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MANAGEMENT AND REGULATION OF PRIMARY / SECONDARY PEST SYSTEMS

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Management and Regulation of Primary / Secondary Pest Systems

Carolyn R. Harper and David Zilberman[1]

The use of chemical pesticides is known to have many effects which are external to the intended reduction in a target pest population. Those often cited include 1) killing of wildlife, 2) worker health damage, 3) water contamination, 4) food residues, 5) pest resistance to pesticides, 6) resurgence of the target pest at high levels after spraying, and 7) inducement of secondary pest infestations. The last two effects commonly arise in reaction to the destruction of beneficial insects (natural predators). In fact most of the problems listed above result from the broad-spectrum character of the major classes of pesticides currently available, which tend to be toxic to a wide range of species.

Pesticide externalities may be roughly divided into those which directly affect agricultural production, 5), 6), and 7), and those which do not, 1) through 4). Although non-agricultural effects are of great public concern, their omission from agricultural optimization models (though not from public policy models) is understandable. Unfortunately, production externalities are usually omitted even from agricultural pest control models, in order to make tractable the study of crop ecosystems, which involve highly complex interactions among plants, multiple pests, and pest predators.

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Optimal pest control for relatively simple systems consisting of one crop, one target pest, and a chemical pesticide, has been explored in considerable detail, both analytically (e.g. Hall and Norgaard; Talpaz and Borosh) and quantitatively through simulation and dynamic programming techniques (e.g. Talpaz et al.; Shoemaker, 1973). The economics of resistance in the target species has also received increasing attention (Hueth and Regev; Taylor and Headley; Regev et al.; Mangel and Plant).

In a few cases the problem of primary pest resurgence following unintended destruction of natural predators has been considered (Feder and Regev; Reichelderfer and Bender; Zavaleta and Ruesink; Shoemaker, 1982). The resurgence effect is known to be so severe in some cases that a new equilibrium is established after chemicals are applied in which target pests are even more numerous than before. Moreover Feder and Regev have shown that any attempt to return to the pre-spraying equilibrium may require a costly adjustment period in which very large pest populations have to be endured.

This paper addresses the other major production externality which results from destroying natural predators: the "worldwide elevation of certain species from relatively innocuous to highly destructive levels" (Getz and Gutierrez, p. 447). Although it is serious and widespread, the problem of secondary pest outbreaks induced by the use of chemical pesticides has been addressed in the economics literature only in passing (Burrows; Regev, Gutierrez and Feder; Shoemaker).

It will be shown that the highly detailed single-pest optimization models commonly used lead to suboptimal recommendations to growers because they ignore secondary pests. A conceptual framework is first introduced to represent the interactions among primary pests, secondary pests, and natural predators. The properties of the optimal solution are compared with the decision rules resulting from the erroneous single-pest model. The impacts of optimal vs. myopic criteria on the adoption or rejection of four Integrated Pest Management options are then considered. These are 1) scouting (monitoring of pest populations), 2) importation of beneficials, 3) adoption of an alternative cultural practice, and 4) the development of a species-selective pesticide. Finally the problem of pink bollworm and associated secondary cotton pests in California's Imperial Valley is considered as an illustration, using a biological simulation model for the primary pest and historical data for secondary pests.

Both the model and the application suggest that the destructive opportunity given to non-target pests when broad-spectrum pesticides are applied needs to be taken into account explicitly in determining optimal pesticide application levels. This type of externality should also be included when comparing the economics of conventional pest control and various integrated pest management (IPM) alternatives. In the area of pesticide regulation, where total social costs and benefits of chemicals need to be weighed, the omission of secondary pest considerations may lead to overestimates of the economic losses from a proposed ban or restriction. Reduced use of chemical sprays may well lead to a larger primary pest population, but this effect may in many cases be offset in part by decreases in the incidence of secondary pest outbreaks.

Primary and Secondary Pests

For a particular crop and region, a primary pest is defined by entomologists as one which can be expected to appear whenever the crop is grown, requiring some type of intervention if losses in yield or quality are to be avoided. Secondary pests are those which are not normally numerous enough to cause significant yield losses, but may become a threat when unusual weather conditions or the destruction of natural predators allows them to proliferate. In the latter case, the secondary infestation is said to be induced. Losses due to induced pest outbreaks can be very large, in some years exceeding losses to the primary pest.

The destruction of beneficials by a broad spectrum insecticide creates or aggravates secondary pest outbreaks, demanding further pesticide applications of some kind if crop damage is to be avoided. The need for the second round of spraying is effectively created by the first. Its cost, as well as any yield losses to the induced secondary pest, are negative externalities from spraying for the primary pest, which should be netted out of the economic benefits attributable to the pest control program. These considerations apply not only to the decision whether or not to apply a pesticide in the first place, but also to choices between spraying at higher or lower frequencies, beginning to spray earlier or later in the growing season, or adopting various IPM practices vs. staying with conventional control.

The Agricultural Optimization Model

Because many pesticides are administered not once but a number of times throughout the growing season, determination of optimal strategies for timing of applications has come to rely increasingly on simulation and dynamic programming models which attempt to reproduce biological and chemical processes within the crop ecosystem. For reasons of computation and interpretation, simplifying assumptions on the system are inevitably made, and models are normally restricted to consideration of a single pest.

The kind of distortions which result from the use of single-pest optimization models for broad-spectrum insecticides can be explored in a simple one-period framework. If we assume that pest damage acts independently of inputs except pesticide, the primary/secondary pest control problem may be characterized as follows:

$$\max_{A,B} \ \Pi = p\,Q - w_1 A - w_2 B - C$$

$$\begin{array}{lll} \text{s.t. } Q = Q^{o}\,[1 - D\,(x,z)] & & \text{Yield} \\ x = x^{o}\,[1 - \alpha\,(A)] & & \text{Primary Pest} \\ z = z^{o}\,[1 - \beta\,(B,\ y] & & \text{Secondary Pest} \\ y = y^{o}\,[1 - \gamma\,(A)] & & \text{Natural Predator} \end{array}$$

where Q is yield per acre, x and z are the populations of two pests, and y is the population of an insect which preys on z. Applications of pesticide A are intended to kill the primary pest x, but also destroy beneficials. Pesticide B can be used to kill the secondary pest z. The exogenous prices of the crop and of chemicals A and B are given by p, w_1, and w_2 respectively; C is per acre costs apart from pest control. The expected value of yield in the absence of any pest damage is given by Q^o, while x^o, z^o and y^o represent expected values of the primary pest, secondary pest, and beneficial populations in the absence of chemical pesticides (and for z, natural predators as well). The unspecified damage functions D, α, β, and γ reflect proportional reductions in yield (from pest damage) or in insect numbers (from pesticide and predator damage).

Pesticides are seen to act differently from normal agricultural inputs since they operate through a compound damage function, achieving positive levels of damage to pest populations which in turn are made less damaging to the quantity and quality of output. Pesticides do not normally enhance yield;

at best they simply permit the full or nearly full realization of a potential yield determined by applications of other inputs.

Optimal Solution. First order conditions for the above problem are the following:

(1.1) $\Pi_A = p\ Q^o\ (D_x\ x^o\ \alpha_A - D_z\ z^o\ \beta_y\ y^o\ \gamma_A) - w_1 \leq 0\ ; \quad A \geq 0\ ; \quad \Pi_A\ A = 0.$

(1.2) $\Pi_B = p\ Q^o\ D_z\ z^o\ \beta_B - w_2 \leq 0;\ B \geq 0\ ; \quad \Pi_B\ B = 0\ .$

Boundary conditions are included to allow for the very real possibility that one or both pesticides should not be used under certain economic or biological conditions.

Sufficient second-order conditions for twice differentiable damage functions are

$$\Pi_{AA} < 0 \text{ and } \Pi_{AA}\ \Pi_{BB} - \Pi_{AB}^2 > 0$$

which in turn imply

$$\Pi_{BB},\ Q_{AA},\ Q_{BB} < 0 \text{ and } D_{AA},\ D_{BB} > 0.$$

Damage--both the effect of pests on crop losses and the effect of pesticides on the mortality rate of pests--takes positive values and increases in the damaging agent:

$$D\ (x,z),\ \alpha(A),\ \beta(B,y),\ \gamma(A) > 0$$
$$D_x,\ D_z,\ \alpha_A,\ \beta_B,\ \gamma_A > 0.$$

The nature of the second derivatives of the damage functions in the relevant range must be determined empirically. Although at the optimum, yield will be concave (and hence damage convex) in A and B as seen above, this does not imply that <u>both</u> of the underlying biological damage functions must be convex, i.e. that marginal yield damage (in x and z) and marginal pesticide effectiveness (in A and B) are both decreasing functions. We will assume that pesticide effectiveness shows decreasing returns in the relevant range, but the possibility is left open that marginal yield damage may be increasing.

There is evidence that some yield damage functions do in fact display a "threshold" effect [e.g. Brazzel and Gaines, 1952]. Numbers of certain pests may increase substantially above zero without causing significant damage. When the threshold range is exceeded, however, losses in yield or quality may increase rapidly. If for example yield damage from the secondary pest has this character then D_{zz}, the change in marginal damage, is positive at low levels of the secondary pest and negative at higher levels, as shown in Figure 1.

Since they take values from 0% to 100% of maximum, the damage functions may be viewed as cumulative distributions [Talpaz and Borosh, 1974], with

$$F(0) = 0 \text{ and } \lim_{s \to \infty} F(s) = 1.$$

The exponential distribution

$$D(x) = 1 - \exp(-ax)$$

which is often used, assumes strict concavity. The more general structure of the Weibull,

$$D(x) = 1 - \exp(-ax^r),$$

permits greater flexibility. For small values of r the function is strictly concave, but for larger r it becomes a sigmoid curve, permitting the expression of threshold effects.

Once the biological yield function Q = Q(x,z) and pesticide kill functions x = x (A), etc., have been fitted on the basis of biological data, it should be possible to derive a compound function Q = Q (A,B). If the underlying biological functions are Weibull, it may be easier to do this numerically than analytically, to avoid a compound exponential form. Whenever yield is thus expressed directly as a function of pesticide, however, it should be borne in mind that a considerable amount of information is lost, particularly where there are related multiple pests.

Myopic Solution. When secondary pests and primary pests are treated as separable problems, the grower will take the natural predator population as given, $y = \overline{y}$. First order conditions (1.2) remains the same, but (1.1) is replaced by:

(2.1) $\Pi_A = p\ Q^o\ D_x\ x^o\ \ \alpha_A\ \ - w_1 \leq 0; \quad A \geq 0; \quad \Pi_A\ A = 0.$

Since the detrimental effect of pesticide A on beneficials is ignored, (2.1) is abbreviated from the optimal case (1.1). One component of the 'cost' of applying pesticide A, its <u>positive</u> effect $p\ Q^o\ D_z\ z^o\ \beta_y\ y^o\ \gamma_A$ on pest z, is not taken into account, so that applications of A (and hence B) will differ from optimal levels.

The separability assumption may nevertheless prevail for several practical reasons: 1) The history of secondary pests is often sporadic and may be cyclical over time, so that the causal relationship to primary pest control is not perceived. 2) It may be difficult for the layperson (or expert) to distinguish weather from broad-spectrum insecticides as a cause of secondary pest outbreaks. 3) The use of single-pest technical models by pest management experts tend to result in control recommendations which treat primary pest dynamics in depth at the expense of other components of the system, notably secondary pests.

It will be shown that when a grower or pest control advisor treats secondary pests as exogenous to the primary pest control program, several types of distortion appear:

1) incorrect comparisons will be made among spray regimes, and the wrong

discrete choice may be made concerning whether or not to apply broad-spectrum insecticides

2) optimal levels of A and B will not be used within a given spray regime

3) the profitability of various IPM alternative pest management programs will be underestimated

4) variances as well as means of spray regimes may be misjudged so that risk is actually increased, when it is thought to be decreased, by a chemical spray program.

Economic Thresholds: Spray vs. No-Spray

Assume for simplicity that the secondary pest problem is entirely induced, so that:

$$D\ (x^o;\ z(y^o)) \ \simeq D\ (x^o;\ 0).$$

Then if pesticide A is not used, beneficials are not destroyed, the secondary pest does not occur at economically damaging levels, and pesticide B is not needed.

There are three choices: to apply no pesticide, in which case profits are

$$\Pi^o = p\ Q^o\ [1- D\ (x^o;\ z^o\ (1- \beta(0;\ y^o)]$$

to apply an optimal level A′ of A without B, with profits

$$\Pi^A = p\ Q^o\ [1- D\ (x^o(1- \alpha(A'));\ z^o(1- \beta(0\ ;y^o(1- \gamma(A')))))] - w_1\ A',$$

or to apply an optimal mix A*,B*, with

$$\Pi^2 = p\ Q^o\ [1- D\ (x^o(1- \alpha(A^*));z^o(1- \beta(B^*;y^o(1- \gamma(A^*)))))] - w_1A^* - w_2B^*.$$

The problem has a continuous-discrete character. Depending whether Π^o, Π^A, or Π^2 is largest, it will be optimal to apply (respectively): no pesticide, A′ alone, or the optimal mix A*, B*. Sensitivity of the above conditions to prices may be seen for example from the economic threshold for use of substance A:

$$\Pi^{o} = \Pi^{A} \rightarrow$$

$$p\, Q^{o}[\, D(x^{o};z^{o}(1-\beta(0;y^{o})) - D(x^{o}(1-\alpha(A'));z^{o}(1-\beta(0\, ;y^{o}(1-\gamma(A')))))] = w_1 A'.$$

As p increases it becomes worthwhile to apply pesticide, whereas for a lower output price the value of reducing yield damage does not justify the cost of pest control. Conversely as the price of pesticide w_1 increases, a point is reached beyond which it is not worthwhile to spray.

> Proposition 1. Profits from the no-spray regime are underestimated by separable pest models, while profits from the use of pesticide A are overestimated. Therefore pesticide use is begun when the output price is too low and continues when the cost of applying pesticides is too high.

When the beneficial population is taken to be exogenous, the above comparison between the spray regimes is distorted as follows:

$$\Pi^{o} = \Pi^{A} \rightarrow p\, Q^{o}\, [\, D(\, x^{o};\, z^{o}(1-\beta(0;\overline{y})) - D(x^{o}(1-\alpha(A'));\, z^{o}(1-\beta(0;\overline{y}))) = w_1 A'.$$

Since $\overline{y}$ is based on historical experience which involved the use of pesticides,

$$\overline{y} < y^{o}$$
$$z\,(0;\,\overline{y}) > z\,(0;\,y^{o})$$
$$\text{and } D\,(x^{o}\,;\,z(0;\overline{y}\,)) > D\,(x^{o};\,z(0;\,y^{o}))\,,$$

so that the level of secondary pest pressure and total pest damage in the absence of any pesticide is exaggerated under myopia, and profits are underestimated. Under myopia, the level of pesticide A, when it is used, is determined by (2.1) rather than the optimal rule (1.1). Since profits are concave in A, pesticide is then used at too high a level which fails to take into account the destruction of beneficials and the stimulus to secondary pests.

As a result of the overestimate of damages in the no-spray case, the spray program will not be dropped at the appropriate point as pesticide costs increase or output price falls, but will be continued longer, resulting in economic losses in the form of a missed opportunity to eliminate an unprofitable input. The economic threshold between use of A alone and use of A and B will be similarly distorted. Most importantly, the assumption that effects of the two pesticides are independent will in many cases lead to comparisons of the wrong alternatives. A grower or advisor undertaking a primary pest control program will compare Π^o with Π^A when the correct comparison is with Π^2.

Sensitivity of Pesticide Applications to Prices

If the kill functions show diminishing returns in the relevant range, and the yield damage function is a sigmoid curve as assumed, the output-price, cross-price, and own-price input responses under optimality are the following:

$$dA^*/dp = [Q_B Q_{AB} - Q_A Q_{BB}]\, p / H \begin{cases} > 0 & \text{if } Q_{AB} > 0 \\ & \text{or } Q_{AB} < 0 \text{ and } Q_B Q_{AB} < Q_A Q_{BB} \\ < 0 & \text{if } Q_{AB} < 0 \text{ and } Q_B Q_{AB} > Q_A Q_{BB} \end{cases}$$

$$dB^*/dp = [Q_A Q_{AB} - Q_B Q_{AA}]\, p / H \begin{cases} > 0 & \text{if } Q_{AB} > 0 \\ & \text{or } Q_{AB} < 0 \text{ and } Q_A Q_{AB} < Q_B Q_{AA} \\ < 0 & \text{if } Q_{AB} < 0 \text{ and } Q_A Q_{AB} > Q_B Q_{AA} \end{cases}$$

$$dA^*/dw_2 = dB^*/dw_1 = - Q_{AB} / H \begin{cases} < 0 & \text{when } D_{zz} > 0 \\ > 0 & \text{when } D_{zz} < 0 \end{cases}$$

$$dA^*/dw_1 = Q_{BB} / H \quad < 0$$

$$dB^*/dw_2 = Q_{AA} / H \quad < 0$$

where H is the positive determinant of the 2x2 Hessian matrix.

Proposition 2. If secondary pest damage has a threshold effect, then under the optimal rule pesticides A and B are seen to be economic complements at low levels of the secondary pest, and substitutes at high levels. Under myopia this substitutability or complementarity between pesticide inputs is no longer perceived.

The first statement holds because Q_A and Q_B must be positive by first order conditions, and Q_{AA} and Q_{BB} must be negative by second order conditions. The relationships occur because pesticide A is simultaneously a good and a bad input, controlling one pest while unleashing another. The need for pesticide B is in turn closely linked to the use of A through the destruction of beneficials.

Under pest separability Q_{AB} vanishes, so that cross-price responses go to zero. In addition, the output price effects become distorted:

$$dA/dp = (-Q_A Q_{BB})\, p / H > 0$$
$$dB/dp = (-Q_B Q_{AA})\, p / H > 0.$$

Since Q^o plays the same role as p, these conditions imply that under myopia any exogenous increase in revenue, whether from a rising product price or enhanced productivity of non-pesticide inputs, always stimulates increased use of both pesticides. Such responses are not optimal, since as seen above there are conditions under which one or both pesticides should be used less in response to a revenue increase.

IPM Alternatives

Several types of alternative pest management can be considered within the present framework. The most familiar IPM action is scouting, in which pest pressure is carefully monitored, for example by trapping and counting insects in the field, in order to determine when a pesticide application is needed. Other options include the importation of beneficials, which increases y^o in the model, adoption of cultural practices such as field sanitation or short season cultivation to reduce primary pest pressure, and the development of a species-selective pesticide.

Scouting. The quantity of pesticide per acre application is usually taken from manufacturers' label recommendations, so that it is the number and timing rather than the intensity of pesticide applications which must be decided. As an alternative to spraying on a fixed schedule, monitoring techniques may be used to determine when pest numbers are large enough to warrant spraying at the recommended dosage.

Proposition 3. Under secondary pest myopia, the threshold number of pests is determined incorrectly, and spraying generally commences at too low an insect count. The critical count value also responds incorrectly to changes in other parameters. Therefore the full economic potential of scouting, whose purpose is to pinpoint and respond to the true pest population cannot be realized.

If $\hat{x}^o$ is the threshold level of the primary pest under optimality for a standard dose $\bar{A}$ of pesticide A, then:

$$F(\hat{x}^o, \cdot) = p\, Q^o\, [\, D\, (x^o\, (1-\alpha(\bar{A}))\, ;\, z^o\, (1-\beta(B^*;\, y^o\, (1-\gamma(\bar{A})))))$$
$$- D\, (x^o\, ;\, z^o\, (1-\beta(B^*;\, y^o)))] + w_1\bar{A} + w_2B^* = 0.$$

The threshold pest count will be sensitive to the kill effectiveness and the standard application rate $\bar{A}$. In case of pesticide effectiveness, if the toxicity γ against non-target organisms is similarly affected, the relationship is:

$$\frac{d\hat{x}^o}{d\alpha} = \frac{\partial F/\partial\alpha}{\partial F/\hat{x}^o} = \frac{\hat{x}^o - \dfrac{D_z(z^o(1-\beta\,))z^o\beta_y y^o}{D_x(x_o(1-\alpha))}}{N}$$

where $N = (D_x(\hat{x}^o))\ /\ [(D_x(\hat{x}^o(1-\alpha\,)))-(1-\alpha\,)]$.

Since $(1-\alpha)$ is generally a number closer to zero than to one, the denominator N (and hence the whole left hand term) is positive unless marginal yield damage D_x is much larger at the lower pest population $\hat{x}^o(1-\alpha\,)$ than the higher one $\hat{x}^o$. The right hand term, which is then positive, tends to dampen the responsiveness of the critical threshold $\hat{x}^o$ to changes in α and γ .

Under myopia the right hand term vanishes, implying that the threshold pest count will typically be adjusted in a way that is over-sensitive to changes in the pesticide kill function, since indirect effects in the primary/secondary system are ignored.

Changes in the recommended "standard dose" affect the economic threshold as follows. Under optimality:

$$\frac{d\hat{x}^o}{dA} = \frac{\alpha_A(\bar{A}) + \dfrac{w_1}{D_x(\hat{x}_o(1-\alpha))} - \dfrac{D_z(z^o(1-\beta))z^o\beta_y y^o \gamma_A(\bar{A})}{D_x(\hat{x}_o(1-\alpha))}}{N}$$

Under myopia, the right hand term disappears, so that in the usual case with positive denominator, the myopic decision rule again leads to an overadjustment in the threshold pest count.

Importing Beneficials. The impact of changes in the initial population of beneficials may also be of interest because they can in some cases be encouraged or imported. If this is possible, there is in principle an optimal mix of pesticides A and B and predators y^o.

> **Proposition 4.** The importation of beneficials will be a neglected strategy when primary and secondary pest management problems are assumed separable.

Since pesticide A destroys a large number of predators, and adjustments are not made to limit this effect, importation of beneficials will not be seen as a valuable option in secondary pest control, and pesticide B will be relied on exclusively for this purpose.

For a given initial level y^o of the natural predator, the optimal input responses are:

$$dA^*/dy^o = 1/H \{-Q_{AB} [D_{zz}z_y(1-\gamma)z_B] + Q_{BB} [D_{zz}z_y(1-\gamma) z_A + D_z z^o \beta_{yy}(1-\gamma)y^o \gamma_A + D_z z^o \beta_y y_A]\}$$

and

$$dB^*/dy^o = 1/H \{ -Q_{AA} [D_{zz}z_y(1-\gamma)z_B]$$
$$- Q_{AB} [D_{zz}z_y(1-\gamma)\ z_A + D_z z^o \beta_{yy}(1-\gamma)y^o\ \gamma_A + D_z z^o \beta_y y_A]\}.$$

Both expressions will be negative so long as

$$D_{zz} > 0 \text{ and } [D_{zz}z_y(1-\gamma)z_A + D_z z^o \beta_{yy}(1-\gamma)y^o \gamma_A + D_z z^o \beta_y y_A] > 0\ ,$$

meaning that we are working with pest population which is not too large and that protection provided by the marginal beneficial outweighs any loss in effectiveness of beneficials as a group due to moving along the damage curves. These conditions seem likely to occur. It is interesting to note that if standard assumptions were made on the shape of the yield damage functions, the above expressions would appear unlikely to be negative in sign, leading to the misleading conclusion that increases in beneficial populations would not be effective means of reducing pesticide use.

As seen above, a change in the initial level of beneficials y^o influences the optimal levels of pesticides A and B. However when primary and secondary pest problems are assumed separable, $dA^*/dy^o = 0$, so the use of the primary chemical control is not adjusted in response to the predator population.

In fact while the conditions on the responses of each pesticide to the initial population level of its 'own' pest (dA/dx^o and dB/dz^o) remain the same under myopia, all of the cross responses vanish:

$$dA/dz^o = dA/d\overline{y} = dB/d_x{}^o = dB/d\overline{y} = 0.$$

When induced pest problems are disregarded, chemical applications will not be adjusted in response to changes in any population level other than the target pest, effectively ruling out a range of IPM options of which the importation of beneficials is only one example.

Cultural Pest Control. A variety of cultural practices can provide protection from pests, and play a role in integrated pest management. In many cases the adoption of the alternative cultural practice is a discrete choice rather than a matter of degree, and often the benefits of adoption may be experienced in subsequent growing seasons rather than the current one. In cotton production, for example, adjustments in the length and timing of the growing season often play a role in reducing pest control costs by preventing overwintering of key pests.

> Proposition 5. The economic value of cultural alternatives which reduce pest pressure on the following year's crop are underestimated by separable pest models.

The choice of long- vs. short-season cultivation is taken as an example. Key variables in the pest management problem are affected by choices of this kind. The yield Q^o associated with zero pest damage will be lower, since plant growth is terminated at an earlier date. In terms of pest control, the primary virtue of shortening the growing season is that it discourages the overwintering of the primary pest. Adoption of the short season thus involves trade-offs between a lower potential yield Q^o and a reduced level of primary pest pressure x^o in the following season.

Under optimality the discrete choice problem is the following, where $\delta = \{ L,S \}$ represents long- or short-season cultivation:

$$\max_{A,B,\delta} \; p\, Q^o_\delta \; [1 - D\,(x^o\,(1-\alpha\,(A));\; z^o\,(1-\beta\,(B;\; y^o(1-\gamma\,(A)))))] - w_1A - w_2B$$

In the separable pest model it is:

$$\max_{A,B,\delta} \; p\, Q^o_\delta \; [1 - D\,(x^o\,(1-\alpha\,(A));\; z^o(1-\beta\,(B;y)))]-w_1A-w_2B.$$

In the optimal case, both A* and B* will be adjusted for the length of season in response to changes in x^o. The relationships under optimality are:

$$dA^*/dx^o = 1/H\ Q_{BB}\ [D_{xx}\ (1-\alpha)x_A\ -\ D_{x\ A}]$$
$$dB^*/dx^o = -1/H\ Q_{AB}\ [D_{xx}\ (1-\alpha)x_A\ -\ D_{x\ A}]$$

Since $Q_{BB} < 0$ by second order conditions, this implies that pesticide A increases in x^o as long as $D_{xx} > 0$ or $D_x\ \alpha_A > D_{xx}\ (1-\alpha)\ x_A$, i.e. if the population of pest x is small and/or if damage from the marginal pest killed is less than the change in marginal damage from pests remaining. These conditions appear likely to hold. If so, then since Q_{AB} follows the sign of D_{zz}, optimal applications of pesticide B will be increasing in x^o for $D_{zz} > 0$ and decreasing for $D_{zz} < 0$.

Under separability, however, $dB^*/dx^o = 0$, so that $B_L = B_S$. As a result, the full cost savings available from reduced pesticide use under the shortened season

$$w_1\ (A^*_L - A^*_S) + w_2\ (B^*_L - B^*_S)$$

are not taken into account. In addition the effect of yield changes on optimal pesticide use will be distorted.

Selective Pesticides. If a broad-spectrum insecticide could be replaced by a treatment which is destructive only to the target pest species, it is clear that most of the negative externalities associated with pesticide use could be eliminated. But the economic value of a new pest control technology of this type can never be demonstrated and may be overlooked in the context of single pest control models. The gain in profits due to adoption of the specific pesticide is

$$p\ Q^o\ [D\ (x^o\ (1-\alpha(A^*)),\ z^o\ (1-\beta(B^*,\ y^o\ (1-\gamma(A^*))))\ -\ D\ (x^o\ (1-\alpha(A')) \ ]$$
$$+\ w_1\ [A^* - A'\}\ +\ w_2\ B^*,$$

i.e. the value of the difference in primary plus secondary pest damage from changing to the specific pesticide, plus the difference in pest control costs, including the elimination of material B, which is no longer needed.

The same expression can also represent the amount by which a pesticide application policy which assumes pest separability will exaggerate profits from adopting the broad-spectrum chemical in the first place as compared with no pest control. In both cases the decision-maker who assumes pest separability will sometimes make the wrong decision, either by failing to adopt the species-specific control when it would be profitable to do so, or by applying the broad-spectrum insecticide when the true partial profit from that spray regime is negative.

An Example: Controlling the Pink Bollworm Complex in Imperial Valley Cotton

The practical importance of secondary pest outbreaks for both private and public decisions over pesticides is illustrated here for the case of Imperial Valley cotton. The economic feasibility of three pest control options is evaluated, two from the producer's point of view and one from the pesticide regulator's. These options are 1) conversion to a shortened growing season as a cultural pest control, 2) adoption of an improved pink bollworm scouting program, and 3) measurement of economic benefits from chlordimeform, a chemical pesticide used primarily against secondary pests. In each instance benefits are calculated both with secondary pest externalities (complete case) and without them (myopic case).

Prior to the appearance of the pink bollworm in 1965, Imperial Valley cotton was some of the highest yielding and most profitable in the United States, due to a hot climate and long growing season. Over time, the same conditions have produced insect problems of major proportions, which in recent years combined with unfavorable market conditions to make cotton a much less attractive crop. Production declined from 96,000 acres in 1979 to fewer than 20,000 in 1986.

Estimated annual losses from pink bollworm, the region's primary pest, and from combined pink bollworm and secondary damage, are shown in Figure 2. For the years 1966 to 1980 pink bollworm costs were between 4% and 44% of total crop value, and total primary and secondary costs were from 8% to 80% of crop value, as shown. These figures include both pest control costs and yield losses attributable to pest damage. Only induced secondary pests were included, defined as those "whose presence at economically damaging levels is a direct result of the destruction of their predators due to spraying for the primary pest" (Burrows et al., p. 287). Losses in quality of fiber were not included.

Although secondary pests--primarily tobacco budworm and cotton leafperforator--were clearly a severe problem in those years when they were present, with losses sometimes equalling 1/4 or 1/3 of total crop value, secondary pest outbreaks were intermittent, as shown, and displayed some tendency toward a cyclical pattern. Primary pest damage on the other hand was a more constant source of economic losses, affecting profits in every year. Under these circumstances it is understandable why growers may have tended to overlook secondary pest effects in formulating pest management plans.

Cultural Control. The short season has long been advocated by agricultural advisors who argue that given existing levels of pink bollworm pressure in the region, the sacrifice of late season contributions to yield will be more than compensated economically by savings in pest control costs. These savings occur predominately in years subsequent to the current growing season, since the main effect of early termination is to curtail sharply the number of pink bollworm larvae which overwinter in soil and in plant debris. For a grower who must decide between the conventional longer season which maximizes yields, and the shorter growing season which reduces pest pressure, a correct evaluation of control costs and yield losses attributable to the pink bollworm/secondary pest complex is essential.

The short season option is examined here by means of a detailed cotton/pink bollworm biological simulation model, which predicts cotton yields from historical weather data using biological growth functions for plants and primary pests. The cotton plant model incorporates nutrient balance equations for populations of leaf, stem, root and fruit (Wang et al.). The pink bollworm submodel (Gutierrez et al.) treats the responses of populations at distinct life stages--adults, eggs, pupae and larvae--to surrounding temperature, photoperiod, and predators, as well as the food and shelter supplied by cotton squares and bolls. Numbers of pink bollworm larvae in turn determine cotton yield and quality losses.

Because of memory limitations and sheer complexity, the cotton/pink bollworm model, like most other pest control models, treats only one pest at a time. In order to incorporate the effects of induced secondary pests, the simulation results are supplemented with the historical data shown in Table 1. Data of this kind are far from ideal for the purpose, since pest pressures, control techniques, and pest resistance change over time. However it is preferable to use even such a rough measure than to assume away secondary pest externalities because of limitations in the available control models.

As seen in Table 1, secondary pest infestations occurred in 7 of 15 years studied. In those years secondary control costs were on average equal to 1.15 times primary control costs. Yield losses in secondary pest years averaged 27.7%, compared with losses of 9.2% from pink bollworm alone in years without secondary pests. These figures are used as best guesses of the frequency of secondary pest outbreaks, and of their effect on costs and yields relative to primary pests, when they occur.

Table 2 compares the results of simulations for long and short season cultivation based on identical historic weather data for Brawley, California. Because weather conditions alter potential yields and pest pressures from year to year and "average weather" is not well defined, the simulations are repeated over eleven seasons, the longest series of weather data available. Maximum yields reflect potential yields in the absence of pest damage, determined by weather conditions and the length of the growing season. Percentage losses from maximum yield and quality are determined by the pink bollworm population throughout the season. A typical chemical spray program is assumed.

Although potential yields vary considerably from year to year with changing weather conditions, they are seen to be substantially lower under the short season, on the order of 1/2 bale per acre. However, since the shortened season drastically reduces pest pressure, it is possible to eliminate weekly pesticide applications. Moreover, significant losses in potential yields to pest damage no longer occur.

Table 2 also shows the economic comparison of short season vs. conventional cultivation, when the simulation results are supplemented by the inclusion of secondary pest control costs and yield losses (complete case) and when they are not included (myopic case). The benefits shown may be considered as returns to a prior capital investment, since a first year loss may have to be endured before the fruits of reduced pest pressure are experienced. The short season values are partial benefits, since savings in water costs under the short season as well as other costs which are independent of the secondary pest issue have not been included.

The simulation model alone indicates partial benefits from the short season averaging -$98.07 per acre per year, but these calculations are based on a single-pest model and hence understate the true benefits. The inclusion of historic information suggests that in nearly half of all growing seasons, induced secondary pests will also be a factor. In those years, the short season will have two additional benefits not shown by the simulation: an additional reduction in the percentage of yield lost to pest damage, and an additional cost savings in control costs for secondary pests. The inclusion of these factors raises expected partial benefits from the short season to $51.96, an increase of nearly $150 per acre. About one-half of this difference is due to savings in secondary control costs, and the rest to elimination of yield damage by induced secondary pests.

Scouting. The proposed new monitoring program for pink bollworm, which involves egg rather than larvae counts, has been estimated to have the potential for reducing pesticide applications targeted at pink bollworm from 12-16 per season (in essence a weekly spray schedule) to only 5-8 applications (Hutchinson). The direct per acre value of the new program is therefore about $119 at current cost levels, assuming chemical applications for pink bollworm are reduced on average from 14 to 7 per season.

The scouting program may also be expected to lower the probability of secondary infestations by reducing chemical use. Supposing the probability of secondary infestations to be proportional to the number of primary pesticide applications, then the complete savings in pest control costs from the monitoring program may be estimated as:

$119 + .5 * prob (induced secondary pests) * secondary control costs. Using the same historical figures as before for relative secondary and primary control costs, the complete cost reduction from the spray program is $119 (1 + .5 * .47 * 1.15) = $151/acre.

An additional saving in yield damage may also be expected. Even if direct yield losses to pink bollworm remain the same, yield losses to induced secondary pests may be expected to decline in proportion to chemical pesticide used, i.e. by:

.5 * prob (induced secondary pests) * magnitude of secondary damage

= .5 * .47 * 18.5% = 4.3% of yield.

Complete benefits estimates of this type are important in comparing the value of monitoring and other IPM programs with their costs.

Secondary Pests in Pesticide Regulation. The case of chlordimeform in California cotton illustrates the importance of primary/secondary systems in evaluating economic benefits of chemical pesticides for regulatory analysis. Chlordimeform, a known animal carcinogen, is used to control the tobacco budworm. Although its use is currently permitted by the U.S. Environmental Protection Agency, chlordimeform is banned in California, and was reinstated in recent years for use in the Imperial Valley in response to claims by some cotton growers that it was urgently needed.

Tobacco budworm is a secondary pest which appears sporadically and is believed to be induced by the application of organophosphates or synthetic pyrethroids for pink bollworm control. The evaluation of economic benefits from the use of chlordimeform therefore depends on whether the secondary pest problem is taken as given, or viewed as an artifact of other pest control measures. In the former case the regulatory agency may anticipate substantial economic losses to growers if the pesticide is banned, since losses in the Imperial Valley from tobacco budworm damage have been large, and may be expected to continue in the future under conventional growing practices.

If on the other hand the secondary character of tobacco budworm infestations is acknowledged, the regulatory agency must ask not only whether there are alternative chemicals available for controlling the secondary pest, but also whether there are alternatives to the conventional primary pest control which might make chemical control of the secondary pest unnecessary by not creating the secondary problem. If so, the evaluation of benefits from the secondary pesticide should be based on only the lesser of two possible costs to growers: the increase in secondary pest control costs under a ban, and the cost of converting to the alternative primary control.

In the present example, when the economics of the alternative primary control (short season cotton) are compared with those of conventional cultivation, the best available estimates indicate that growers will experience no economic losses at all, and in fact may be expected to gain. Economic benefits from chemicals used to control induced secondary pests therefore appear to be nil.

Conclusions

The use of single-pest models which ignore the broad-spectrum nature of most chemical pesticides and wrongly assume separability between primary and secondary pest problems leads to overuse of chemical pesticides. It also results in underestimation of the economic value of all the integrated pest management strategies which were considered: scouting, importation of beneficials, and short season cultivation.

If increases in the incidence or seriousness of secondary pest outbreaks are not accounted for in the decision to spray for a primary pest, the result is likely to be one version of the pesticide treadmill, in which increased pesticide applications are accompanied by increased pest populations and smaller profits.

Interactive relationships among various pests and pesticides in a given crop system are often acknowledged in principle but are seldom specified in theoretical or quantitative models. The primary/secondary pest system is a common phenomenon which is worth incorporating into pest management models even at the expense of some detail in other areas.

From the regulator's point of view, failure to consider secondary pest outbreaks may lead to incorrect evaluations of economic benefits from pesticide use and hence to wrong assessments of the costs of imposing (or relaxing) restrictions on chemical pesticides.

Since negative externalities of pesticides on wildlife and human health, as well as those which affect producer profits, generally suggest less intensive rather than more intensive use of chemical pesticides, it is all the more important that agricultural pest management models be designed which do not overstate optimal pesticide levels from the grower's point of view.

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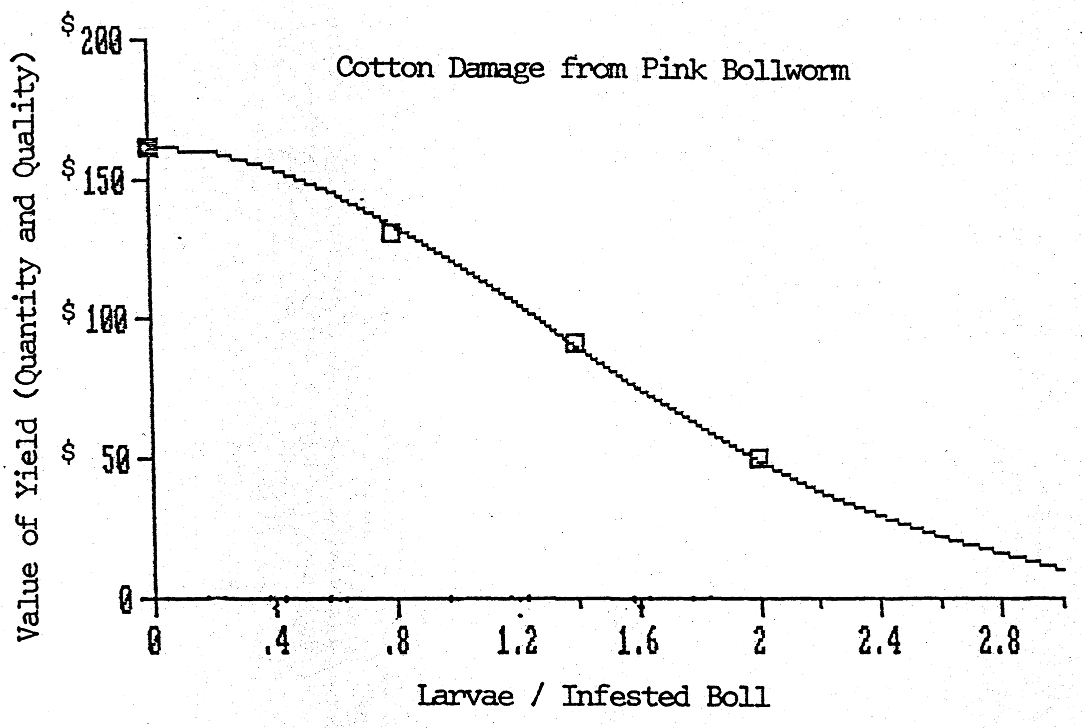
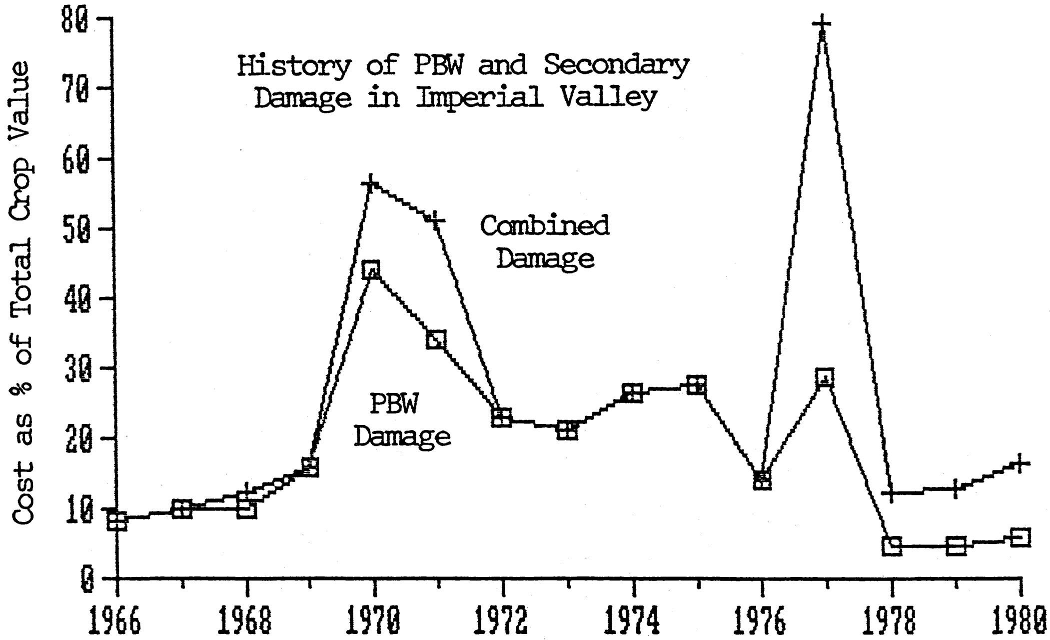


Source: Brazzel and Gaines

Figure 1



Source: Burrows et al. (1982)

Figure 2

HISTORY OF CONTROL COSTS AND YIELD LOSSES TO PBW AND SECONDARY PESTS IN IMPERIAL VALLEY

Year	PBW CONTROL COSTS (as % of Crop Value)	SEC CONTROL COSTS (as % of Crop Value)	SEC CONTROL /PBW CONTROL	YIELD LOSS IN YEARS WITH NO SEC PESTS	YIELD LOSS IN YEARS WITH SEC PESTS
1966	3.6%			4.3%	
1967	4.8%			4.8%	
1968	4.5%	1.2%	.26		5.7%
1969	8.8%			5.7%	
1970	9.5%	2.7%	.28		42.5%
1971	5.3%	2.6%	.49		41.5%
1972	7.0%			14.5%	
1973	7.4%			12.4%	
1974	9.4%			15.0%	
1975	10.6%			12.9%	
1976	8.2%			4.0%	
1977	9.8%	17.2%	1.75		49.3%
1978	2.4%	4.2%	1.75		3.9%
1979	3.9%	6.8%	1.75		46.0%
1980	3.4%	5.9%	1.75		5.0%
		AVERAGE	1.15	9.2%	27.7%
		FREQUENCY	7/15	8/15	7/15

Source: Burrows et al. (1982)

TABLE 1

RETURNS TO SHORT SEASON CULTIVATION
BASED ON COTTON/PBW SIMULATION AND HISTORIC SECONDARY PEST DATA

	------Simulation Results------						
Year	REDUCTION IN MAX YIELD Bales/Acre	PBW LARVAE /BOLL (Long	% YIELD LOSS TO PBW DAMAGE Season)	PRICE /LB. COTTON ($1980)	COST/ACRE PBW CONTROL ($1980)	MYOPIC VALUE SHORT SEASON	COMPLETE VALUE SHORT SEASON
1968	2.52-1.90	1.25	5.1%	$1.14	$89.52	($190.35)	($73.25)
1969	2.65-2.11	3.22	13.7%	$1.05	$93.38	$.25	$230.79
1970	2.27-1.83	3.80	16.4%	$1.28	$109.37	$65.96	$350.01
1971	2.42-1.89	2.95	12.5%	$1.46	$61.76	($104.71)	$137.48
1972	2.53-2.02	1.77	7.3%	$1.09	$100.39	($77.05)	$71.91
1973	2.53-1.99	1.34	5.5%	$1.23	$126.97	($118.83)	$29.81
1974	2.61-1.95	1.90	7.9%	$.83	$116.67	($72.42)	$71.25
1975	2.53-1.85	1.52	6.3%	$.83	$110.99	($105.93)	$16.28
1976	2.42-1.82	.41	1.6%	$.93	$89.34	($171.26)	($106.40)
1977	2.53-1.97	.40	1.6%	$.83	$60.05	($156.41)	($108.30)
1978	3.10-2.45	1.69	7.0%	$.82	$29.61	($148.03)	($48.06)
					AVERAGE	($98.07)	$51.96

TABLE 2