started at 14 or 21 days after planting (equivalent to 0.006 or 0.023 female per leaf, respectively), effective control could be achieved by spraying at 16 day intervals. The spraying frequency became 10 or 11 times, which was the same or a little less than the frequency when CT level was set at very low density (Fig. 5). However, when spraying began at a slightly high density, the frequency of spraying time for effective control became great. Spraying frequency for effective control by periodical spraying with no invasion was almost the same as in the case that invasion occurred every day.

Prevention of invasion

Prevention of invasion refers to use some type of material to physically prevent adult invasion by flight. This includes covering the opening of a plastic greenhouse with cheesecloth, or covering the entire greenhouse with ultraviolet absorbing vinyl

film, or covering the ground with silver polyethylene film. In this model, invasion prevention was examined by changing the parameter representing the number of invading adult females per day.

Effect of the invasion prevention after planting on delay of population increase was simulated and is shown in Fig. 8, assuming that no seedlings were infested by *T. palmi* at the time of planting. As the number of invading adult females decreased, the duration of effective control until the population reached EIL lengthened. When the number of invaders per day was less than 0.00005 per leaf, the population did not reach EIL within 180 days. When the invading number decreased to one tenth, the duration of effective control lengthened to 29 days (from 0.01 adult per leaf per day to 0.001 adult), to 74 days (from 0.001 adult to 0.0001 adult) and to 103 days (from 0.007 adult to 0.0007). The prevention of invasion might be a more effective method when the population is low.

Reduction of density on seedlings

Insecticide spraying of seedlings before planting, insecticide spraying of weeds around the greenhouse and removal of weeds around the breeding sites on which *T. palmi* feed are involved in this method. The effect of the reduction of density on seedlings was evaluated by changing the initial density in the model.

Effect of reduction of initial density on seedlings on the delay of population increase was examined and is shown in Fig. 9, assuming that the number of females invading the greenhouse per day was 0 or 0.0001 per leaf. As the initial density decreased, the duration of effective control until the population reached EIL lengthened. When the initial density was less than 0.002 per leaf and no adults invaded after planting, the population did not reach EIL within 180 days. When no invasion was assumed and the initial density decreased to one tenth, the duration of effective control lengthened to 35 days (from 0.1 adult per leaf to 0.01 adult), to 59 days (from 0.05 adult to 0.005 adult) and to 106 days (from 0.03 adult to 0.003). In the case that 0.0001 adult female per leaf invaded every day after planting and the initial density decreased to one tenth, the duration of effective control lengthened to 31 days (from 0.1 adult per leaf to 0.01 adult), to 41 days (from 0.05 adult to 0.005 adult), to 62 days (from 0.01 adult to 0.001 adult) and to 49 days (from 0.005 adult to 0.0005). Reduction of the density on seedlings might be a more effective method when no adults invade after planting.

Mass trapping using sticky trap

Adults of *T. palmi* have been reported to be attracted to blue or white color (YAMAMOTO et al., 1981; KITAKATA and YOSHIDA, 1982), so a commercially available blue sticky ribbon (Seiryu®) was used for mass trapping in a plastic greenhouse (1 trap per 2–3 m²). Considering that trapping rate of matured adults was one third that of unmatured adults (KAWAI, unpublished) and using the data on trapping rate in a plastic greenhouse reported by NISHINO and ONO (1984), it was assumed that trapping rate of matured females was 2.00% and of unmatured females was 6.00% when traps were set every 2.0 m², and when set every 3.3 m² was 0.67% of matured females and 2.00% of unmatured females.

Effect of the mass trapping using sticky ribbons was simulated and is shown in Fig. 10 on the assumption that no adults invaded after planting. When the initial density was over 0.05 female per leaf, the difference with and without sticky ribbon

Fig. 9. Effect of the reduction of initial density on the delay of population growth. ○: no adult invades after planting, ●: 0.0001 adult female per leaf invades every day after planting, ●: population does not exceed economic injury level. The abscissa is represented in log scale.

Fig. 10. Effect of mass trapping using sticky ribbons on the assumption that initial density is 0.01 adult female per leaf and no adult invades after planting. ○: 1 trap/2.0 m², △: 1 trap/3.3 m², □: no trap. The abscissa is represented in log scale.

Fig. 11. Effect of mass trapping using sticky traps assuming that initial density is 0.01 adult female per leaf, and 0.0001 female adult per leaf invades every day after planting. Symbols are the same as in Fig. 10. The abscissa is represented in log scale.

in the duration of effective control until the population reached EIL was less than 2 days (1 trap per 2.0 m²). However, as the initial density decreased, this difference increased. The differences were 11 days (when initial density was 0.01 female per leaf), 36 days (0.005 female), and 65 days (0.004 female). Effect of mass trapping when 0.0001 adult per leaf was assumed to invade every day after planting is shown in Fig. 11. The relationship between the initial density and the duration of effective control until the population reached EIL was the same as when no invasion was assumed after planting. When the initial density was over 0.07 female per leaf, the difference in duration of effective control with and without sticky ribbon was less than 2 days. However, as the initial density lowered, the difference increased: 3 days (when initial density was 0.05 female per leaf), 12 days (0.01 female), 19 days (0.005 female), 42 days (0.001 female), 43 days (0.0005 female), and when the initial density was below 0.0004 female, the population never reached EIL with sticky traps (1 trap per 2.0 m²). From this result, it is supposed that the mass trapping method might be effective while the density at the trap setting is low, but not effective when that density is high.

DISCUSSION

Assuming that insecticide is sprayed when the population exceeds CT level (using either the conventional or pursuit method), the frequency of spraying time decreased as CT level rose whenever CT was set at over 0.5 adult female per leaf. With the pursuit method, the interval of spraying remained nearly the same regardless of the CT level, and the beginning date of spraying was the main factor involved in the difference in frequency required. In conventional spraying, the difference in frequency among different CT levels was very large (Fig. 4), and this difference cannot be explained by the difference in the time spraying was begun.

On the other hand, when CT level was set at under 0.5 female per leaf, spraying frequency decreased as CT level decreased in either spraying method. Spraying frequency generally rises as CT level lowers against most insect pests, but the results of this simulation is adverse at low density. The low density effect to *T. palmi* is supposed to be responsible for this result. Therefore, in order to control *T. palmi*, it is important that the population be controlled at a very low density level that the low density effect operates. As mentioned above, for insect pests like *T. palmi* that have a strong low density effect, high intrinsic rate of natural increase and low sensitivity to insecticides, CT level must be set at a very low density, not near EIL as for many other insect pests.

The frequency of spraying by the pursuit spraying method is less than that by conventional spraying. Since eggs and pupae of *T. palmi* are free from insecticidal effects, pursuit spraying is more effective. MATSUZAKI (1983) reported that on egg-plant, insecticides must be applied to *T. palmi* two or three times at 4–5 day intervals from the start of the infestation. NAGAI and NONAKA (1983) also reported that on sweet pepper spraying is necessary twice or three times at 5 day intervals when the population density is high. They showed empirically the effectiveness of the pursuit spraying method, and this method seems effective on insect pests which have a stage at which they are free from the effect of insecticides.

As CT level lowers, the frequency of necessary spraying becomes less. However, the lower the population becomes, the more plants are required to estimate the density as calculated by IWAO and KUNO (1971). Assuming the random sampling of cucumber plants and checking of the number of adults on two young developed leaves of each plant, the number of plants required with a relative precision of 0.2 would be 350 when the density is 0.1 adult per leaf and 3,500 when the density is 0.01 adult. A relative precision of 0.5 would require 60 when the density is 0.1 adult and 570 when the density is 0.01 adult (KAWAI, unpublished). From a practical point of view, it seems impossible to set a CT level at under 0.1 adult per leaf. Therefore, a simple method of population estimation must be developed.

When periodical spraying was started at very low density, spraying frequency was almost the same as that when CT was set at a very low density. NAGAI and NONAKA (1983) reported that *T. palmi* on sweet pepper was controlled effectively by periodical spraying at 15 day intervals when begun at very low density. This result well agreed with the result of the simulation. Since density estimation is necessary only once at the start of spraying with the periodical method, this means is more practical than setting CT at a very low density. However, even for periodical spraying, it is necessary to estimate the population density as precisely as possible when the density is very low to determine the start of spraying.

Since the population of *T. palmi* has a stable age structure, the number of one stage can be estimated from the number of another stage. However, the population has an unstable age structure after application of certain control methods, since the methods affect stages differently. With insecticide spraying, the effect on adults and larvae is the same but that on eggs and pupae is different. In this model, EIL is shown based only on the number of adult females. Since this number does not represent the total population of *T. palmi* after control has been applied, some spraying is excessive and some necessary spraying is lacking. Therefore, the frequency of spraying using periodical spraying is the same as that using CT.

The effect of materials used to prevent invasion was tested in a plastic greenhouse or open field. Insect density on cucumber covered by cheesecloth was 1/4–1/10 (NAGAI, 1981) or 1/5–1/50 (SUZUKI and MIYARA, 1984) that without covering. The number of immigrants to a plastic house covered with ultraviolet absorbing vinyl film was 1/10 that to a plastic house covered with common agricultural vinyl film (NONAKA and NAGAI, 1983). The density on cucumber mulched by silver polyethylene film was less than 1/10 (MAKINO, 1984) or 1/6–1/8 (NAGAI, 1981) of that without mulching, and 1/3 of that mulched by black polyethylene film (SUZUKI and MIYARA, 1984). Since the duration of effective control until the population reaches EIL lengthens 70 to 100 days according to the simulation if the number of immigrants decreases by 1/10, an effective means of controlling *T. palmi* is use of materials which prevent invasion.

The effect of mass trapping using sticky traps was tested in a plastic greenhouse. The density on cucumber in a greenhouse with traps (1 trap per 3.3 m²) was about 1/10 that in a greenhouse without traps (NISHINO and ONO, 1984). The density on eggplant in a greenhouse with traps was 1/7–1/10 (1 trap per 3.3 m²) or 1/10–1/20 (1 trap per 2.0 m²) (NISHINO and ONO, 1984), and about 1/10 (1 trap per 3.3 m²) or 1/5 (1 trap per 6.7 m²) (TAKEUTI et al., 1983) that in a greenhouse without traps. On sweet pepper density with traps (1 trap per 3.6 m² or 7.2 m²) was about 1/2–1/5 to that in a greenhouse without traps (NONAKA and NAGAI, 1984). The result of the simulation indicates that mass trapping is effective at low density conditions. Therefore, it is concluded that this is an effective means to control *T. palmi* when traps are set at low population density or are used in combination with an insecticide.

The frequency of spraying times within 180 days is more than 10 by periodical spraying or setting CT level, except in one instance (no invasion after planting, CT is 0.015 adult female per leaf and using the pursuit spraying method). Considering the need for the safe use of agricultural chemicals, it is unthinkable that more than 10 applications of an insecticide should be made during one cropping. Therefore, control of *T. palmi* using insecticide alone is difficult. Since there are many physical control methods which have been shown effective in suppressing populations of this insect, an integrated control system for each plant should be established.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to Dr. A. TAKAFUJI of Kyoto University for his helpful suggestions.

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