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Pink Bollworm Control in Southwestern Desert Cotton

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II. A Strategic Management Model

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III. Strategies for Control: An Economic Simulation Study

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UNIVERSITY OF CALIFORNIA DIVISION OF AGRICULTURE AND NATURAL RESOURCES

ABSTRACT

I. A Field-Oriented Simulation Model

A simulation model for pink bollworm (PBW) and cotton was developed, field validated, and incorporated into an industry sponsored regional PBW management program for southwestern desert cotton. The PBW model differs from earlier versions in its incorporation of stochastic development, the expansion of the concept of physiological time to include nutritional influences of the cotton host on larval development, and its ability to simulate the kinds of data typically collected by pest control advisors when monitoring cotton for pink bollworm.

II. A Strategic Management Model

A simulation model of pink bollworm populations, as affected by insecticide and pheromone applications in cotton, is described. The simulation results compared favorably to field data. The study indicates that use of sex pheromone for control of pink bollworm by mating disruption inversely depends on density and therefore is most effective in the early season when populations are low. Compared to untreated fields, pheromone-treated fields show delayed population peaks and reduced overall infestation. Pheromone applications in the early season delay but do not obviate the need to spray insecticide to limit infestation levels.

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THE AUTHORS:

N. D. Stone is Assistant Professor, Department of Entomology, Texas A&M University, College Station, Texas and was formerly Research Assistant, Division of Biological Control, Department of Entomological Sciences, Berkeley.

A. P. Gutierrez is Professor, Division of Biological Control, Department of Entomological Sciences, Berkeley.

W. M. Getz is Associate Professor, Division of Biological Control, Department of Entomological Sciences, Berkeley.

R. Norgaard is Professor, Department of Agricultural Economics, Berkeley.

N. D. Stone, A. P. Gutierrez, W. M. Getz, and R. Norgaard

III. Strategies for Control: An Economic Simulation Study

INTRODUCTION

THE FIRST MAJOR USE use of artificial sex attractant to disrupt pink bollworm, *Pectinophora gossypiella* (Saunders), mating in cotton, *Gossypium hirsutum* L., was conducted in the early 1970s (McLaughlin et al. 1972). Gossyplure, the true sex pheromone of pink bollworm (PBW), has been used commercially in the desert cotton-growing regions of California and Arizona since 1977 (Brooks, Doane, and Staten 1979). However, a consensus has not been reached on the utility of pheromonal control in an integrated control program for PBW (Stone and Gutierrez II., this series). Pheromone use as an alternative to pesticides is still seen as risky, due partly to its inconsistent record in the field and partly to the perception that its use is still experimental.

Two major factors influence the likelihood of a grower adopting an alternative pest control strategy. The first is the cost compared with anticipated returns from reduced pest damage and increased yield. The second is the risk seen in using the new strategy (Norgaard 1976). Growers are interested in maximizing profits; however, a grower may value less profits that vary greatly from season to season than steady profits of an equal long-term value simply because of the fiscal dangers and associated hardships of a single poor season (Friedman and Savage 1948).

Therefore, if pheromones are to become more widely used as an alternative to insecticides in controlling PBW, one of three things must occur:

(1) The price of pheromones must drop. Barring the discovery of a new method of synthesis and purification, a drop in prices without increased use and economies of scale in production seems unlikely.

(2) The efficacy of gossyplure must increase. Better formulations, better strategies for gossyplure's use, and increased purity of commercial-grade gossyplure could all contribute to increasing the effectiveness of the chemical in the field.

(3) The perceived risk in using pheromone must be lessened. This can be achieved simply by making available more complete information about the mode of action of pheromonal disruption of PBW mating and distributing that information to growers. This would make the pheromone's effects more predictable and hence more easily used in an integrated control program without high risk.

This paper addresses alternatives two and three. We present a computer simulation study of the efficacy of pheromones and insecticide, both alone and together, in various control strategies. The goals of this analysis are: to increase the knowledge available to growers on the dynamics of the biological system, thereby reducing the perceived risk of using pheromone in an IPM program, and to suggest profitable strategies for PBW control using insecticides and gossyplure.

METHODS

Simulated Treatments

The linked cotton and PBW models (Stone and Gutierrez I., this series) and the PBW management model (Stone and Gutierrez II., this series) were adapted here to simulate six control strategies or treatments involving the use of pheromone and insecticide for the control of PBW in cotton. The six simulated treatments and their variants were:

(1) Control. Neither pheromone or insecticide was applied for the entire season.

(2) Pheromone only, applied at a rate of 5 grams of gossyplure per hectare, beginning 150 degree-days after the initiation of squaring of the cotton. Variants of this treatment were produced by using different application intervals. Seven intervals, from 100 to 400 degree-days (about 8 to 14 days), were used. Intervals were held constant within each simulation. The 5-gram rate of gossyplure is slightly higher than the average rate currently used in California and Arizona cotton where disruption of PBW mating is the goal; rates as high as 7.5 g gossyplure per hectare were used frequently in 1984. The range of application intervals includes those commonly used in the field.

(3) Insecticide only, applied from the time that susceptible bolls first appear in the field. Applications were made whenever the percentage of PBW larvae in susceptible bolls reached a specified threshold. The seven variants of this treatment used different thresholds, from 2 to 20 percent. A constant threshold was used within each simulation. The insecticide was assumed to achieve a kill rate of 85 percent of adults and susceptible eggs (Stone and Gutierrez II., this series) on the day of application, decaying to near zero kill rate in 100 degree-days.

(4) Insecticide only, applied twice before bolls are present and then based on a threshold of PBW larvae in susceptible bolls as described in (3). The two early season applications were based on degree-days from planting and were chosen to coincide with the peak emergence of overwintered PBW and the appearance of the first squares old enough to support a larva.

(5) Pheromone and insecticide—I. Pheromone was applied in the early season exactly as described in (2) except that pheromone applications were discontinued in late July to mimic the typical pattern of pheromone use in the area. Pesticides were applied as needed, based on a threshold of 15 percent PBW larval infestation of susceptible bolls. This treatment is similar to current practices of farmers using gossyplure as part of their pest control strategy for PBW.

(6) Pheromone and insecticide—II. This treatment was identical to (5) except that the insecticide threshold was kept at 5 percent infested bolls instead of 15 percent. This treatment represents the conservative variation of the standard practices of farmers who use pheromone to supplement their insecticide spray program.

Weather data for 4,200 simulated growing seasons were generated at random from 10 years of weather data collected at the Palo Verde Irrigation District weather station in Blythe, California from 1973 to 1983. The 1977 data were not used because they were incomplete. Daily high and low temperatures and the total horizontal solar radiation were used to drive the simulations. All six treatments were run once for each weather file produced. This ensured that each treatment was tested under identical growing conditions.

Briefly, the process of building a weather file for each set of simulations was as follows. The high temperatures for each of the 10 years were ranked for each day. Low temperatures and solar radiation values were given the same rank as their respective high temperatures. A number from 1 to 10 was chosen at random for the first day. The correspondingly ranked high temperature, low temperature, and solar radiation were selected. The temperatures were then modified by adding to each a random number from -3 to 3, and the solar radiation was modified by adding a random number from -15 to 15. Each subsequent day of the simulated season was chosen as above, except that only the seven ranks closest to the previous day's chosen rank were included in the random selection of the new rank. This effectively prevented a transition from one day's highest temperature to the next day's lowest, and seemed to mimic well the general temperature trends observed in an actual season's weather.

The simulated cotton fields were planted April 1 and harvested October 15. Initial infestations of adult PBW (i.e., those emerging from overwintered larvae) were chosen at random from a uniform distribution above 1,250 and below 50,000 larvae per hectare, corresponding to very light through extremely heavy initial PBW pressure. Heavy field infestations in the lower desert valleys have been observed between 37,000 and 70,000 emerging larvae per hectare (T. J. Henneberry, personal communication). These infestations were grouped evenly into five infestation categories for analysis. Category 1 represented the lowest infestations; category 5, the highest infestations.

Evaluation Criteria

The economic evaluation of the simulated treatments was based on profit, calculated using yield, PBW damage, and cost of insect control. Various simplifying assumptions were made to convert the model's output into dollars so that these figures could be extracted from the simulations. If p_c is the price per kg of cotton and Y is the production function for the cotton plant, then the revenue (R) from growing a cotton crop can be described mathematically as:

$$R = p_c\, Y(\mathbf{A},\mathbf{P},\mathbf{W},x_i,x_p)$$

where Y depends on: agronomical practices (vector **A**), the population dynamics of PBW (vector **P**) the weather pattern for the season (vector **W**), and two insect control variables (x_i and x_p), representing applications of insecticide and pheromone respectively. If all the fixed costs of cotton production are included in C_f, the cost (C) of producing the crop becomes:

$$C = C_f + C_v(x_i,x_p).$$

Here, C_f includes standard costs of fertilizer, water, and cultivations as well as land preparation, the rent on the land, cost of seed, and interest payments. $C_v(x)$ includes the variable costs of applying insecticide (x_i) and pheromone (x_p), including cost of the chemicals and application costs. For this analysis, insecticide cost \$28.41 per ha and pheromone cost \$25.95 per ha, including material and application. Ignored here are future costs associated with PBW larvae which go into diapause and represent next season's initial infestation, and the cost of reducing the natural enemy complex by applying pesticides (Regev, Gutierrez, and Feder 1976). The latter is expressed as increased costs for secondary pest control in the late season when natural enemies are eliminated.

Profit is the difference, $\pi = R - C$, and could be maximized by assuming **A**, **W**, and **P** to be constants for any particular season and setting the derivative of the profit function with respect to the control vector (x) equal to zero:

$$d(P_c\,Y(x) - C(x))/dx = 0$$

Notice that fixed costs of cotton production drop out here.

In this analysis, however, the profit function was examined numerically. Yield, Y(**A**,**P**,**W**,**x**), was simulated by the cotton-PBW-management model, while letting the control variables and weather vary as described above. This approach does not provide a numerical solution to the maximization problem, but it does provide mean profit and variance data for each control strategy examined.

Such output is ideally suited to analyze choices where risk plays a role. The variance associated with a particular result is a measure of the risk involved in adopting the particular set of initial conditions that produce that average result. For example, a grower presented with both the average profit expected from adopting a particular control strategy against PBW and the variance involved would be able to decide whether or not to adopt that strategy. A strategy that produces a high average profit with a similarly high variance might be less appealing than a strategy that produces a lower average profit with small variance. The actual strategy chosen by a particular grower will depend on his or her particular aversion to risk. This risk aversion has been measured in some instances (e.g., Farnsworth 1980); if the risk aversion of cotton growers in the desert growing regions of California and Arizona were quantified, it would be possible to select the best control strategy from this analysis. Measuring this risk aversion was beyond the scope of this project.

SIMULATION RESULTS

For each of the six treatments, 700 simulated seasons were run. In all but the control (check) treatment, these runs were divided among seven variants of the treatment's pest management strategy, based on either intervals between pheromone applications or insecticide spray threshold of PBW infestations in bolls. Twenty simulations were run for each of the five infestation levels of each variant.

1. Check: No pheromone or insecticide

The untreated check field showed substantial losses in all the simulations (fig. 1). Losses were lower when PBW infestation was lower, and tended to plateau at about \$1,400 for the high infestations, indicating that untreated cotton with even moderate initial PBW infestations will be damaged at nearly maximal rates. Also, the variance associated with the losses declined with increasing PBW infestation, as would be expected if nearly total crop loss were occurring at moderately high PBW initial infestations.

2. Pheromone alone

Pheromone applied throughout the season for control of PBW was a highly unprofitable strategy (fig. 2). Only when applications were made at least every 150 degree-days against the lightest PBW infestations (category 1) did this strategy show a mean profit. At the 400 degree-day application interval, profits were statistically indistinguishable from those in the check field.

This seemingly poor showing of the pheromone was expected due to its inversely density dependent effectiveness, and its tendency not to eliminate PBW population buildup, but to delay it and reduce its magnitude (Stone and Gutierrez II., this series). *This mode of action must be kept in mind when examining the rest of the treatments.* Even in situations of initially light PBW infestation, pheromone cannot keep the pest's populations below unacceptable levels for the entire season. Only at the lowest initial infestations tested did pheromone succeed in halting PBW population increase. At higher infestations, PBW eventually expressed its potential to increase explosively, and generally did so early enough in the season to cause severe damage.

The fact, however, that pheromone reduces PBW population buildup is evident in the simulation results. Comparing the losses attained in the pheromone treatment to the losses in the control field shows that in all cases of light-to-moderate infestation

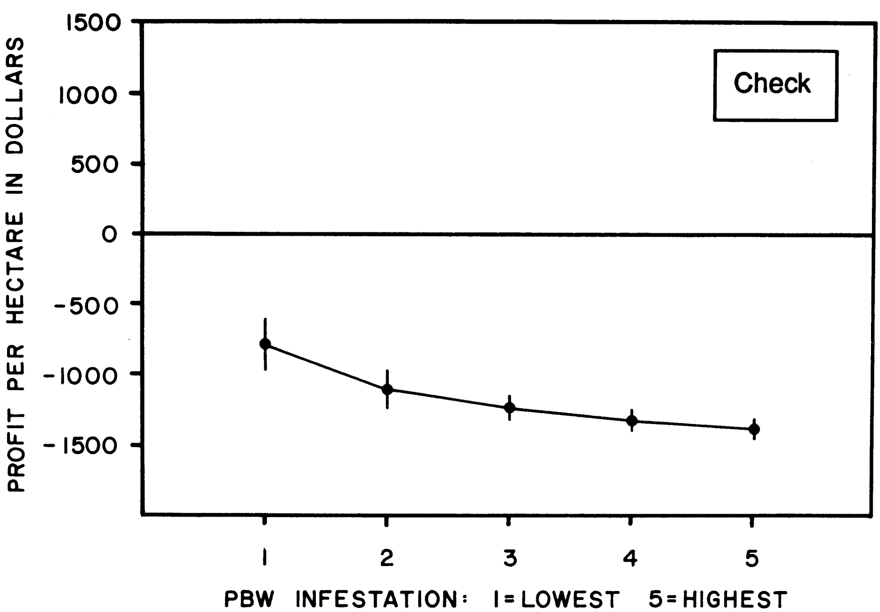

Fig. 1. Simulated mean profit and standard deviation in dollars achieved in treatment no. 1: Control plot (no PBW control attempted).

levels of PBW, losses were less severe when pheromone was applied. Still, it is evident that if pheromone is to maintain a place in PBW pest control, it must be as part of an integrated approach.

3. Insecticide only (beginning midseason)

When insecticide is applied against PBW, based on a threshold infestation percentage in susceptible bolls, results are mixed (fig. 3*A*). At the two most conservative thresholds tested, the strategy showed a consistent profit across all initial PBW infestations. However, for each spray threshold over 8 percent, a profit was achieved only for the lowest initial PBW infestation level if at all.

These results indicate:

(a) Once a PBW infestation in the bolls achieves a level somewhere between 5 and 11 percent, insecticides become incapable of preventing further population buildup.

(b) Only at very low initial infestations, from which PBW populations increase slowly to the threshold level, will profits be possible. In such low-density situations, enough bolls will escape heavy infestation to limit the season-long damage to acceptable levels.

(c) The infestation level above which PBW populations increase cannot be controlled is likely to be close to 8 percent infested bolls. At this spray threshold, profits were variable around zero; it was equivocal whether this strategy prevented the infestation from increasing.

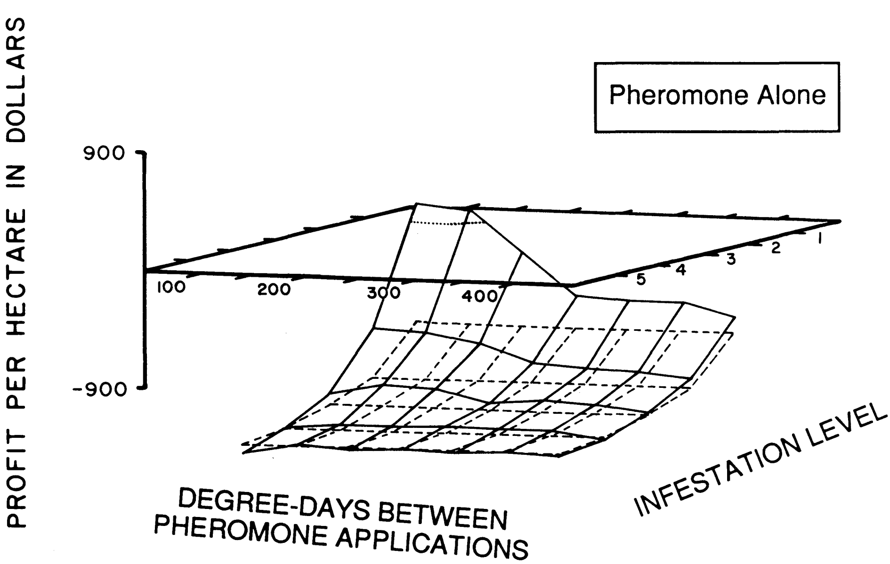

Fig. 2. Simulated mean profit earned in cotton fields treated for PBW using only pheromone throughout the season (solid surface), compared with a check field (dashed surface). The timing variable is the number of degree-days between pheromone applications, the infestation level is an ordinal category of initial PBW infestation; 1 = lowest, 5 = highest. The intersection of the solid surface with the zero profit plane is shown as a dotted line.

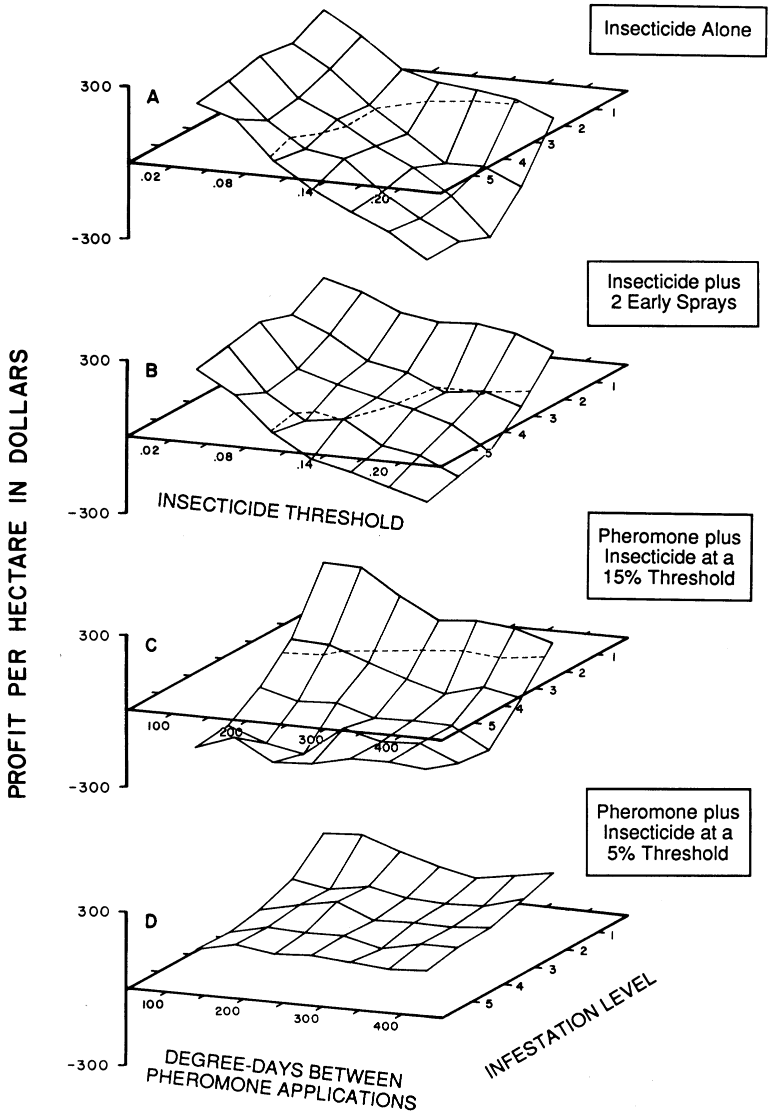

Fig. 3. Simulated mean profit earned in cotton fields treated for PBW using four different control strategies: *A* insecticide applied from the appearance of the first susceptible boll based on a spray threshold of percent infested bolls (timing variable). *B* insecticide applied as in *A* but including as well two sprays before bolls are present. *C* insecticide applied as in *A* but always at a 15 percent threshold level in addition to early season use of pheromone applied at degree-day intervals as shown (timing variable). *D* identical to *C* except that the insecticide spray threshold was constant at 5 percent infested bolls. The infestation level is an ordinal category of initial PBW infestation; 1 = lowest, 5 = highest. The dashed lines indicate the intersection of each surface with the zero profit plane.

4. Insecticide alone (with two early season sprays)

The addition of two insecticide sprays in the early season (before bolls are present) to treatment 3 (insecticide only) greatly enhanced the resulting profits (fig. 3*B*). Again, the most profitable variant of this control strategy was also the most conservative, and again increasing the spray threshold above 8 percent resulted in economic losses at high initial PBW densities. However, significant losses with intermediate initial infestations of PBW occurred, starting at thresholds above 14 percent instead of above 8 percent as seen in treatment 3, and profits of all threshold variants were higher at low PBW infestation levels.

Apparently, the early sprays shifted down the effective initial PBW infestation. Thus, profits achieved using pesticide only from midseason onward, for PBW infestation categories 1 to 4, are comparable to profits achieved at infestation levels of 2 to 5 with the added early season sprays. Furthermore, by reducing the early season population of PBW, the early sprays delayed the buildup of PBW larvae in bolls in midseason. As was suggested for treatment 3, this would allow more uninfested bolls to mature in midseason and would therefore increase yields.

Perhaps a more surprising effect of adding two early season sprays is that it reduced the total number of insecticides sprayed throughout the season (fig. 4*A, B*). Thus, the inclusion of two early sprays saved more than two late-season sprays. The effect is seen clearly only at the lower spray thresholds of 2 through 8 percent. This pattern again indicates that the early sprays slow the buildup of PBW populations to damaging levels, thus delaying initiation of late-season spraying.

5. Pheromone and insecticide—I

In this treatment, pheromones were applied at different intervals in the different variants; however, the spray threshold for insecticide remained constant at 15 percent. Unfortunately, as shown here, the 15 percent threshold for insecticide is far from the best insecticide strategy, since it may be too high to control PBW population buildup.

Nevertheless, pheromone in combination with insecticide produced high profits when applied at 100 or 150 degree-day intervals in a low PBW density sytem (fig. 3*C*). Increasing either the interval of pheromone application or the initial PBW infestation reduced profits, the results for the four variants with application intervals over 200 degree-days being remarkably similar. Furthermore, applying pheromone at 100 degree-day intervals versus 150 degree-day intervals did not significantly change the resulting profit. This indicates that the marginal return from reducing the application interval is nearly zero at a 150 degree-day interval, and such closely spaced applications would be unsound economically.

The value of adding early season pheromone treatments to the pesticide strategy can be seen by comparing results from these treatments with those from treatment 3 above. However, because all the pheromone-insecticide treatment variants used a pesticide spray threshold of 15 percent infested bolls, comparisons can be made only to the variant of treatment number 3 that used a spray threshold of 14 percent. This is as close as possible to a check field for the effects of pheromone. The results indicate that pheromone, when applied at frequent intervals in the early season, greatly enhanced profits over those achieved by using pesticides alone. The increase in profit diminishes

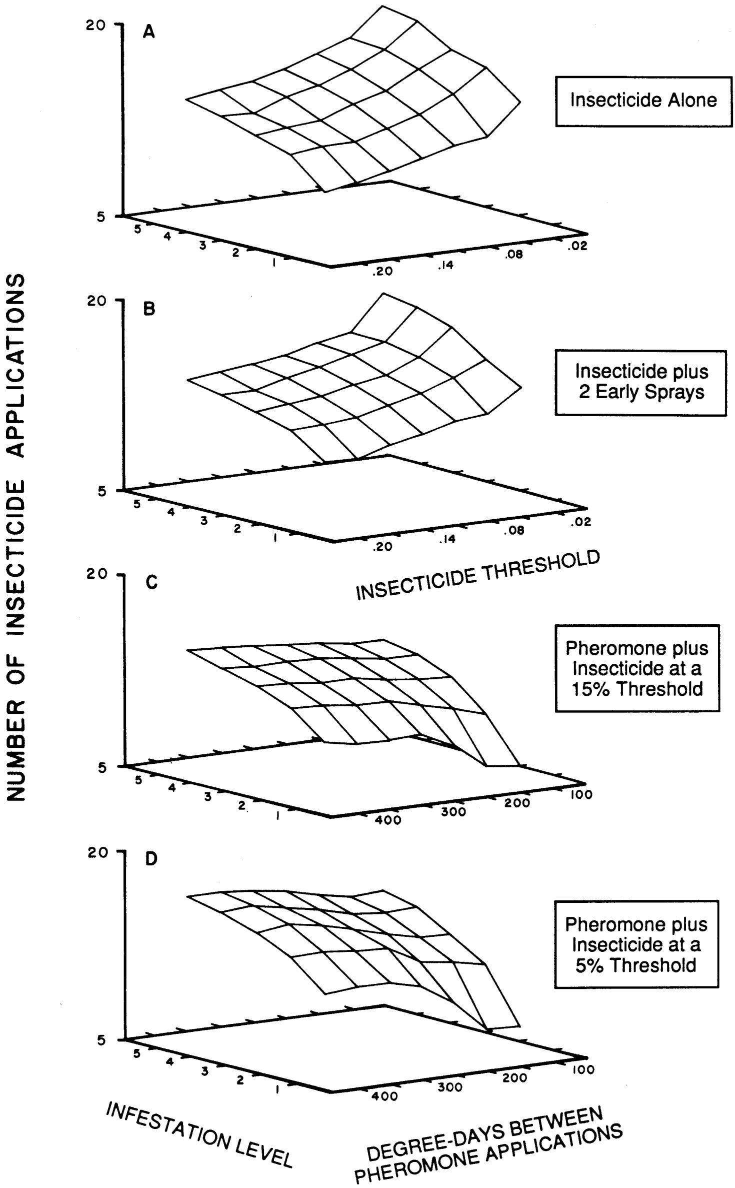

Fig. 4. Mean number of insecticide sprays required by the strategies *A* through *D:* Insecticide alone, insecticide with two early season sprays, pheromone and insecticide at a 15 percent threshold, and pheromone and insecticide at a 5 percent spray threshold, respectively (see figure 2 for an explanation of the timing variable and infestation level).

with increasing initial PBW infestation and with increasing pheromone application intervals. However, the failure of this strategy at high densities cannot be blamed entirely on a breakdown of pheromone effectiveness. The profit obtained at high densities matches that achieved by the insecticide alone. Thus, the inadequacy of pesticides in controlling high PBW densities probably played at least an equal role in producing such low profits for the higher categories of PBW infestation.

As shown in figure 4, using pheromone at low degree-day intervals in the early season also decreased the number of insecticide applications required if using pesticide alone, either with or without the two early sprays. However, pheromone applied at long intervals (above 300 degree-days) showed only a small reduction in the number of insecticide sprays required.

6. Pheromone and insecticide—II

Pheromone in combination with a conservative pesticide strategy (spray threshold of 5 percent infested bolls) produced the most consistent profits, but not the highest profits overall (fig. 3*D*). It was the only strategy tested to provide a positive mean profit over all the variants and infestation levels tested.

As was the case in treatment 5, adding pheromone to the 5 percent variant of using only insecticides tended to increase the profits attained, especially at low infestation levels. Also, this strategy greatly reduced the number of insecticide sprays required during the season when the application interval was low, but actually increased pesticide use when the application intervals were highest.

The most striking feature of this strategy, that it never lost control of the PBW population to the point of economic loss, can be attributed to the fact that the insecticide threshold was below 8 percent (see discussion on treatment 3). The strategy of adding pheromone to the system must be evaluated solely on its effects on profit and pesticide use. When this is done, one finds again that gossyplure is an attractive addition in two ways: *It enhances profits when initial PBW infestations are light, and it greatly reduces the reliance on pesticides when used frequently, even at high initial PBW infestation levels.*

The patterns observed here for pheromone used in combination with an insecticide are consistent with earlier hypotheses about the mode of action of pheromone. When PBW are present in high densities, pheromone will not long suppress their population buildup because of the occurrence of random mating. However, at lower PBW densities, pheromone both delays population increases and reduces the magnitude of population peaks (Stone and Gutierrez II., this series). This effect tends to delay the first application of insecticide by delaying larval population increase in bolls, and at very low densities it would control the PBW population entirely as was shown in treatment 2.

EVALUATION OF PBW CONTROL WITH PHEROMONE AND INSECTICIDE

The comparisons above between the pest control strategies that use insecticides sprayed on the basis of an economic threshold (treatments 3 through 6) assume that the observed patterns of profit are due to the timing element of the strategies themselves and not to the actual number of insecticide sprays made. Figure 5 shows the profit for all the simulations in each of three treatments that used insecticides (3 through 5), plotted against the number of sprays made. No plot suggests that profit is a simple function of number of applications. In fact, *these data are only explicable in terms of the timing strategies that produced them.* For example, the pheromone and insecticide treatment (fig. 5*C*) shows diminishing profit with increasing sprays. This is because when the pheromone was most effective (low PBW densities) few sprays were needed, and profit was high. Similarly, when many sprays were needed, it was because the pheromone and pesticide had failed to keep the PBW population in check; hence, the low profit. In figure 5*A,* the highest profits occurred either when the PBW densities were so low that sprays were not needed, or when sprays were initiated quickly (i.e., at a low threshold), and the population was controlled.

Taking the best strategy tested for PBW control at each level of initial PBW infestation produces a maximum profit envelope (fig. 6) for PBW control. As shown, the best strategy tested in every infestation category was the insecticide with two early sprays at a 2 percent boll infestation threshold. This is not surprising since the algorithm for computing profit placed no penalty on heavy use of insecticides nor on their early season use. Furthermore, since lowering the threshold does not necessarily mean increasing the number of sprays there is no reason to assume that at some lower threshold, the marginal return will fall to zero, as was the case when lowering the pheromone application interval.

If an economic penalty were associated with heavy pesticide use, the pheromone-insecticide treatments would certainly be more competitive in this analysis (Regev, Gutierrez, and Feder 1976). Such a penalty would be appropriate (if difficult to assess) because intensive pesticide use often causes outbreaks of secondary pests and may increase the level of pesticide resistance in pest populations (Regev, Shalit, and Gutierrez 1983). Furthermore, there are other hidden costs of insecticide use (e.g., environmental pollution, secondary pest outbreaks, and resistance) which, if internalized, would enhance the economics of pheromone use.

The dashed line in figure 6 shows the maximum profit envelope when all 2 percent infestation variants are ignored. Such an exclusion of the 2 percent variant may be appropriate if field sampling is not accurate enough to distinguish between a 2 percent infestation and a 5 percent infestation. Thresholds of 2 percent have been successfully implemented in some crops, for example for *Heliothis zea* on tomatoes in California (L. T. Wilson, personal communication). However, since boll infestations must be estimated from the boll-cracking method (Stone and Gutierrez I., this series), there is a good chance that infestations could reach 5 percent or even 8 percent without being detected in a sample of 25 to 100 bolls per field.

If a 2 percent boll infestation trigger is deemed unusable, the best strategy tested becomes pheromone and insecticide with the latter applied at a 5 percent infestation threshold at all infestation levels. The interesting feature of this, apart from the fact that the pheromone and insecticide strategy was consistently the most profitable, is that the best variant of the strategy changes with different initial PBW infestations. This was not the case earlier when the 2 percent variant of the pesticide early and late strategy was optimal across all infestation levels.

A possible explanation is that at very low infestation levels, the pheromone is controlling PBW enough so that virtually no sprays are needed, resulting in high profits.

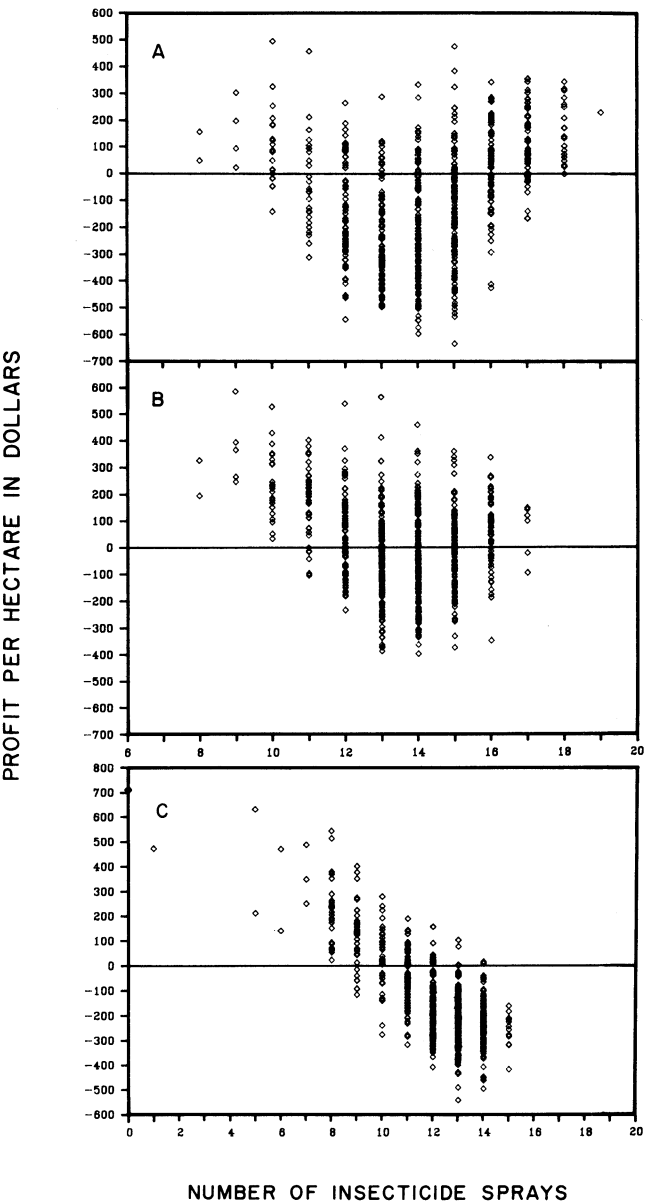

Fig. 5. Simulated profit earned in cotton fields treated for PBW using three control strategies: (*A*) Insecticide alone, (*B*) insecticide with two early season sprays, and (*C*) pheromone and insecticide applied at a 15 percent spray threshold (fig. 2). Profit is plotted against the number of insecticide applications made across all the PBW initial infestations recorded.

However, whn the infestation is moderate, intense pheromone use delays the buildup of PBW so that it parallels the increase in bolls. Thus, the spray threshold is not reached until many more bolls have been infested. The simulation results indicate that it is better, in moderate infestations, to use pheromone less intensively and to rely on insecticides to keep the population in check. In heavy infestations, the ability of intensive pheromone use to delay and lower the population peaks of PBW again shows economic value (fig. 6). At the same time, it does not greatly delay the initiation of spraying since it cannot contain the initial PBW buildup.

CONCLUSIONS

Pesticides applied based on a conservative threshold of 2 percent and 5 percent infested bolls for the control of PBW gave consistent profits. However, the data suggested that when boll infestations climb over 8 percent, insecticides may be unable to contain PBW population increase and damage. Since boll infestations could climb to 5 or 8 percent without being detected, this could cause economic losses despite using a seemingly profitable strategy. Because the margin of error is so slim, highly accurate

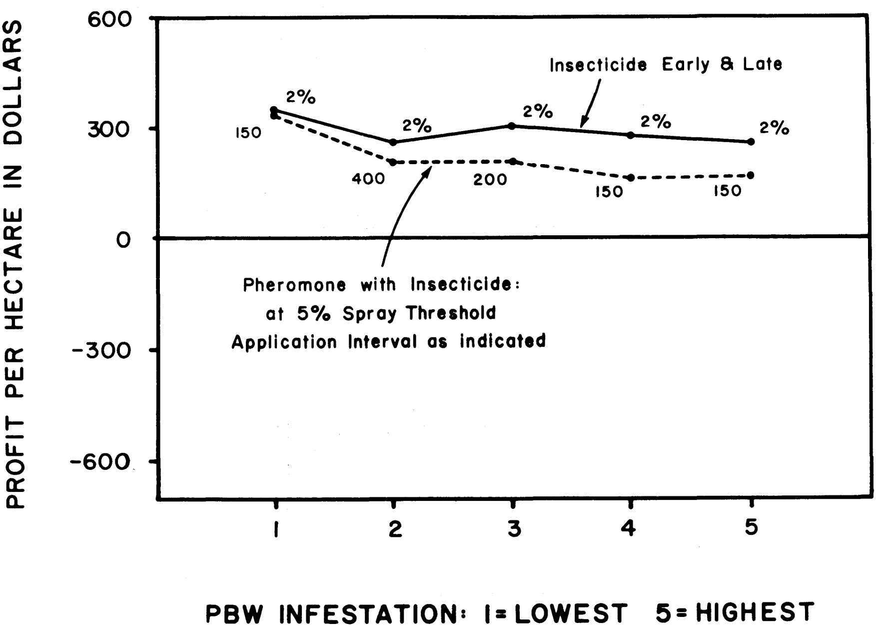

Fig. 6. Maximum profit envelope for cotton production in the presence of PBW. Shown are the maximum mean profits found from the above simulation analyses for each infestation level of PBW. The pest control strategy that gave that maximum is also shown. The solid line is the maximum profit envelope when a level of 2 percent infested bolls is used to trigger spraying; the dashed line is the maximum profit envelope when strategies requiring a 2 percent boll infestation estimate are ignored and 5 percent infested bolls is considered the lowest threshold that can be accurately sampled.

estimates of boll infestation in the field must be obtained to make such a strategy work consistently.

The use of early season sprays against PBW populations before bolls are present on the plant delays the onset of late-season spraying and does not cause an increase in the number of sprays over the season. However, the danger exists that early season use of insecticides can cause late season secondary pest outbreaks and increase pest resistance. The detrimental effects of such early use of insecticide were not included in the simulation analysis.

The addition of early season pheromone applications to a pesticide control strategy based on a threshold boll infestation greatly enhanced profits. However, this result could not be fully generalized because pheromone was examined in combination with insecticide applications based on only two thresholds. All pheromone-insecticide treatments failed to control high initial densities of PBW below levels achieved using insecticides alone, showing that pheromone use is not profitable in a heavily infested system.

Pheromone used in conjunction with an insecticide reduces the number of insecticide sprays necessary during the course of a season, and thus is a more appealing early season strategy than using early applications of insecticide. However, early season pesticide sprays, in conjunction with early season pheromone, could greatly enhance the pheromone's effectiveness. The early sprays would reduce high-density PBW infestations at the outset to lower levels that are more easily controlled by pheromone. Once the pheromone is working, fewer mid- and late-season insecticide sprays should be necessary.

The type of analysis presented here is purely theoretical, yet the results seem to agree with, and add to, the current understanding of how pesticides and pheromone can be used against PBW. The preferred strategy suggested by this analysis is the one currently becoming popular in the southwestern desert, namely pheromone applications in the early season with pesticides sprayed on a conservative threshold of PBW in bolls. However, more work needs to be done before a thorough and fair comparison can be made between pheromone and insecticides and definitive recommendations given for the control of PBW in cotton.

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III. Strategies for Control: An Economic Simulation Study

The cotton-pink bollworm model and the management model developed by Stone and Gutierrez (I and II of this series) are used to evaluate different strategies for controlling pink bollworm in the southwestern desert. Pesticide sprays based on an ultraconservative economic threshold of 2 percent infested bolls are found to be the most profitable in the absence of penalties for heavy insecticide use. Insecticide sprayed on thresholds over 8 percent infested bolls did not control pink bollworm.

Pheromone in combination with insecticide greatly enhanced profits and was the best workable strategy tested since a 2 percent threshold is probably too difficult to sample accurately in the field. The efficacy of using early season insecticide applications at and before the first hostable squares are present is discussed, as is the possible impact of early season insecticide applications on beneficial insect populations.

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