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A SYSTEMS ANALYSIS APPROACH TO BROWN PLANTHOPPER CONTROL ON RICE IN ZHEJIANG PROVINCE, CHINA. II. INVESTIGATION OF CONTROL STRATEGIES

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SUMMARY

(1) A simulation model of brown planthopper (BPH) (*Nilaparvata lugens* Stal.) population dynamics, described by Cheng & Holt (1990), was used to assess the performance of different insecticide control strategies.

(2) Since field trials indicated that the loss in rice yield associated with BPH attack was linearly related to the peak density of the second generation, control strategies were assessed in terms of the ability to minimize this peak density.

(3) Where a single insecticide treatment was given, the best time at which to apply it was at 30 days after transplanting (DAT). This was true for a range of insecticides, transplanting times, temperatures, and immigration patterns.

(4) Where two insecticide treatments were used, treating at 30 DAT remained a robust strategy and allowed considerable flexibility in the timing of the second spray while still achieving an acceptable performance.

(5) The main problem concerning BPH control in Zhejiang Province is to decide whether insecticide treatment should be applied and, if so, whether one, two or more treatments should be given. Thresholds at which treatment is required to prevent BPH causing 5% yield loss were determined for single and two-treatment strategies. These thresholds were found to be particularly sensitive to transplanting time and to September temperatures.

INTRODUCTION

In the central rice-growing area of China, outbreaks of the brown planthopper (BPH) (*Nilaparvata lugens* Stal.) often occur (Cheng & Holt 1990). One means of controlling these outbreaks is to plant BPH-resistant varieties of rice, but in Zhejiang Province, where two rice crops per season are often grown, susceptible varieties are usually planted. There are two main reasons for this: the high risk of frost damage and the poor eating quality of long duration, resistant varieties. With no other realistic alternatives at present, it seems inevitable that insecticides will continue to play an important role in BPH control in the second crop (Cheng 1983).

There are two problems with chemical control. First, insecticide-induced resurgence can occur (Chelliah & Heinrichs 1980; Raman & Vehamasamy 1983) due to: (i) the deleterious effects of pesticides on natural enemies; (ii) the stimulation of BPH reproduction, by improving the nutritive quality of host-plants or by neuro-hormonal influences; or (iii) by the reduction of competition with other insect herbivores. Secondly,

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the egg stage of BPH is not killed by insecticide. Because BPH females lay their eggs inside the leaf sheath, most pesticides cannot kill the eggs, nor is the residual effect of the pesticide long-lasting enough to kill the nymphs when they emerge. As a result, a proportion of the population, as eggs, will often survive insecticide treatment.

This paper is concerned with using the simulation model described by Cheng & Holt (1989) to improve recommendations for BPH control in the second rice crop in Zhejiang Province. It has already been shown that this simulation model gives a more reliable forecast than that given by regression analysis (Cheng & Holt 1990). Here the model is used to simulate the effect of different control strategies on BPH numbers, allowing pesticide strategies for different circumstances to be assessed.

THE CHOICE OF A CONTROL STRATEGY

When farmers decide on a control strategy, or extension agents make a recommendation, the costs and benefits of treatment are important and the extent to which BPH damage is reduced must be considered. Figure 1 indicates the major factors that determine the impact of control practices on crop yield and revenue, through influencing the damage and control relationships (Southwood & Norton 1973). It is on the basis of these two relationships that the performance of control strategies are assessed.

Damage relationship

Although BPH attack can affect the quality of grain, the main effect of BPH on crop revenue is through loss of yield (Chen & Cheng 1978). During the period 1978–82, a series

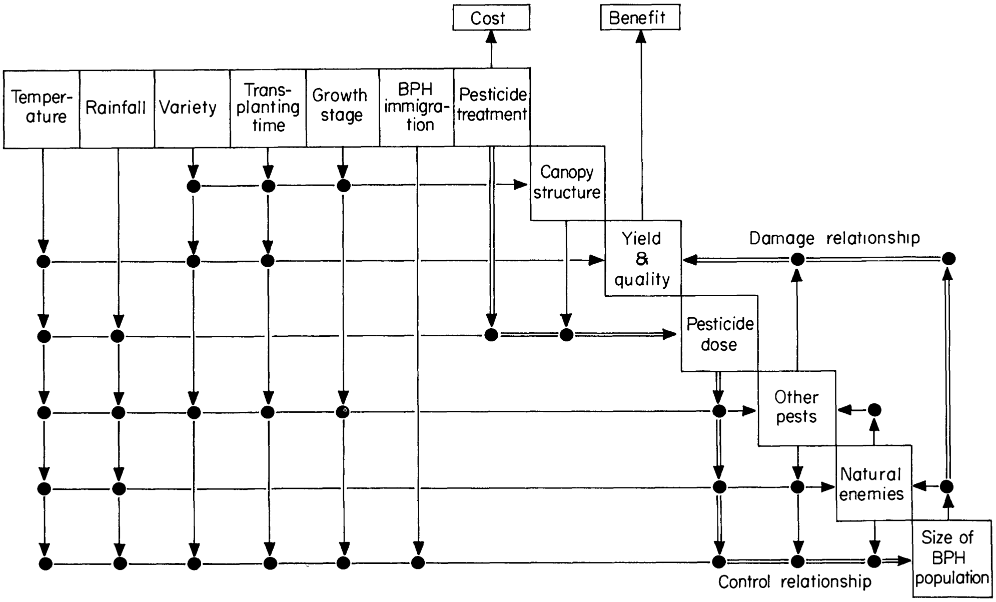

FIG. 1. Relationships and interactions affecting the costs and benefits of BPH control. Each ● in the matrix indicates that the component at the head of the column has a direct effect on the row component, shown to the right. The arrows indicate the secondary and subsequent effects that can occur. The broad arrows indicate the component of the control relationship (effect of pesticide treatment on BPH populations) and the damage relationship (effect of BPH populations on yield).

of experiments were carried out in Jiaxing, Zhejiang Province, to assess the yield loss associated with BPH attack (J. A. Cheng, unpublished). In the treated plots, pesticide was used to keep the population density of BPH below 1 hill^{-1} for the whole season. In the untreated plots, the peak density of adults and nymphs in the second generation was recorded. By subtracting the yield of the untreated plots from the yield of the treated plots, the percentage yield loss associated with the peak density of BPH was determined.

The correlation between peak density and yield loss for individual years is good ($r^2 = 0{\cdot}83$). The higher the daily average temperature during the main damaging period—51–70 days after transplanting (DAT)—the steeper the slope of the damage relationship. This is probably due to higher feeding rates at high temperatures (Zhang *et al.* 1982). Thus, a linear damage relationship is assumed between peak density and yield: the temperature during 51–70 DAT affecting the slope of this line. A more complex damage index, which also accounts for age structure of the population and crop growth stage, is discussed later.

Control relationship

In Zhejiang Province, although up to four insecticide treatments can be made against BPH, zero, one or two treatments are the most common. To investigate the performance of these different insecticide strategies, the simulation model (Cheng & Holt 1990) is used to assess the impact of control on peak BPH numbers. The effect in reducing yield loss can then be assessed from the damage relationship (Fig. 2). The analysis proceeds by addressing the following three questions:

(1) If a single spray is to be applied, when is the best time to apply it?
(2) At what times should two sprays be applied?
(3) Under what circumstances should none, one or two sprays be recommended?

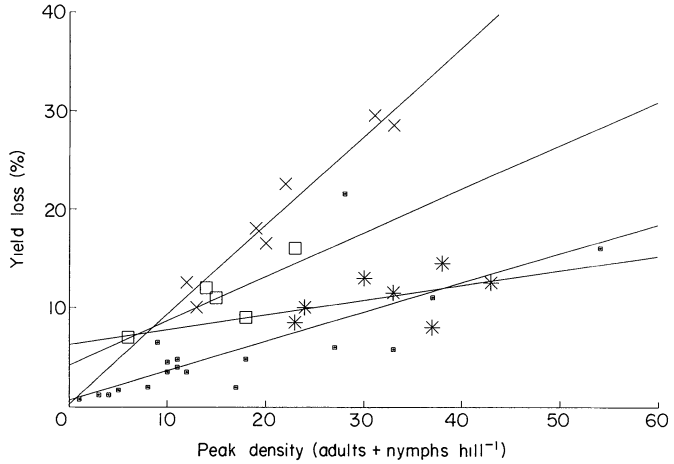

FIG. 2. BPH damage relationships: the effect of peak density on percentage yield loss. Data points are for field trials in 1976 (▣), 1979 (*), 1981–82 (□), and 1983, (×) in Jiaxing, Zhejiang Province (J. A. Cheng, unpublished). Average daily temperatures over the damaging period (51–70 DAT) were (▣) 19·4 °C ($y = 0{\cdot}8 + 0{\cdot}29x$); (*) 18·9 °C ($y = 6{\cdot}3 + 0{\cdot}16x$); (□) 19·7 °C ($y = 4{\cdot}2 + 0{\cdot}46x$); and (×) 21·1 °C ($y = 0{\cdot}2 + 0{\cdot}92x$).

WHEN IS THE BEST TIME TO APPLY A SINGLE INSECTICIDE TREATMENT?

When pesticide is sprayed against a BPH population, the mortality of nymphs and adults in the crop will depend on the application method and the type of pesticide used. The mortality in subsequent days will be determined by the persistence of the pesticide. The reduction in pesticide concentration over time has been represented by Wilson, Desmarchelier & Malafant (1983) as an exponential decay curve. A modification of their model is used to represent the reduction in pesticide-induced mortality over time. It is of the form:

$$M\mathrm{p}(t) = a\ \mathrm{Exp}\ [-\mathrm{b}(t-1)^{\mathrm{c}}] \qquad (1)$$

where $M\mathrm{p}(t)$ is the percentage mortality caused by pesticide on day t after treatment ($t = 2, 3, 4 \ldots n$); a is the maximum mortality occurring within 24 hours of treatment ($t = 1$); and b, c are parameters.

From the pot and field trials of Asai, Kajihara & Maekawa (1984), Koshiya, Bhattacharya & Verma (1980), Mayabini, Pasalu & Rajaman (1983), and Nagata (1982), mortality curves for various pesticides can be determined on the basis of maximum mortality (a), the total period when the pesticide causes mortality (tn), and the half-life of the pesticide, i.e. the time taken for pesticide-induced mortality to decline to 50% of that achieved on day 1. By fitting the curve described by expression (1) to these three points, a good approximation has been obtained (Fig. 3). This function (expression (1)) is used to simulate the mortality caused to nymphs and adults by particular pesticides.

The next stage is to assess the impact of pesticide-induced mortality on the total BPH population or, more specifically, on the peak density. For this, the model of Cheng & Holt (1990) is used, with the following standard values.

Transplanting time: 1 August
Immigration: Starts 1 day after transplanting
Total number of 5·5 macropters 100 hills^{-1}
Pattern (b) (see Fig. 5b in Cheng & Holt (1990))
Temperature (Aug/Sep): Average for the period 1976–85.

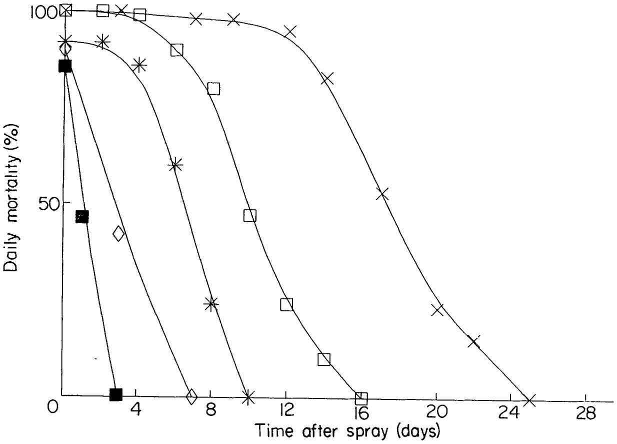

FIG. 3. Mortality curves for five insecticides: MTMC[1] (■), Dimethoate[2] (*), Carbaryl[3] (□), Carbosulfan[4] (×), and Diazinon[5] (◇). Data points are from Koshiya, Bhattacharya & Verma (1980)[2,3] Mayabini, Pasalu & Rajaman (1983)[4], and Nagata (1982)[1,5].

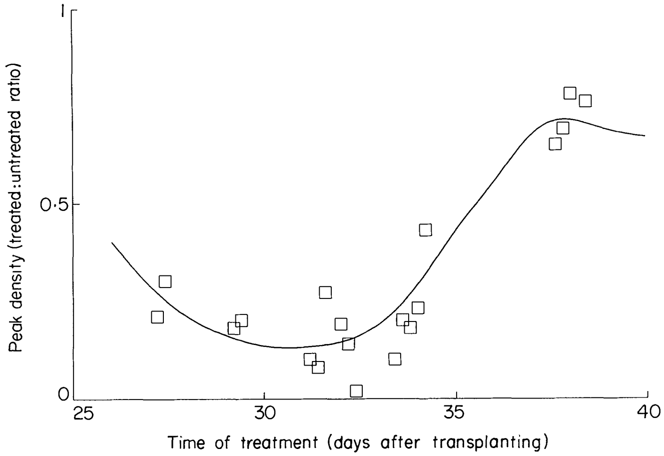

FIG. 4. The effect of application time of a single treatment of MTMC on BPH peak density: results from a simulated, standard outbreak (—), and from field trials (□) carried out in Zhejiang Province over the period 1976–82 (J. A. Cheng, unpublished).

To simulate pesticide application, Expression (1) is used to determine the percentage of adults and nymphs killed on each day after the application. These numbers are removed from the simulated population and the model run to determine the peak density.

To assess the best time to apply one insecticide treatment a series of simulation runs were made. For each run, the simulated population was treated with a single application of MTMC at 25, 30, 35, 40, 45 and 50 DAT. Assuming a linear damage relationship (Fig. 2) and that the cost of spraying is not affected by the time of application, the most effective time to spray is when peak density is minimized.

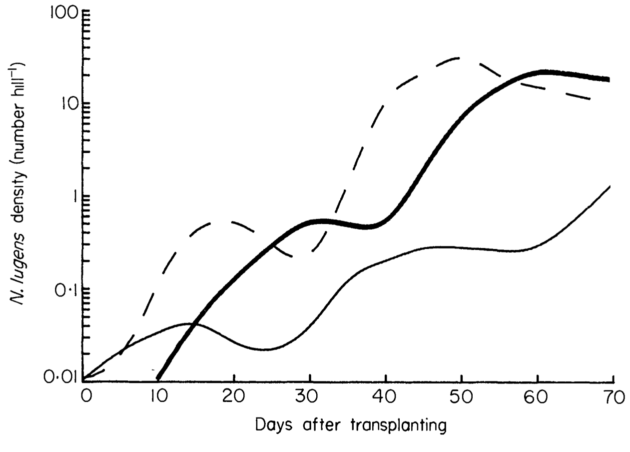

FIG. 5. Population dynamics of an untreated, standard outbreak (simulation results): total adults (——), total nymphs (**——**), total eggs (– – –).

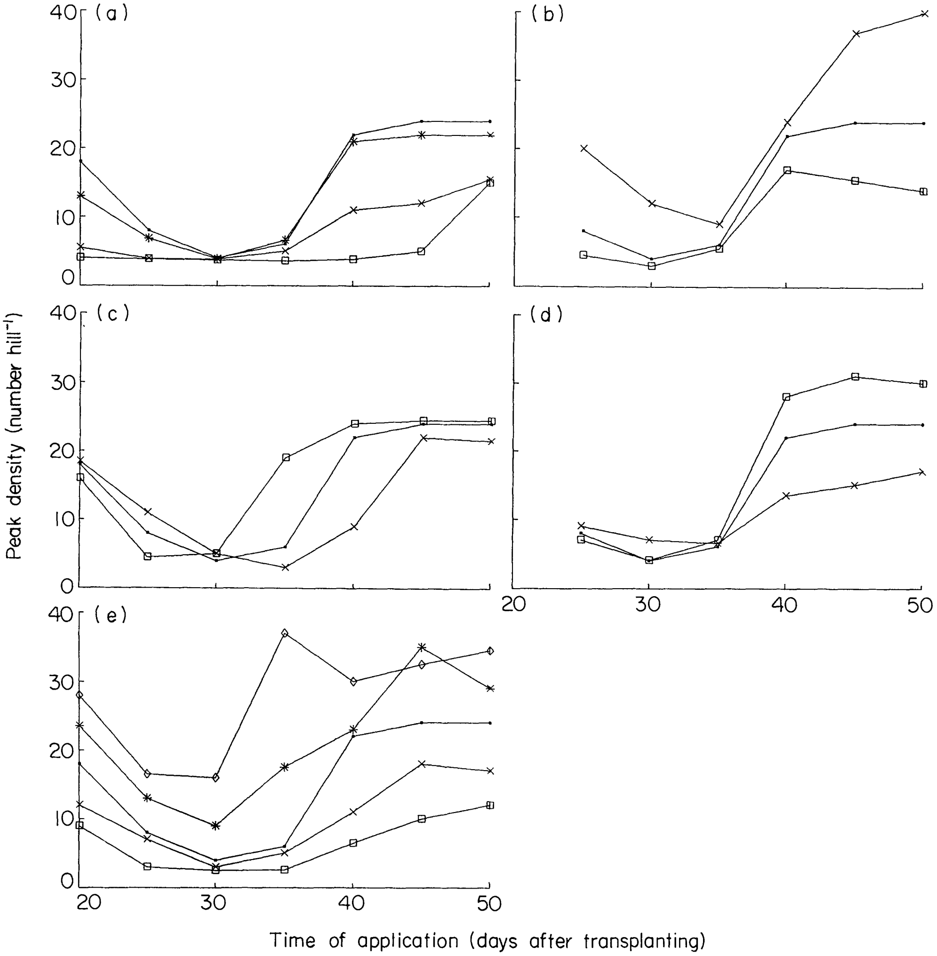

FIG. 6. The effect of application time of a single insecticide treatment on peak density, as modified by the following variables. (a) Type of insecticide: MTMC (1 day = half-life of insecticide) (——); Diazinon (3 days) (×); Carbaryl (10 days) (*); and Carbosulfan (18 days) (□). (b) Temperature: average temperature for August and September (——); favourable to BPH—August temperature 1 °C below average, September temperature 1 °C above average (×); unfavourable to BPH—August temperature 1 °C average, September temperature 1 °C below average (□). (c) Time at which immigrants first enter the crop: −5 DAT (□), 1 DAT (——), and 5 DAT (×). (d) Immigration pattern: concentrated (□), standard (——), and protracted (×), (as used and described in Cheng & Holt (1990) Fig. 5). (e) Transplanting time: 22 July (◇), 27 July (*), 1 August (——), 6 August (×), 11 August (□).

The results indicate that 30 DAT is the best time at which to apply MTMC (Fig. 4). This reflects closely the findings of field trials carried out in Zhejiang Province, where single applications of MTMC were applied to the first generation at different times (Fig. 4). This strategy performs best because egg density is almost at a minimum at 30 DAT (Fig. 5), confirming Nagata's (1985) findings in Japan.

The next question is whether the strategy of spraying at 30 DAT is still the most effective time when other situations are considered. For instance, if different pesticides with different degrees of persistence are used, will 30 DAT still be the best time to spray?

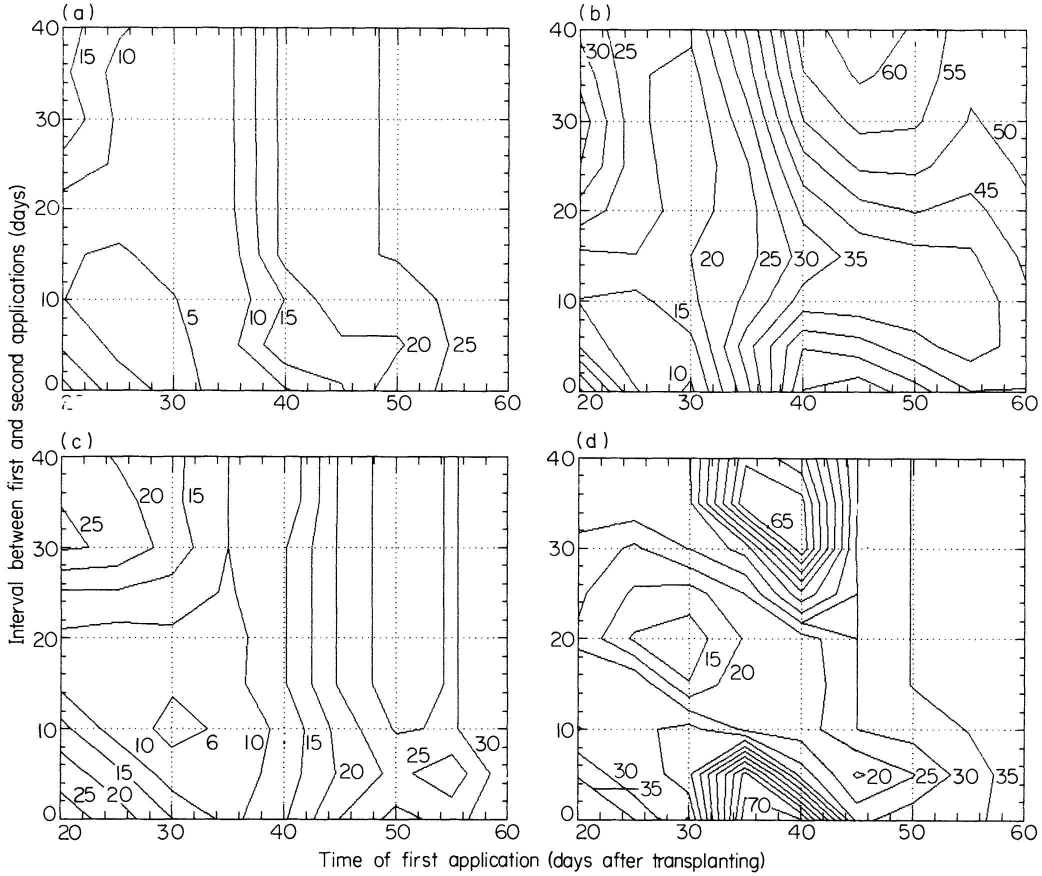

FIG. 7. The effect of application time of two treatments of MTMC: (a) on peak density of BPH, standard conditions; (b) as for (a) but the effect on BPH damage index; (c) as for (a), except protracted immigration pattern ((Fig. 5c) in Cheng & Holt 1989) and temperatures favourable to BPH; (d) as (c), except transplanted 22 July. Iso-lines indicate peak density (a,c,d) or damage index (b).

To investigate this, the series of simulation runs involving a single spray application were repeated but on this occasion, insecticides with a different half-life—the time taken for daily mortality to fall to 50% of the maximum (Fig. 3)—were used. The effect of insecticides with a half-life of 1, 3, 10, and 18 days were simulated.

The results (Fig. 6a), indicate that spraying at 30 DAT is a good option for a range of persistence levels. However, for more persistent pesticides such as Carbosulfan, the reduction in peak density is insensitive to the time of application, at least over the range 20–45 DAT.

When other parameters are varied (Fig. 6b–e), 30 DAT remains the optimal time, or is very close to it. The greatest discrepancy is associated with the time at which immigrants first enter the crop (Fig. 6c). Usually this coincides with transplanting but, where this is not the case, a single treatment is best applied 30 days after the time at which immigrants first enter the crop.

Although treating at 30 DAT is also best for the wide range of transplanting times considered (Fig. 6e), for early transplanted crops the peak density after a single treatment is still likely to be at an unacceptably high level (in excess of 8 BPH hill^{-1}). This implies that a second treatment is likely to be necessary.

AT WHAT TIMES SHOULD TWO INSECTICIDE TREATMENTS BE APPLIED?

To investigate this question, the simulated population is subjected to two insecticide (MTMC) treatments. As well as varying the time of the initial treatment, the time interval between the initial treatment and the second one is also varied.

The impact of these different treatments on peak density is shown in Fig. 7a. It is clear that the single treatment rule—apply at 30 DAT—is still largely true. Although a minimum peak density can be obtained by treating at 25 DAT and again 10 days later, treating initially at 30 DAT allows much greater flexibility in the timing of the second treatment while still achieving acceptable control.

In evaluating treatment against the second generation, the assumption that damage is a linear function of peak density (Fig. 2) needs to be reconsidered. In general, where insecticide is applied against the first generation, this relationship holds true. However, a problem does appear to arise with insecticide application against the second generation, which can markedly shift the time and age structure of the peak (second generation) population, or even be applied after the peak. Since estimation of the linear damage relationship (Fig. 2) is based on data from untreated populations, it may be misleading to use peak density as a measure of the reduction in damage resulting from second generation treatments.

To investigate this, an alternative, damage index has been developed (Appendix I). It reflects a more biologically realistic model of damage by incorporating crop growth stage and BPH population structure, as well as BPH density and temperature. However, since empirical validation of the damage index has not been possible at this stage, it is used here as an ordinal measure of damage: the higher the index, the more damage caused.

In Fig. 7b, the impact of two insecticide treatments against a simulated (standard) population is expressed in terms of the damage index. The merit of treating initially at 30 DAT is still evident. Thus, in comparing Fig. 7a and b, it appears that peak density is adequate for identifying the best timing of two treatments, at least, where the initial one is applied in the first generation.

Our approach to assessing the robustness of the two-treatment strategy is to investigate situations where serious levels of BPH attack might be expected. Two situations are considered, both involving a standard number of immigrants arriving at 1 DAT, a protracted immigration pattern, and temperatures that are favourable to BPH. The difference is in transplanting time: one crop is transplanted on 1 August (Fig. 7c), the other on 22 July (Fig. 7d).

For the later transplanting time (Fig. 7c), a strategy of treating at 30 and 40 DAT gives the best outcome. However, the degree of flexibility in choosing an interval between treatments, that still gives an acceptable outcome (certainly below 10 BPH hill^{-1}), is much reduced (cf. Fig. 7a).

When the crop is transplanted earlier (Fig. 7d), 30 DAT is still the best time to treat initially but the best time to apply the second treatment is now 50 DAT. Since this earlier transplanting time allows a third generation to develop, however, peak density is only reduced to 15 hill^{-1}. In such cases, where more than two treatments may be needed, further simulation has shown that it is generally best to apply two initial treatments against the first generation.

UNDER WHAT CIRCUMSTANCES SHOULD NONE, ONE OR TWO TREATMENTS BE RECOMMENDED?

One way to assess whether it is worth treating a population is to determine the economic threshold, i.e. the level of attack at which it is just profitable to treat. This can be obtained from the following equation (Norton 1976; Mumford & Norton 1984):

$$\theta = \frac{C}{Pdk} \qquad (2)$$

Where θ is the economic threshold level of pest attack, expressed here as peak BPH (adult and nymph) density; C is the cost of insecticide treatment (R20 ha^{-1}); P is the price of rice (R 360 tonne^{-1}); d is the loss in yield associated with each BPH (adult and nymph) hill^{-1} at peak density (0·03 tonnes ha^{-1}, with a 0·5% loss of yield for each BPH hill^{-1} and a yield of 6 tonnes ha^{-1}); k is the percentage reduction in peak density associated with insecticide treatment (70%).

Using the values shown in the brackets above, the economic threshold for a single treatment of MTMC against BPH is 2·6 adults and nymphs hill^{-1}. In practice, the objective of recommendations on BPH control in Zhejiang Province, provided by Provincial and County extension staff (Holt, Cheng & Norton 1990), is to limit losses caused by BPH to below 5% (Ding, Chen & Li 1981). This is the criterion we use to determine under what circumstances none, one or two insecticide treatments should be recommended.

One complication in determining treatment thresholds is the variation in rate of damage caused by BPH from year to year, depending on temperatures during the period 51–70 DAT (Fig. 2). This, in turn, depends on the combination of transplanting time and autumn weather, which also affects the development of BPH populations (see Fig. 7, Cheng & Holt 1990). Therefore, treatment thresholds, expressed either in terms of peak immigration numbers or peak density of adults and nymphs in the first generation, are determined separately for nine cases, i.e. the various combinations of three transplanting times (27 July, 1 and 6 August) and three weather conditions (favourable to BPH, average, and unfavourable).

The procedure for determining these treatment thresholds is as follows.

(a) The average daily temperature (°C) is assessed for the period 51–70 DAT, and the peak density associated with a 5% yield loss is determined using the following regression relationship, based on the data shown in Fig. 2:

$$Y = 100/[1 + \mathrm{Exp}(17{\cdot}0 - 1{\cdot}06 \ln O - 0{\cdot}584T)]$$
$$(r^2 = 0{\cdot}83;\ \mathrm{d.f.} = 34;\ P = 0{\cdot}01) \qquad (3)$$

where Y is the percentage yield loss; O is the peak density per hill; and T is the daily average temperature during 51–79 DAT.

An early transplanting time (27 July) and favourable weather conditions give an average daily temperature during 51–70 DAT of 21·9 °C. From expression (3), the peak BPH density associated with 5% yield loss at this temperature is 3·4 BPH hill^{-1}. This is the specific level for this particular scenario below which peak BPH density has to be maintained.

TABLE 1. Treatment thresholds for a single and two applications of MTMC as derived from the simulation model

Transplanting time	Temperature	Daily average temperature (51–70 DAT)	Peak density hill^{-1} of 2nd generation that will cause 5% yield loss	Treatment thresholds (number 100 hills^{-1} in 1st generation) 1 spray	2 sprays
27 July	Favourable	21·9	3·4	3	13
	Average	20·9	5·8	6	26
	Unfavourable	19·9	10·2	13	62
1 August	Favourable	21·1	5·1	6	24
	Average	20·1	8·9	17	100
	Unfavourable	19·1	15·5	39	187
6 August	Favourable	20·4	7·7	13	94
	Average	19·4	13·3	45	343
	Unfavourable	18·4	23·1	122	777

(b) Next, a series of simulation runs are made for an untreated population, for the particular case considered, the number of immigrants being increased in successive runs. When this untreated population reaches the maximum peak density allowed (3·4 BPH hill^{-1} in this case), the values for immigrant numbers and peak density of the first generation are noted. These provide the threshold values for a single treatment.

(c) Then, a similar series of runs are made to determine the threshold for two treatments, only this time, an insecticide application (MTMC) is given at 30 DAT. By increasing the number of immigrants in successive runs, a second threshold figure is

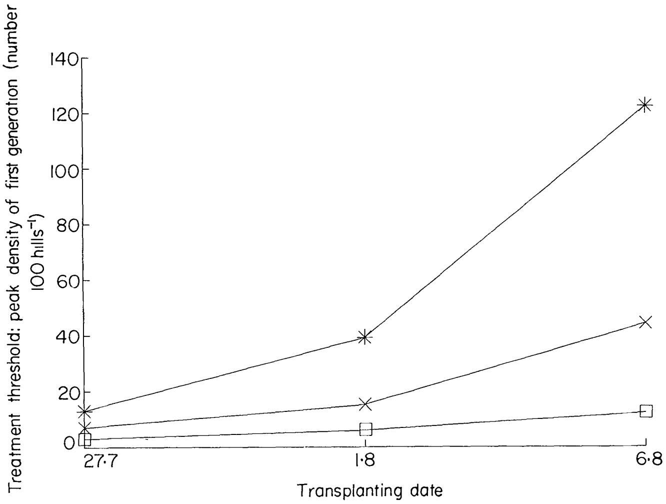

FIG. 8. Treatment thresholds for a single application of MTMC depending on transplanting time and unfavourable (□), average (×), and favourable (*) temperatures for BPH (simulation results).

reached, when the treated population just exceeds the maximum peak density allowed. This is the threshold at which a second treatment is necessary.

The results of these simulations (Table 1 and Fig. 8) indicate a favourable interaction of transplanting time and weather in determining treatment thresholds. With an early transplanting time the threshold is practically the same for all weather conditions. If the crop is transplanted late however, treatment thresholds are far more dependent on the temperature in August and September. Since the decision to spray at 30 DAT need not be made until (say) 25 DAT, some indication of temperature favourability for that season can be included.

DISCUSSION

It was pointed out by Cheng & Holt (1990) that, despite certain imperfections, the simulation model appears to give a good explanation of BPH population dynamics in Zhejiang Province. In this paper, where we have used the simulation model to assess the impact of insecticide treatment, these imperfections are of even less concern. Nevertheless, there are certain relationships and interactions, identified in Fig. 1, which have so far been ignored.

Of particular concern is the consequence of reduced effectiveness of pesticides, associated with poor application, and the effect of insecticide treatment on natural enemies. Both of these have been investigated in further simulation runs. Reducing the effectiveness of insecticides modifies the action thresholds but the conclusions reached concerning timing are generally unaffected. A similar conclusion is reached for natural enemies, a very different conclusion to that reached in the tropics, where natural enemies generally appear to prevent outbreaks occurring (Kenmore *et al.* 1984).

These results reinforce the central conclusion of this work that, in making recommendations on BPH control in Zhejiang Province, deciding on the best time of insecticide application is relatively easy. For a single insecticide treatment, application at 30 DAT is a remarkably robust strategy (*sensu* Norton, Sutherst & Maywald 1983). It applies to the majority of outbreaks with the exception of those situations where the crop is transplanted very early or where eggs are present on transplanted seedlings: both being situations that give rise to a third BPH generation. Even so, the best application time under these conditions is only 5 days different, at 25 DAT; and treating at 30 DAT is not much less effective. Treating initially at 30 DAT is also a robust strategy where two treatments are required, allowing considerable flexibility in the timing of the second spray.

The major problem in making recommendations on BPH control is to decide if treatment is necessary and, if so, the number of treatments required. Addressing this issue in general terms, the simulation model has been used to determine action thresholds, expressed as immigrant numbers or peak density of the first generation at which treatment is required if losses are to be kept below 5%. The results of this analysis (Fig. 8) show that the action threshold is primarily determined by transplanting time, especially if transplanting time is delayed by the weather in September.

Such general decision rules, derived from simulation modelling, can make an important contribution to improved BPH control. However, this needs to be qualified in two ways. First, these treatment strategies need to be tested further to provide practical confirmation of their validity. Second, simulation modelling has not been used to address directly the problem of making recommendations on BPH control during the course of the growing season. A variety of other factors may also need to be considered (Fig. 1) as well as situations when information is incomplete. An expert system for BPH control, developed for this purpose, is described by Holt, Cheng & Norton (1990).

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APPENDIX

BPH Damage Index

The empirical damage relationship (Fig. 2) ignores two important factors that influence the feeding rate, and therefore the damage, associated with BPH: the age structure of the population and the growth stage of the crop. Zhang *et al.* (1983), using C^{14} labelling techniques, measured the feeding rate of various life stages of BPH. They found that feeding rate was highest with brachypterous females and lower for macropterous adults and nymphs (Table A1).

TABLE A1. Feeding rates for different life stages of BPH measured as scintillation counts per minute from C^{14}. The relative daily damage index is proportional to the feeding rate (from Zhang *et al.* 1983)

Life stage	Feeding rate (counts min^{-1})	Relative daily damage index
First instar	1·90	0·08
Second instar	3·15	0·13
Third instar	5·93	0·24
Fourth instar	9·65	0·39
Fifth instar	10·53	0·66
Macro. (male)	7·03	0·28
Macro. (female)	20·50	0·82
Brachy. (female)	24·90	1·00

The sensitivity of the crop at different growth stages to BPH feeding has been investigated by Cheng & Zhang (unpublished) and Kisimoto (1977). They obtained the following figures for percentage yield loss by introducing BPH adults to pot plants for a 2-week period at different crop stages (DAT): 61% (36 DAT), 80% (45 DAT), 41% (85 DAT), 21% (100 DAT).

These additional features have been incorporated in a damage index, where brachypterous females, feeding for 1 day at the most sensitive crop growth stage and the most damaging temperature, produce a damage index of 1. The damage index over a season is a cumulative total of the daily damage caused by BPH nymphs and adults, expressed as follows:

$$\sum_{t=25}^{100} \sum_{i=1}^{9} [N_i(t)\, D_i(t) T(t)\, G(t)]$$

where $N_i(t)$ is the BPH population present on day t; i (1, 2, . . 9) are first, second, third, fourth and fifth instars, macropterous males and females, and brachypterous males and females, respectively; $Di(t)$ is the relative daily damage caused by each of the nine life stages (Table A1); $T(t)$ is a coefficient that modifies daily damage according to the temperature of that day; and $G(t)$ is a coefficient that modifies daily damage according to the current growth stage. Using this expression with simulated BPH populations, the total damage index can be determined.