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Pests as a Common Property Resource: A Case Study of Alfalfa Weevil Control

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The biological interactions of a pest-plant system are incorporated into an optimal pest-control model, using data and estimated parameters specific to the alfalfa weevil. Due to the externalities inherent in situations involving common property resources, different solutions are obtained for private and societal formulations of the optimization problem. In contrast to current pesticide-spraying practices, it is shown that pesticide should be applied early in the season, before any damage can be observed.

Key words: aestivation, alfalfa weevil, common property resource, pesticide.

Recently, problems in pest management have attracted considerable attention in economic literature. Entomologists have concentrated on understanding the biological characteristics of the pest-crop relationships.[1] Economists have long recognized pest populations as detrimental common property resources. (Detailed definitions of common property resources and a development of the economics of common property resources are found in Brown; Cummings; Gordon; Plourde; Quirk and Smith.) Many have focused their attention on some of the economic aspects relating to economic thresholds (Headley; Hall and Norgaard), pest resistance (Taylor and Headley, Hueth and Regev), and pest-predator relationships (Feder and Regev). Others have used various optimization methods to solve single-season pest management problems (Shoemaker 1973a, 1973b; Talpaz and Borosh).

This paper describes an economic optimization model that incorporates detailed biological input specific to the alfalfa weevil. Using the available biological data and estimates, the problem is examined from a societal point of view and recognizes specific common property characteristics of the pest. The analysis points out the gap between private and societal control policies, offers estimates of shadow prices, and indicates a direction toward optimal pest-control policy.

Many features of pest-control problems lead to divergence between the optimal policy of a single decisionmaker and the society as a whole. The major types of externalities involved in pest-control problems include interseasonal dynamics, biological relationships with other pests and predators, environmental contamination by pesticide residues, resistance to chemical pesticides, effects of control on neighboring fields, and health problems relating to pesticides.[2] In this paper, attention is focused on only one of these aspects—stock externalities (Smith). These externalities, which are common among highly mobile pests, result from the dependence of population dynamics of the pest between seasons on the total population level in the region. During the season the farmer can control only the pest population in his field, which is, presumably, a small fraction of the total.[3] From an intersea-

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[1] A survey of this literature is beyond the scope of this paper. Most of this literature is pest specific where an attempt is made to understand and model a given species. References on the biology of the Egyptian alfalfa weevil [*Hypera brunneipennis (boh.)*] can be found in Gutierrez et al.

[2] The extent of some of these externalities depends on the degree of pest mobility between fields.

[3] Intraseasonal pest migration between fields is negligible.

sonal point of view, the pest is a nonappropriable resource leading to a gap between marginal private and social benefits.

The Biological Model

A biological model for the relationships between the pest and the plant and the mortality effects of pesticide application on the pest is developed in this section. While the formulation is made specifically for the alfalfa weevil, the major pest for alfalfa in California, it can be generalized and adopted for many other pest problems as well. For a detailed description of the life cycle of the Egyptian alfalfa weevil, see Gutierrez et al.

Biological Background

Alfalfa is a woody perennial and is grown for hay and/or seed. The alfalfa stand grows for three to five years, at which time it has to be replaced because it has been invaded by weed species. The crop normally goes through two phases: a winter dormant period and a vegetative phase between harvest dates.[4]

Alfalfa regrowth during the spring begins when night temperatures are consistently above its thermal threshold (42° F.) and severe ground frosts have ceased. The rate of growth of alfalfa (i.e., dry matter production) is regulated by physiological time, measured in degree days and denoted by D° (Campbell et al., Wang). Alfalfa grows approximately 1,000D° between harvest dates.[5]

The alfalfa weevil has one generation per year. The adult spends the hot summer in sheltered places usually out of the alfalfa fields. It emerges to feed and lay eggs during the autumn after night temperatures of less than 42° F. occur (Gutierrez et al.). The population of adults migrates into the field at a rate that is a linear function of D°, reaching a maximum at about 180D°. The adult weevils mature, and females begin laying eggs after approximately 400D° and continue laying them until their death. A single larva hatches from each egg and begins to consume leaves at a rate that increases approximately in a geometric pattern over D°. Since larvae cannot survive a frost, all larvae that hatch before the last frost die prematurely and are not considered here. After 360D° of feeding, the larva is transformed into a nonfeeding pupa and, after a period, reaches the adult stage. The adult emerging from the pupa feeds for a while and then aestivates (summer hibernation), ending the year-long cycle. Adult feeding (both newly hatched and overwintering adults) is relatively minor and will be ignored in this study.

In the following, the behavior of the three major components of the system (the adult pest, the larva, and the plant), their interrelationships, and how they are affected by pesticide application are formulated. The specific algebraic forms chosen in this application, together with estimates of many of the parameters, rely heavily on a simulation model for the alfalfa weevil developed by Gutierrez et al. A detailed explanation of the parameters and data sources is given in the appendix.

The Time Dimension

As the developmental process of both the plant and the pest strongly depends on temperatures above certain thresholds (42° F. and 44.7° F., respectively), the physiological time scale of the plant has been used for both rather than calendar time. The time unit t is defined by a fixed interval, 60D°.

The choice of the initial time period, t_0, is related to the last frost and is based on the fact that frost suppresses the plant and kills the larvae, but not the adults. No damage is done by larvae prior to the last frost because the regrowth of the crop begins at the same time. Thus, t_0 is chosen at 240D° (four time intervals) before the last frost, which is the time interval from egg oviposition to hatching of the larvae because any larvae appearing before the last frost will not survive. The growth of the plant resumes following the last frost (t = 4).

In the single-season decision problem, the horizon, t_f, is chosen as the (physiological) time of the first alfalfa cropping. This is based on the observation that damage from the alfalfa weevil is negligible after that time.[6]

The Adult Stage

The dynamics of the adult weevil in the absence of control are presented in figure 1.

[4] When the alfalfa is grown for seeds, there is an additional phase. This paper deals primarily with alfalfa grown for hay.

[5] In the summer 1,000D° is approximately one month, and in the late winter and spring 1,000D° is approximately 3½ months.

[6] Although earlier cropping could be used as a pest control means (t_f becoming a decision variable), this possibility is not pursued here since the primary focus is on chemical control only.

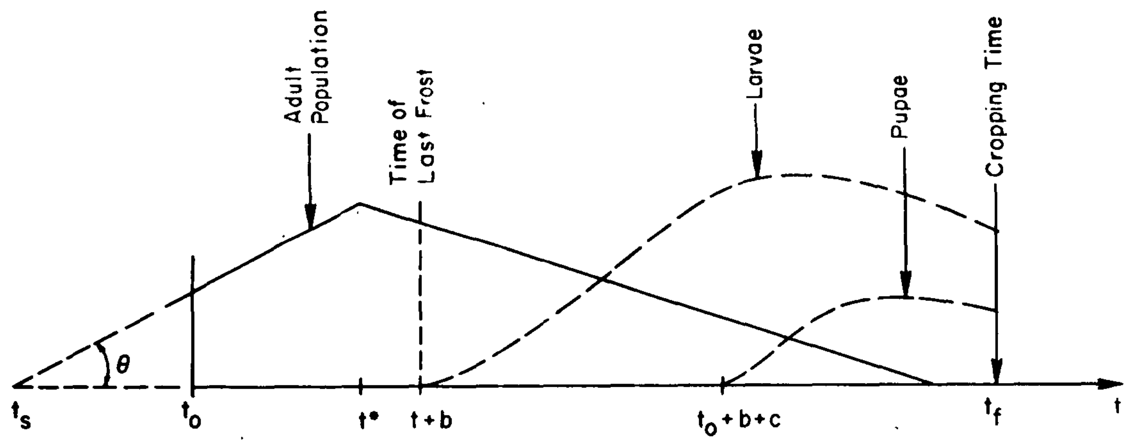

Figure 1. Time phenology of egyptian alfalfa weevil

The effect of pesticide application on the pest population is estimated by a dosage response curve (kill function). Using field data from Cothran and Christiansen, it has been estimated by the form $k = 1 - e^{-\alpha x}$, where k is the percentage of pests killed and x is the amount of pesticide (Hueth). Larvae have a higher susceptibility rate than adults.

The dynamics of the adult pest is then given by

$$(1)\quad y_{t+1} = \begin{cases} y_t e^{-\alpha x_t} + \theta & t_0 \le t \le t^* - 1 \\ y_t e^{-\alpha x_t}\left(1 - \dfrac{1}{t^+ - t}\right), & t^* \le t \le t^+ - 1 \le t_f \end{cases}$$

$$y_{t_0} = (t_0 - t_s)\,\theta,$$

where y_t = number of adult pests per square foot at the beginning of the tth time period before spray, x_t, is applied, x_t = amount of pesticide applied (ounces per acre), θ = infestation rate (number of pests immigrating per square foot per time period), t_s = time of arrival of the first pest, t_o = initial time of the problem ($t_s < t_o$), t^* = time of peak adult population, t^+ = time of zero adult population, and t_f = time of cropping. Equation (1) reflects the effect of pesticide application on the natural adult pest level, which is presented in figure 1. The parameter θ (infestation rate) plays a crucial role in the problem, as it determines the severity of the potential pest damage.

Eggs, Larvae, and Pupae

The rate of oviposition, E_t, depends upon whether conditions and the age composition of the adult pests (see appendix). After time interval b, the eggs hatch, and the number of first-day larvae, L_t, in each time period is given by

$$(2)\quad L_t = y_{t-b}\, e^{-\alpha x_{t-b}}\, E_{t-b}$$

for $t_o + b \le t \le t_f$; otherwise, $L_t = 0$.

The number of larvae that become pupae, Z_t, at each time interval is the number of first-day larvae that survive all pesticide applications throughout their lifetime:[7]

$$(3)\quad Z_t = L_{t-c}\, e^{-\delta \Sigma x_\tau}$$

for $t_o + b + c \le t \le t_f$; otherwise, $Z_t = 0$, where δ = susceptibility parameter for larvae, c = length of larval life, and Σx_τ = total insecticides applied in time period $t - c + 1, \ldots, t$, which spans the lifetime of larva that becomes a pupa at time t.

Leaf Mass Consumed by Larvae

Consumption of leaf mass by a single larva is estimated by a geometric function of its age, and total consumption of leaf mass by all larvae (v_{t+1}) in period $t + 1$ is given by

$$(4)\quad v_{t+1} = v_t\,(1 + a)\, e^{-\delta x_t} + \rho\, L_t - Z_t\, \rho\, (1 + a)^c$$

for $t_0 + b - 1 \le t \le t_f - 1$,

$$v_{t_0+b-1} = 0,$$

[7] Equations (1) through (4) slightly overestimate the population levels (after the adult peak), since natural mortality within the period is not considered. This, however, is not expected to cause a significant error. Equation (4) is a good approximation in the economically relevant region where $x_t > 0$ for some t. If $x_t = 0$ for all t, then the number of pupae is greatly reduced by internal competition; however, in that case the crop is completely destroyed.

where a = rate of increase in leaf consumption by the larvae and ρ = leaf mass consumption by a first-day larva during one time interval. The first term on the right-hand side of equation (4) represents the consumption of larvae that survived from the preceding time period. However, this term also includes consumption by larvae that had, in fact, become pupae. Therefore, their share is subtracted (the last term). The second term is the consumption by larvae that hatch in the tth time interval.

The Plant

Two components of the plant are considered—the stem and the leaves.[8] The leaf mass, m_t, measured in grams, grows as a function of both leaf mass and root reserves. The algorithm presented by Gutierrez et al. was too complex to utilize; hence, the following form is used:

$$(5)\quad m_{t+1} = m_t(1 + \eta_1) + \eta_2 - v_t; \quad t_0 + b \le t \le t_f - 1;$$

m_{t_0+b} is given. This captures the essence of the simulation model. The plant grows from current photo-synthetic production, which is a feedback function, $m_t(1 + \eta_1)$, and from root reserves, η_2, which in reality fluctuate with time (i.e., if the plant is completely defoliated, $m_t = 0$, and it can regenerate by η_2). The stem mass is not directly damaged by the pest to any great extent but is indirectly affected by the leaf damage.

Using field data by Christiansen and Gutierrez, it has been possible to estimate the stem mass, S, at time t_f as a positively related function of the leaf mass in that time, $S = h(M)$, where $M = m_{t_f}$ is the leaf mass at cropping time.

Interseasonal Pest Dynamics

The infestation rate, θ, is a parameter that is determined by the following factors: total number of pests that aestivated from all the fields in the region, weather and ecological conditions during aestivation time, and the location of the field.[9]

Since pesticide applications do not appear to affect the pupae, the number of young adults per acre, A, that leave a given field can be approximated by $A = 43{,}560 \sum_t Z_t$.[10] Assuming that there are J acres in the region, then for a given acre i at a given season n, the infestation parameter, $\theta_{i,n}$, is given by the function

$$(6)\qquad \theta_{i,n+1} = g^*_i\left(\sum_{j=1}^{J} A_{j,n}\right),$$

where $A_{j,n}$ is the total number of adults that leave the jth acre for aestivation during the nth season.

The Economic Problem

The economic problem is to find the pest control policy that will maximize net gains. In the following analysis, a distinction is made between gains collected by each decisionmaker separately and those considered from the societal viewpoint.

The Private Viewpoint

The crop of alfalfa hay is measured by the weight of stems and leaves. However, its price is not fixed (even to the competitive farmer) and positively depends on the quality of the hay. A measure of the quality is the leaf-stem ratio. Let $p_m(M)$ denote the price of the hay; then

$$(7)\quad p_m \equiv g\left(\frac{M}{S}\right) \equiv g\left(\frac{M}{h(M)}\right) \equiv p_m(M),$$

where S is stem weight at cropping time and $h(M)$ is a function relating stems to leaves $[h'(M) > 0]$.[11] It is further assumed that p_m is continuous with $0 \le [p'_m(M) = g'(\cdot)\ (h -$

[8] The horizon is one season (until the first cutting of the hay). The effect of leaf damage on root reserve depletion was considered originally since this factor may affect second and third croppings. However, observations in commercial fields show a negligible effect of the pest either within the horizon or on the subsequent croppings and no effect later on.

[9] A region is defined here as the area comprising all fields such that an aestivating pest from one field could possibly reach any other field in the region during the following season. Although the weevil has a tendency to aggregate during the aestivation period, it is believed to be highly mobile during the phases of migration to and from the fields. Experience with other insects of the same biological order suggests that the weevil may cover considerable distances at the time of migration. It is thus very likely that weevils originating from any one field will eventually arrive at other fields in the region. One should recall that most alfalfa growing farms in California are less than 200 acres in size, which is considered well within the migration range of the weevil.

[10] Since biological data were given per square foot and economic functions are on a per acre basis, the conversion factor (43,560) was used when necessary.

[11] Prime denotes first derivative, and double prime denotes second derivative. When functions of two or more variables are defined, their partial derivative will be denoted by subscripts of the variable with respect to which derivative is taken.

$h'm)/h^2] < \infty$, namely, that the price is nonnegatively related to leaf mass, M. The revenue of a single farmer is thus

$$(8) \qquad R(M) = p_m(M)[M + h(M)],$$

and, under the above assumptions, $R'(M) \geq 0$. The sign of $R''(M)$ depends on the signs and magnitudes of $g''(M)$ and $h''(M)$; but if both equal 0, then $R''(M) \geq 0$.

The farmers are assumed to be pricetakers in the pesticide market, and a one-season objective function is

$$(9) \qquad \Pi^{(1)} = R(M) - p_x \sum_{t_0}^{t_f} x_t,$$

where p_x is the fixed pesticide price.[12] The first problem is a single-season decision: maximize equation (9) subject to the equations (1), (4), (5), and (8) and the constraint that all variables in the system be nonnegative. It is assumed that no single farmer is large enough to affect the regional pest dynamics significantly and therefore would not take it into consideration in his pest control policy.

The objective defined by equation (9) fails to consider the possibility that secondary pests are likely to develop following pesticide applications because of the disturbed ecological relationships in the field. In alfalfa, it has been observed that, when pesticides are applied late in the season against the major pest—the weevil, secondary pest outbreaks may occur, requiring the use of additional control measures in subsequent time periods of the season (Summers and Cothran 1972a). As the secondary outbreaks occur beyond the specific horizon adopted in this model, they are taken into account by a set of extra charges on pesticide applications that occur at later time periods within the model's horizon. The penalties reflect the cost of additional controls that will result later from the current use of pesticides. Alternatively, these charges may be considered as a reflection of yield reduction in later croppings in the season resulting from secondary pest outbreaks. The objective function is then

$$(10) \qquad \Pi^{(2)}(x, \theta) = R(M) - \sum_t (p_x + \mu_t)x_t,$$

where μ_t is the appropriate charge that accounts for the damage of the secondary pest. A discussion of μ_t is presented in the appendix.

[12] This objective function ignores the possibility of fixed application costs, which will be discussed later when the computational results are analyzed.

The Societal Viewpoint

The objective function defined by equation (10) overlooks several major aspects of the pest-control problem. Among them are the aspects of pest resistance, interseasonal pest dynamics, and a few types of external effects of pesticide applications on the environment. The present model, however, focuses only on the interseasonal relationships and assumes that no other external effects exist.

Assuming pests are identically distributed over the region, a central decision agency would maximize the present value of the net returns per acre:

$$(11) \qquad \Pi^{(3)} = \max_{\{x_n\}} \sum_{n=0}^{N} \beta^n \Pi^{(2)}(x_n, \theta_n),$$

where x_n = vector $(x_{1n}, x_{2n}, \ldots, x_{tn}, \ldots, x_{t_f n})$ of controls at the nth season, $\beta^n = 1/(1 + r)^n$ = discount factor using the appropriate discount rate, r, and N = planning horizon. This maximization is subject to the same constraints as before, equations (1), (4), (5), and (8), repeated for each season. An additional set of constraints accounts for the interseasonal relationship

$$(12) \quad \theta_{n+1} = g^*\left(\sum_j^J A_{jn}\right) = g^*(JA_n) = g(A_n) = \gamma \cdot A(x_n, \theta_n); \quad n = 0, 1, \ldots, N,$$

where A_n is the number of adult pests leaving for aestivation per acre during the nth season, γ is the parameter of proportion between adults leaving per acre at the nth season and the rate of infestation in season $n + 1$, and the initial infestation rate, θ_0, is a given parameter. This equation is similar to equation (6) but is simplified due to the assumption of identical pest distribution and the linearity of the function $g(\cdot)$.

Private Vis-à-Vis Societal Policies

Private decision rules are obtained by a maximization of the problem for one season. Define $G(x, \theta)$ as the Lagrangian corresponding to $\Pi^{(2)}(x, \theta)$ and the constraints (1), (4), (5), and (8). The private decision rules obtained by the maximization of $G(\cdot)$ are

(13) $$G_x(x, \theta) = 0.$$

Societal decision rules are obtained by

(14) $$\max_{\{x_n\}} \sum_{n=0}^{N} \beta^n \{G(x_n, \theta_n) - \beta\lambda_{n+1} [\gamma A(x_n, \theta_n) - \theta_{n+1}]\},$$

where λ_{n+1} is the Lagrangian multiplier associated with the constraint (12).

Burt and Cummings describe a general optimization model for natural resource management. Necessary conditions for a solution to this problem include

(15) $$G_{x_n} - \lambda_{n+1} \beta\gamma A_{x_n} = 0, \quad n = 0, 1, \ldots, N,$$

and

(16) $$\lambda_n - \lambda_{n+1} \beta\gamma A_{\theta_n} = -G_{\theta_n}, \quad n = 0, 1, \ldots, N.$$

The expression $\lambda_{n+1} \beta\gamma A_{x_n}$ reflects the future gains (by reducing θ) of a marginal increase in the control at the nth period; it is appropriate to denote it as a (negative) "user cost" (Scott).

If a solution to equation (14) were possible, λ_n could be found, and a path of optimal shadow prices over time would yield the optimal policy. The curse of dimensionality, however, impedes such a solution.[13] One approach adopted here is to derive the societal steady-state solution by means of solving iteratively a sequence of one-season problems.

At the steady state, if it exists, for sufficiently large n, $\theta_n = \theta_{n+1} = \theta$, and $\lambda_n = \lambda_{n+1} = \lambda$. For this case, equations (15) and (16) become

(17) $$G_x - \lambda\beta\gamma A_x = 0,$$

and since $A_\theta = 1/\gamma$,

(18) $$-G_\theta = (1 - \beta)\lambda.$$

In the following, it is shown how the steady-state infestation rate, θ, and its corresponding shadow price, λ^*, could be found and the implications for pest-control policies analyzed. Define a modified one-season problem,

(19) $$\max \mathscr{L} = G(x, \theta) - P \cdot A(x, \theta),$$

where P is now an arbitrary parameter. The necessary condition is

(20) $$G_x - PA_x = 0.$$

Comparison of equations (17) and (20) indicates that, if one could find a value of P such that $P = \lambda^*\beta\gamma$, this would represent at steady state the marginal cost to society of pests leaving for aestivation and, therefore, yield the optimal steady-state solution. The procedure is as follows. Equation (19) is solved for some arbitrary P and a given θ_0. Using equation (12), θ_1 is obtained and the solution procedure is carried out iteratively. For any arbitrary P, the solution for the modified problem, equation (19), yields a value for $\mathscr{L}_\theta = G_\theta - PA_\theta$. In the above iterative procedure, $\{\theta_n\}$ converges to a steady state $\theta^*(P)$; insert $P = \gamma\lambda\beta$ and use equation (18). Then

(21) $$P = -\beta\gamma\mathscr{L}_\theta = -\frac{\gamma\mathscr{L}_\theta}{1 + r}.$$

This equation gives the optimal steady-state value, P^*, as a function of the discount rate, r.

[13] The complexity of the biological relations has been greatly simplified in the current model, but the size of a single-season problem for the case study actually solved could not be reduced below 50 variables and 40 constraints, with most of the constraints nonlinear.

Analysis of Results

The results presented here for the pest-control policies in alfalfa are based on the data and estimation procedures explained in the appendix. The analysis of the results focuses on the comparison of optimal pest-control policies obtained from private and societal decision rules and currently used practices. The solutions have been obtained by a nonlinear programming computer program written by Abadie (Generalized Reduced Gradient Algorithm), which was executed on a CDC 6400 computer (Abadie and Guigou).

Solution for a Single Decisionmaker

A single farmer is concerned only with pest control within a single season. He should, however, be aware of outbreaks of secondary pests and consider them in his decisions. Therefore, the problem of maximizing $\Pi^{(2)}$ (equation (10)) is regarded as the relevant problem for the single farmer.

Application of a total of twenty-eight ounces per acre of the pesticides is optimal in this case where applications are made in time

Table 1. Current and Optimal Private Pesticide Application

Type of Solution	Application Time (60 D°) 1	2	3	4	5	6	7	8	9–21	Total Amount Applied	Net Pest Control Revenue Per Acre
				(Oz./Acre)							
Current practices	0	0	0	0	0	0	0	16–32	0	16–32	\$88–\$101
Unrestricted private optimal solutions	1.5	9.8	4.3	12.6	0	0	0	0	0	28.2	\$116.84

periods 1 through 4 only (table 1). The optimal timing of pest-control applications is in time periods up to and including the time of peak adult population (cf. figure 1). This is prior to the last frost, at which time the seasonal regrowth of the alfalfa starts. Furthermore, since the frosts destroy the larvae, pesticide applications prior to the last frost are directed primarily against the adult pest. This result is strengthened by the fact that pesticides are more efficient in the control of larvae than of the adult pest (e.g., given the parameters estimated here for pesticide application of sixteen ounces, about 20% of the adults compared with 4% of the larvae will survive; see appendix). Pesticide applications made early in the season reduce not only adult numbers but also the future population of eggs and larvae. The common practice at present is to apply pesticide only when large larvae are found in the field, which is approximately three time periods after the last frost. The amount of pesticide applied varies greatly in practice, ranging from less than sixteen ounces to thirty-two ounces per acre depending upon the timing of the first application and on the actual damage throughout the season. Comparison of the net pest-control gains of private optimal policy with current practices (table 1) clearly indicates the advantage of the former. The most important practical conclusion of these results is, however, the indicated shift in the timing of pesticide applications to a new control target (i.e., the adult pest rather than the larvae).

The results presented above are based on the model assumptions that include time-dependent charges on applications. These charges impose heavier costs on applications that occur later in the season. Compared with the basic pesticide cost of forty cents per ounce, the charges actually used to obtain the above results are zero up to (and including) the fifth time period but increase linearly thereafter, reaching \$1 per ounce in the tenth period and remaining constant at that level (see explanation in the appendix). Since the timing of applications is a major point of difference between the results obtained here and current practices, it is interesting to examine the sensitivity of the control policy to the extra charges, μ_t, imposed on pesticides. The solution to the problem with all extra charges set at the zero level is found to be identical with the solution of the problem incorporating the charges. It is thus concluded that, even without consideration of secondary outbreaks, spraying should take place before the last frost and be directed against the adult pest.

This last result is not changed when the effects of fixed application cost are considered. Since fixed costs could not be directly treated in our computer program, an indirect approach was used. Solutions were obtained to the problem under constraints imposing one or two treatments in specific time periods. Comparing the values of the objective function, it was observed that one treatment in the third period or two treatments in the second and fourth periods were superior to all other single or double treatments, respectively (table 2). The difference between the best two-treatment and one-treatment objective functions is \$2.70 per acre. Thus, if the fixed application cost is more than \$2.70, then a single treatment (in the third period) is preferred. The unrestricted solution calls for four treatments; however, its objective function is only ten cents per acre higher than the two-treatment solution. In any case, treatments are suggested early in the season only.[14]

Aspects of a Societal Solution

The previous results took no account of the future potential damage embodied in pests that currently leave for aestivation. As noted be-

[14] Not all possible 190 combinations of two treatments were calculated, since the pattern of results allowed us to discard most of the combinations a priori.

Table 2. Policies for Spraying When Application is Imposed in Specific Periods

Periods of Application	Value of Objective Function ($)	Amount of Pesticide in Respective Periods (oz./acre)
One treatment		
1	109.6	23.0
2	112.8	24.0
3	113.9	24.4
4	113.5	24.2
5	110.5	23.3
6	102.8	17.9
7	97.6	13.6
8	94.5	10.3
Two-treatment combination		
1–3	114.8	8.2–18.1
1–4	116.1	11.6–16.9
1–5	114.9	13.9–15.0
1–7	109.6	22.6– 0.5
2–4	116.7	13.4–14.6
2–6	113.7	20.6– 5.5
3–4	115.7	13.8–12.6
3–6	114.0	23.1–16.5
4–8	114.3	22.9– 2.7

Note: These results are for the individual farmer problem and assume that no spraying occurs in all other time periods.

fore, the sequence of shadow prices and the optimal policy cannot be practically calculated. One way to account for the dynamic effects is to impose various values for the shadow price, λ, and to study the sensitivity of the solutions. Another approach used here is to calculate the optimal solution at steady state by iterative procedures.

For the first method three alternative values for *P* are used, and the results are presented in table 3. As in the solution for a single farmer's problem, for all shadow prices, the bulk of the spraying takes place early in the season prior to the last frost. However, larger values of *P* imply that both a greater total dosage and an additional application in the eighth period are required, even though the latter application is relatively small. From an examination of the suggested amount of pesticides applied (using different values of *P*), it appears that *P* = 0.23¢ per 1,000 pests is a reasonable upper limit for *P* and, if this is the case, no pesticides should be applied after the fourth period.

Using the results in table 3 as an indication of the effects of various values of shadow prices is one way to examine the effect of fixed application costs on spraying policy. The procedure used is similar to the one employed when fixed application costs were introduced for the single farmer's problem. In this case only a few relevant combinations were checked (*P* = 0.23¢ and *P* = 2.3¢ per 1,000 pests). Table 4 brings together those results but only for the time combinations that yielded the highest values of the objective function. For *P* = 2.3¢ the eighth period application should be eliminated if the fixed application cost is more than $2.75. The amount of pesticides is essen-

Table 3. Sensitivity of Solutions to Arbitrary Shadow Prices Imposed on the Modified One-Season Problem

	Solution 1	Solution 2	Solution 3	Solution 4
P (¢/1,000 pests)	0	0.23	2.3	9
Objective function ($/acre)	116.84	113.01	100.79	90.2[illegible]
Pesticide application (oz./acre)				
Spraying period				
1	1.49	4.16	8.74	9.55
2	9.78	10.42	11.75	12.13
3	4.30	5.23	7.26	7.69
4	12.62	16.59	27.80	37.87
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	3.39	9.01
9–21	0	0	0	0
Pest leaving field per square foot (A/43,560)	50.70	30.25	7.094	2.006
Rate of infestation (θ_{n+1}) under the assumption				
$\gamma = 0.003846$	0.1950	0.1163	0.0273	0.0077
$\gamma = 0.001538$	0.0780	0.0465	0.0109	0.0031

Note: This analysis assumes $\theta_n = 0.174$; $\mu_t = 0$ for $t \leq 5$; $\mu_t = -1 + 0.2t$ for $t = 6, 7, \ldots, 10$; and $\mu_t = 1.00$ for $t \geq 10$.

Table 4. Optimal Policies for Specific Shadow Prices When Application Is Constrained to Specific Time Periods

	Unconstrained Solution[a]	Constrained Solution[a]		Unconstrained Solution[b]	Constrained Solution[b]
Objective function ($/acre)	100.79	97.26	100.01	113.01	112.71
Pesticide application (oz./acre)					
Spraying period					
1	8.7	0	0	4.2	0
2	11.8	28.3	19.6	10.4	16.9
3	7.3	0	0	5.2	0
4	27.8	31.1	31.2	16.6	19.0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	3.4	0	5.9	0	0
9–21	0	0	0	0	0
Number of aestivating pests (A) per square foot	7.10	11.82	7.23	30.25	32.32

[a] P = 2.3¢/1,000 pests.
[b] P = 0.23.

tially not affected by fixed cost (for both prices), and the same timing of application is generally retained.

Comparing the societal with the private solution, it is concluded that the inclusion of future damage results in heavier spraying and smaller numbers of pests leaving for aestivation. This conclusion is maintained with or without fixed application costs. As will be demonstrated below, pesticide use at steady state is only slightly higher than the solution suggested by the last row in table 1 (private solution) but is much lower than the one suggested by tables 3 and 4. This may suggest that, along the unknown optimal path for the societal solution, pesticide use should be high initially and then decline as it approaches the steady state. It should be noted that this policy would be the optimal one only if resistance to pesticides is absent and is not expected to develop. The problem may be further complicated by the recognition of other externalities.

The steady-state solution is based on successive iterative solutions of the modified one-season problem, and the optimal steady-state shadow price is obtained as a function of the interest rate. The procedure is based on the results obtained in equation (21) in the following way. For some (arbitrarily fixed) value of γP (using $\gamma = 0.0038$), the problem defined by equation (19) is solved iteratively, where in each iteration θ_{n+1} is determined by the value of A_n using equation (12). $|\theta_{n+1} - \theta_n| < \epsilon$ has been used as the criterion for terminating the iterative process and determining $\theta^*(P)$ in the steady-state value. In the computation, $\epsilon = .01\theta_n$ has been used. Equation (21) is then used to determine the discount rate r for which the above values of P and $\theta^*(P)$ would be optimal. The results form a mapping from r into $[P, \theta^*(P)]$ (figure 2). $P(r)$ is negatively sloped function that goes to 0 as r goes to ∞ and reaches a finite value when $r = 0$. This mapping gives a target for pest-control policy in the sense that, given a discount rate of, say, 9%, an optimal societal steady-state rate of infestation should be about 0.02, and the corresponding shadow price P is 2.3¢ per 1,000 pests. It is important to note that, once a steady state $\theta^*(r)$ is obtained, the level of pesticide application is about the same for all values of P that have been tried—around thirty-two ounces per acre—compared with the private optimum of twenty-eight ounces per acre. The timing for pesticide applications is, however, similar to the solution for the former (private) problem. Unlike the results in table 3, the eighth period application is eliminated in the steady-state solution. The impact of fixed application costs is as before; it reduces the number of applications without changing the general timing of the applications and their total amount.[15]

[15] In order to save space, these results are not presented.

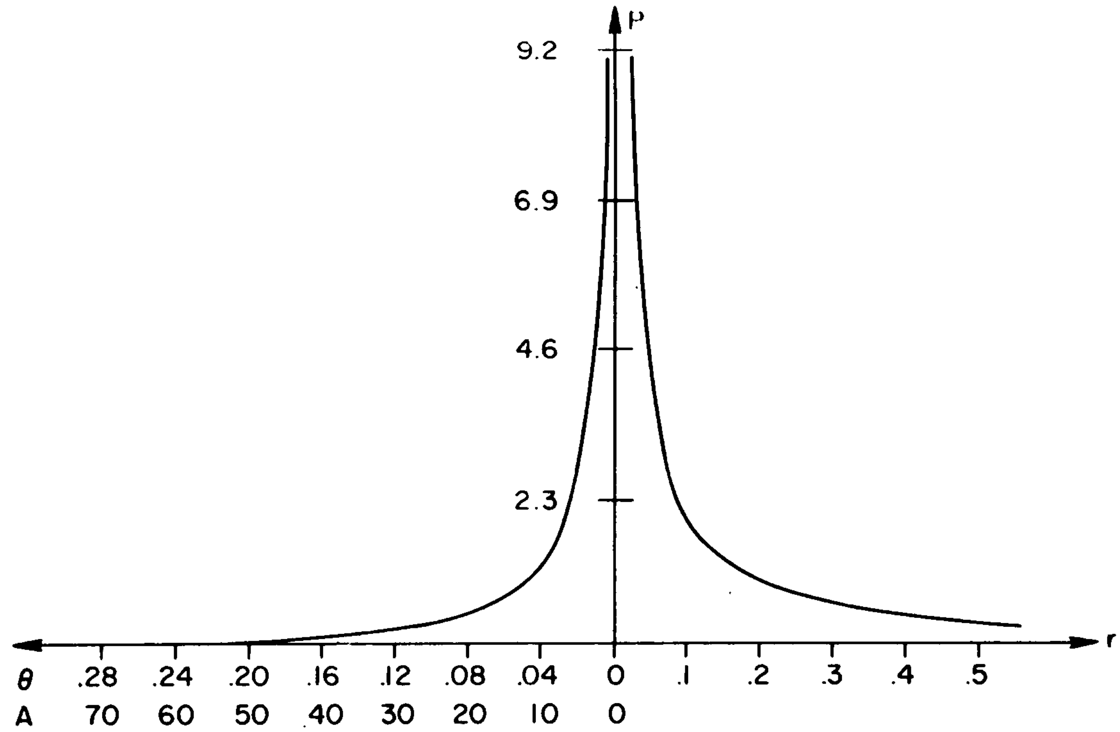

Figure 2. Optimal steady-state relationships between discount rate, *r*, penalty on pests leaving the field, *P*, in cents per 1,000 pests, and the number of pests, *A*, leaving the field (infestation rate, θ, is a fixed proportion of the number of pests leaving the field)

Conclusion, Policy Implications and Extensions

The following points summarize the major results and offer some suggestions for future research. The major discrepancy between the results obtained here and current practices involves the timing of pesticide application. The results obtained here indicate the advantage in applying pesticide prior to the growth season. Specifically, application is centered around the time period in which the number of adult pests peaches its peak. Within a given season, the individual farmer is not affected by his neighbors' decisions; however, in the long run each farmer is affected by the cumulative effects of the individual decisions. In this case the pest constitutes a "common property resource," and a nonregulated market would not yield the optimal solution. The optimal societal solution could be implemented by an information agency that would enhance mutual cooperation between farmers (e.g., the Extension Service). It has been shown that a shadow price of 2.3¢ per 1,000 adults emerging per acre is the steady-state social cost. This corresponds to a discount rate of approximately 9%. Higher discount rates imply lower social cost and higher steady-state infestation rates.

Future research is clearly desirable to ascertain many of the functions and to obtain better estimates for some of the parameters before this solution is to be applied. These results are, therefore, important in indicating the direction for better pest-control policies and in pointing out directions for future research regarding critical parameters and functional relations upon which the solution rests. Further work is also needed to obtain the optimal policy path over time. This model can be extended by using the interseasonal results obtained here in a dynamic programming framework to find a multiseasonal optimal policy. One important component that has not been incorporated in this model is pest resistance to chemical pesticides. However, this possibility raises the question whether a policy that leads to heavy suppression of the pest by chemical pesticides is desirable, as it may bring on a speedy development of resistance.

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Appendix

Data Sources and Estimation Procedures

The appendix presents the data sources, estimation, and derivation procedures of the various parameters in the model as applied to the control of the Egyptian alfalfa weevil in California.

The Rate of Infestation, θ

For a one-season problem, the pest infestation rate θ is a constant. This has been estimated at 0.174 by Gutierrez et al. from early season field counts. The interseasonal relationship $\theta_n = \gamma A_{n-1}$ is an approximation adopted here. The estimate of γ (0.0038) is based on the observation that, using current practices, the average adult peak is about 0.05 of the number of adults that leave the field, and adult peak time occurs thirteen time periods after the arrival of the first adults from aestivation.

The Kill Function

The kill function is taken from a field pesticide experiment by Cothran and Christiansen. Pesticides were applied against the adult population early in the season, and the effect measured the number of offspring produced by the survivors. This is a reasonable estimate of survivorship because the adults remain in a very limited area of the field, and the subsequent count of larvae accurately reflects their survivorship via fecundity when compared to an untreated control. The resultant survivorship curve was estimated from their field data by the curve $e^{-\alpha x}$ with

$\alpha = 0.1$ and is representative of the effects of Carbofuran and Heptachlor on adult Egyptian alfalfa weevil populations ($R^2 = 0.89$ and the student t-value was 16.7). Pesticide applications are more effective against larvae, and $\delta = 0.2$ (equations (4) and (5)) has been estimated from Summers and Cothran (1972b) by comparing equivalent application rates on estimated larval survivorship and assuming that the kill function has the same form.

Oviposition Rates, E_t

The maximum oviposition rate is 2.2 eggs per female per D° (= 132 eggs per one time interval). Laboratory feeding experiments and field observations indicate that the beetles fail to feed during periods of adverse weather conditions (i.e., too cold, rainy, etc.) and, as a result, fecundity declines. Gutierrez et al. describe these experiments and formulate equations to estimate weather effects on egg laying. These occur annually, although the pattern may vary. Hence, a pattern and magnitude of these effects for a typical year were estimated and included in the model. Fecundity is also age dependent and was estimated from laboratory experiments. Field and laboratory data indicate that adults entering the field must feed approximately 400 D° before they can oviposit. Incorporating all of these effects resulted in the following oviposition rates per adult: $\{E_t\} = \{1.8, 9.6, 14.2, 11.7, 19.2, 27.0, 33.3, 37.8, 42.5, 41.9, 55.8, 60.9, 66.0, 32.2\}$, for $t = 1, 2, \ldots, 14$.

Larval Consumption Rate

Koehler and Pimentel estimated leaf consumption rates for a related species of alfalfa weevil. Because the species are taxonomically close and of approximately the same size, it was felt that this was a reasonable value to use in the model. A geometric function was fitted to their data.

$$\rho \sum_{t=1}^{6} (1 + a)^{t-1} = 7.5,$$

where the total consumption of a larva during its lifetime (six periods) is 7.5 milligrams of leaf tissue, $1 + a$ (= 2.3) is the geometric rate of increase of the function per 60 D°, and ρ (≐ 0.0043 grams) is the consumption of a larva during its first 60 D°.

The Plant

The parameters η_1 and η_2 of equation (5) were estimated as follows. Using a simulation model of the plant, eight successive observations of m_t were obtained for the hypothetical situation of zero pest population (i.e., $V_t = 0$). As the simulation model's time period is approximately twice as long as the present model, the following equation was estimated:

$$m_{t+2} = (1 + \eta_1)^2 m_t + [2 + \eta_1]\, \eta_2.$$

This equation is easily derived from equation (5). The estimates were

$$(1 + \eta_1)^2 = \underset{(3.5)}{1.1256}$$

and

$$\eta_2 [2 + \eta_1] = \underset{(16.1)}{1.0914},$$

where the figures in parentheses denote student t-values. The R^2 of the regression was 0.977. On the basis of these estimates, η_1 and η_2 were calculated. Total stem weight, S, (grams per square foot) is linearly related to the amount of leaf tissue at harvest, M, by the function $S = 9 + (15/16)\, M$, $0 \le M \le 16$, grams per square foot. All field estimates were estimated on a square foot basis, but economic values are scaled to dollars per acre.

Alfalfa Quality and Price

The quality of alfalfa hay can be measured by its leaf-to-stem ratio. The price P_m per gram of alfalfa is strongly influenced by this ratio. The price for alfalfa which has been used here is $80 per ton for maximum quality and $5 per ton if completely defoliated. By linear interpolation, $P_m = (0.55 + 0.516\, M)10^{-5}$ in dollars per gram. The revenue, R, is then $R = (S + M)\, P_m = 2.16 + 2.49\, M + 0.435\, M^2$ in dollars per acre.

Pesticide Cost

Pesticide costs (forty cents per ounce) are reasonable estimates for alfalfa production in northern California during the 1972–74 period and were obtained by consultation with W. R. Cothren and R. W. Bushing, University of California, Davis. This is the current cost estimate for Furdan, the most commonly used pesticide applied for the control of the Egyptian alfalfa weevil. Exact estimates for the cost of secondary pest outbreaks, μ_t, of aphids, lepidopterous, and other pests are unavailable and have been estimated from experience. It is commonly observed by entomologists that applications of pesticides on alfalfa (and other crops, e.g., cotton) to control pests result in additional pesticide use to control the induced secondary pests. Pesticides applied late in the spring disrupt the ecological relationships more than pesticides applied during the winter period when most of the nontarget species are dormant (Summers and Cothren 1972b). This is reflected as an increasing linear charge of 0 from the last frost (the fifth period) to a maximum of $1 at the tenth period and thereafter; i.e., $\{\mu_5, \mu_6, \mu_7, \mu_8, \mu_9, \mu_{10}, \mu_{11}, \ldots\} = \{0, 0.20, 0.40, 0.60, 0.80, 1.00, 1.00, \ldots\}$.

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