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ON THE OPTIMAL CONTROL OF CORN ROOTWORM IN MINNESOTA

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I.1 Background

Pest management in agricultural production involves the employment of certain inputs to reduce potential production losses, or the likelihood of production losses, attributable to pest infestation. In economic parlance, pests are "...an uninvited input with negative marginal product", (Robison and Barry, 1986), and their presence in production systems lends economic importance to pest abatement inputs.

Pest abatement inputs may take the form of purely mechanical devices such as vermin-proof fencing, cultural or tillage practices, or the use of chemical pesticides. Agrichemicals are widely used in pest management, (for a review, see Swanson and Dahl, 1989), however, the increasing public concern for the adverse side effects of pesticides have led to efforts to reduce commercial agriculture's dependence upon chemicals.[1]

In view of the external costs of pesticides, private pest management is often characterized as being over-dependent on agrichemicals (Daberkow and Reichelderfer 1988, p.1160). The suboptimality of private pest management choices in the presence of negative externalities has been investigated in a number of papers including Babu and Hallam (1988), Carlson (1977), Feder and Regev (1975), and Regev, Gutierrez and Feder (1976).

I.2 The Problem Statement

In this paper, the results of an investigation of the pest management options of Minnesota farmers for the control of northern corn rootworm are reported. In North America, there are three important species of corn rootworms are; *Diabrotica virgifera virgifera*, the western corn rootworm [WCR], *Diabrotica barberi*, the northern corn rootworm [NCR], and *Diabrotica undecimpunctata*, the southern corn rootworm [SCR]. The NCR and the WCR are primarily responsible for damage to Minnesota corn (NAPIAP, 1985a,b). Since 1976-77, the more winter-hardy NCR has become more abundant and now represents over 90 percent of the population statewide (Ostlie and Noetzel, 1987).

The root feeding of *Diabrotica* larvae cause yield losses in corn by impairing the plants ability to take up soil moisture and nutrients. Crop losses of 10-12 percent have been reported although estimates of yield losses due to rootworms vary widely (Apple *et al.*, 1977; Kuhlman and Petty, 1973). In experimental plots, Branson, Sutter and Fisher (1980) found corn yield losses of up to 19 percent, but suggest yield losses could be considerably higher when corn is subject to stress. Apart from direct yield losses, feeding of the corn rootworm on the root system may predispose the corn plant to lodging[2] and the possibility of harvest difficulties and further crop

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1 Harper and Zilberman (1987) identify the following external costs of pesticides: 1) killing of wildlife, 2) operator health damage, 3) water contamination, 4) pesticide residues in food, 5) pest resistance, 6) resurgence of the target pest, and 7) inducement of secondary pest infestations.

2 Lodging refers to the collapse of the corn stand which is generally caused by damage to the root system coupled with high winds Lodging is a

yield losses.

Corn rootworms are generally controlled either by the application of a soil insecticide applied at corn planting, or by crop rotation.[3] The application of soil insecticides is directed toward killing the larvae which emerge some 6 to 8 weeks after corn planting. In 1980, over 52 percent of all corn acres were treated with chemical pesticides (Suguiyama and Carlson, 1985) accounting for over 30 million pounds of soil insecticides (Swanson and Dahl, 1989). By virtue of a narrow host range, corn rootworm larvae which emerge into a field of soybeans, or some other non-host crop, will perish. Thus the latter strategy of crop rotation achieves control by denying the emerging rootworm larvae a suitable plant host.

The future for rootworm control strategies is clouded with considerable uncertainty. Public concern for the environmental damage and health risks posed by soil insecticides continues to grow, leading to the increasing likelihood of bans or limitations being placed on soil insecticide use (Osteen and Kuchler, 1986).[4] Moreover, the use of pesticides has generally been accompanied by a decline in pesticide productivity through the process of resistance development. Finally, although crop rotation plays an important role in rootworm control, recent evidence of NCR infestation in first year corn[5] suggests the failure of this form of control and a necessary reassessment of crop rotation as a means of rootworm control.

Although the process of pesticide resistance development is well-known, the apparent adaptation of NCR to crop rotation is both recent and only partially understood. Studies have shown that the adaptation by NCR to crop rotation is conferred by the ability of NCR eggs to undergo extended dormancy (diapause) in the soil (Krysan *et al* 1984).[6] Expression of the trait in a corn-nonhost rotation allows a significant proportion of NCR eggs to remain dormant over 2 or more winters and hatch into corn, rather than hatch in the nonhost crop (Krysan *et al.*, 1986).

A corn-soybean rotation (or some other corn non-host rotation), places strong selection pressure on the NCR population, unambiguously in favor of the extended diapause trait. In a recent study of the NCR eggs taken from adults collected in fields with a corn-soybean crop history, 40-50 percent of the eggs were found to possess the extended diapause trait, compared to only 9 percent in eggs taken from fields in continuous corn (*ibid*).

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characteristic of severe rootworm infestation, however, lodging may occur in the absence of corn rootworm if the root system is poorly developed (Ostlie and Noetzel, 1987).

3 Strategies for the management of corn rootworms are discussed in greater detail in Ostlie and Noetzel (1987).

4 The EPA has issued a call for a ban on granular formulations of carbofuran, sold as Furadan (Agrichemical Age, 1989).

5 First-year corn refers to corn planted in fields which were previously planted to a non-host crop such as soybeans.

6 Diapause refers to a state of suspended biological development which occurs within the life cycle of the insect.

In view of the diminishing effectiveness of the primary instruments of rootworm control, and the possible imposition of limitations on the use of soil insecticides, rootworm management advice (for example, see Stockdale and DeWitt, 1976) may be superseded.[7] This study evaluates corn rootworm strategies in a model which incorporates both the potential for pesticide resistance development, and, through extended dormancy, for a proportion of NCR eggs to survive crop rotation.

I.3 Some Key Assumptions

The model of NCR control does not include an assessment of the environmental costs associated with soil insecticides and therefore possibly underestimates the gains from regional coordination. The model is deterministic and the social planner is assumed to possess perfect knowledge of the pest management system over a 10-year planning horizon. A more realistic model, given the vagaries of climate and the effects of differences in soil type on insecticide performance, would be to estimate the optimal control of an uncertain process. Such a model could be specified to allow the passive updating of production parameters, or could incorporate an active control formulation where the decision maker recognizes the opportunity to learn about the system from previous input decisions (Taylor and Chavas, 1980). However, these refinements to the fundamental problem of corn rootworm control fall outside the objectives of this study.

The rootworm management environment is assumed to be comprised of a large number of identical farm units, characterized by the representative farmer (RF). The representative farmer is assumed to evaluate his or her pest management options with the expectation that state variables will persist at their current levels over the planning horizon. Although the RF solves a N-year problem, where N = 10 in this problem, only the first period decisions in each iteration are implemented. In the following period, the initial state variables are updated exogenously, by assuming all farmers act identically in the presence of uniformly distributed corn rootworms. Subsequently, a new N-period problem is solved by the RF. The 10-period pest management decision rule for the RF is thus obtained by solving a rolling time-horizon problem ten times. The social planner (SP) is assumed to be an amalgamation of all the identical, individual farm units into a single, coordinated body. The SP solves for the N periods simultaneously where the state variables are given for the initial period, but are henceforth assumed endogenous.

II.1 Optimal Pest Management

Optimal pest management is an intertemporal resource allocation problem (McConnell, 1984). The intertemporal linkages in the NCR management problem are due to the depletion of the stock of pesticide susceptibility, the existence within the pest population upon which the future effectiveness of the pesticide depends; and the growth of the pest population, which carries the possibility of production

7 Recent advice on corn rootworm management indicates that the occurrence of extended diapause may affect management decisions (see for example, Ostlie *et al.*, 1987; Ostlie and Noetzel, 1987).

losses into the future.

Although the optimal "harvest" of renewable resources or "extraction" of exhaustible resources are inherently dynamic allocation problems, (Conrad and Clark, 1987), pest mobility may prevent farm firms capturing the benefits of their individual pest management decisions (Miranowski and Carlson, 1985). Private decision makers are assumed to take into account the consequences of their pest management actions only if the pest is non-migrating or relatively immobile (Feder, 1979; Hueth and Regev, 1974). Although resistance in immobile pest populations may develop over time, in the absence of market failure, no case can be made for intervention to preserve pesticide susceptibility. The issue is therefore not necessarily one of preventing pesticide resistance emerging, but one of determining the optimal rate of pesticide resistance development. For mobile pest populations, optimality is determined by solving the pest management problem for the regional planner for whom the dynamic externalities have been endogenized.

In the classic example, overuse of the common property resource is predicted when individuals do not hold well-defined property rights over the resource (Gordon, 1954). In this situation it is assumed individuals will equate *average* benefits with *average* costs in determining privately optimal levels of resource use. In contrast to this, and other examples in the common property literature, the representative farmer is assumed to hold property rights to the rootworm *at the time of treatment* with the rootworm population located in the soil on the farmers property. With property rights to the current period rootworm population thus well-defined, the farmer will choose pest abatement inputs so as to equate current marginal private benefits with current marginal private costs. On the other hand, due to pest mobility, individual farmers do not hold property rights to next periods' corn rootworm infestation or the resistance characteristics of the future population. The individual farmers will not therefore, in determining their optimal pest management strategies, include the user costs associated with the intertemporal external effects of pest abatement.

II.2 Methods for Dynamic Optimization

The dynamic optimization problem involves the allocation of scarce resources among competing ends over an interval of time. In mathematical terms, the dynamic optimization problem is one of choosing the time path for control variables from a class of time paths called the control or admissible set. The constraint condition is implied by a set of equations known as the equations of motion or transition equations, although other constraints may be involved. The equations of motion imply the time paths for variables which describe the model system, called the state variables. The time path of the control variables are chosen so as to maximize a given real-valued function which depends on the state and control variables. The dynamic optimization problem may be written in continuous time form as

$$\max_{\{u(t)\}} \Phi = \int_{t_0}^{t_1} I(x,u,t) + F(x_1,t_1)$$

subject to

$$\dot{x} = f(x,u,t),$$

$$\{u(t)\} \in \Omega, \qquad t_0 \le t \le t_1,$$

$$x(t_0) = x_0$$

where Φ is the objective (or value) function for which the control path $u(t)$ is sought which maximizes Φ and simultaneously satisfies the state variable transition path $f(x,u,t)$ and the constraints on the admissible control trajectory, $\{u(t)\} \in \Omega$. The function $I(x,u,t)$ is the intermediate value function and $F(x_1,t_1)$ is the terminal value function, where both $I(.,.,.)$ and $F(.,.)$ are assumed given and continuously differentiable. Time, t, is measured in continuous units and defined over the interval from initial time t_0 to terminal time t_1.

III.1 A Description of the Model

The problem of NCR control is assessed for the regional or social planner, and a representative farmer, in a discrete time optimization framework. The regional planner is assumed to choose a soil insecticide application rate and crop rotation strategy to maximize returns over a specified time horizon in an environment of complete knowledge of the bioeconomic system. In contrast, the representative farmer is assumed to behave as his/her individual actions will not perceptibly affect either pest resistance or the future pest populations. In this sense, the representative farmer operates with a myopic optimizing framework (Lichtenberg and Zilberman, 1986). The model incorporates equations which characterize the relationship between pesticide use and pesticide resistance, and the model also allows for the expression of extended diapause in NCR populations. The optimization problem was solved using GAMS (Brooke, Kendrick and Meeraus, 1989) on a VAX mainframe.

As a caricature of the NCR control problem, this model necessarily abstracts from many of the complexities of nature which influence the growth and development of an organism and its effects on plant growth and yields. The principle followed here and by authors elsewhere,[8] is to establish properties of the pest which are believed to be important in the determination of pest abatement strategies and to find suitable mathematical forms to represent these properties.

Crop damage abatement concerns both the pest-pesticide interactions characterized by the dose-mortality function, and the crop damage function, against which the benefits of pest control are evaluated. Representation of the ecology of the NCR involves the

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[8] See, for example, the model of the Egyptian Alfalfa weevil by Gutierrez, Regev and Shalit (1979) and Regev, Shalit and Gutierrez (1983).

specification of a population growth function, an equation which characterizes oviposition behavior and the consequences of extended diapause for future infestation, and another mathematical relationship which establishes the link between insecticide use and resistance. The crop production component establishes crop yields for corn and soybeans for different rotational sequences. Yield differences mainly reflect improvements in soil nitrogen status due to leguminous crops and the control of pests other than NCR conferred by rotation. Yield penalties were also calculated to account for the effects of increasing crop acreages on the timeliness of field operations.

III.1.1 Damage Abatement

This component of the model relates to the efficacy of pesticides in reducing crop damage.[9] Pesticides do not increase potential output[10], but may increase realized yields by reducing damage (Lichtenberg and Zilberman, 1986). Central to damage abatement is the dose-mortality or kill function, which expresses the relationship between the proportion of the pest population killed by treatment and the rate of pesticide application. The incremental approach of equating marginal benefits with marginal costs treats pesticide rate as a continuous variable. The continuous decision rule requires not only knowledge of the pest infestation but must determine the dosage which satisfies this marginal condition.[11] The marginal choice rule will however, in general, yield more profit than the discrete "if-then-else" application rule (Plant, 1986).

A specification of the dose-mortality function which has been frequently applied in empirical studies (Moffitt and Farnsworth, 1981; Talpaz and Borosh, 1974; Talpaz *et al.*, 1978) is based on the Weibull distribution where the cumulative density is given by

$$W[x/a,b] = 1 - \exp\{-aX^{b}\}, \qquad X \geq 0,\ b \geq 0$$

where X is insecticide dose, and W[.] is the proportion of the insect population killed by exposure to the insecticide such that $W[.] \in [0,1]$. The dose-mortality function was estimated from data generated from soil bioassays.

Lichtenberg and Zilberman remark that typically, "damage abatement functions are dynamic, ...in particular, there is a tendency for the efficacy of damage control measures to decline over time" (p.269). One way to represent the decline in productivity of insecticides is to incorporate a model of resistance development within the control problem (Taylor and Headley, 1975; Regev, Shalit and Gutierrez, 1983). The model of resistance development subdivides

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9 In this model, crop damage is measured as corn yield losses. However, in other situations pest damage may affect the quality of the output, for example, blemishes on table fruit (see Babcock *et al.*, 1988). In this case, the losses are likely to be reflected in price discounts on the damaged crop.

10 It may even be possible that chemical pesticides reduce productivity. For example, some soil insecticides are toxic to corn plants.

11 See Moffitt (1988) for a comparison the decision rules for discrete and continuous application strategies.

the pest population into three genotypic groups; resistant homozygous, heterozygous, and susceptible homozygous. A dose-mortality function, which is a measure of the fitness of the genotypic group with respect to the pesticide, is associated with each subgroup. Although the parameters of the dose mortality function remain constant, the proportions of each population subgroup are assumed to vary over time, depending upon the relative survivorship of each group, which in turn depends on the rate of insecticide use.

The estimated dose-mortality function provides the foundation for the damage abatement component of the model. However, the marginal productivity of an insecticide depends not only upon its toxicity, but also upon the damage potential of the pest. A second part of the damage abatement model is therefore the estimation of crop losses attributable to corn rootworm infestation.[12] Let the yield function be expressed as

$$Y = f(Z, I, X)$$

where Y is realized yield, Z is a vector of productive inputs, I is pest infestation, and X are the pest control inputs. The production function which underlies the specification of the crop yield is assumed to be weakly additive and the productive factors of production are assumed to be employed at optimal levels. Following Lazarus and Swanson, 1983; Zacharias and Grube, 1986; Archibald, 1984; and Foster *et al.*, 1986, pest damage is estimated as a linear function of pest infestation.

III.1.2 Insect Ecology

Two state variables, population resistance and pest infestation, are assumed to represent the important features of the biological resource, and by the assumptions concerning the RF's and SP's decision problem, are responsible for the potential divergence in the decision rules for the competitive and optimal rootworm management strategies.

Population Dynamics

The growth of the rootworm population is modeled in terms of discrete time intervals. It is assumed the following seasons' population is based entirely on the population in the preceding season, and, in the absence of abatement, the dynamics of the pest population takes the following discrete time form

$$I_{t+1} = G[I_t],$$

where I_t is the corn rootworm density, and the rootworm population I is therefore wholly dependent on the previous period's population.

It is desirable the growth fraction G[.] satisfy the following properties

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12 Corn rootworm damage principally affects crop yields. However, pests may also effect crop quality (Babcock *et al* 1988), where the effects of infestation are typically measured through price discounts on damaged production.

$$0 \leq G[It] \leq \bar{N} < \infty ,$$

where $\bar{N}$ is a finite upper bound on the population approached only in the limit, thus

$$\lim_{I \to \bar{N}} G[.] = 0.$$

The density dependent biomass function G[.] is frequently written as the logistic or Verhulst equation (Curry and Feldman, 1987)

$$\frac{dI}{dt} = \rho I \left(1 - \frac{I}{K} \right) \quad ,\rho > 0 ,$$

where I is the population biomass, ρ is known as the intrinsic growth rate, and K is the environmental carrying capacity or saturation level. The equation possesses two equilibrium solutions, namely I = 0, and I = K. In natural populations, extinction (X = 0) is ruled out by specifying a lower bound n.

Insecticide Resistance

An equation of motion for pest resistance is developed based on the assumed presence of R (resistance) and S (susceptible) alleles and the following key assumptions:[13]

1. Resistance is controlled primarily by single-gene locus with a fixed dose-mortality function for each genotype.
2. The dose-mortality function for RS heterozygotes is intermediate between the SS (homozygote susceptible) and RR (resistant) functions.
3. Mating within the population is random.
4. There is a 1:1 sex ratio.
5. Genotypic frequencies are independent of sex.
6. There is no immigration or emigration from the region.
7. The resistant genotype is present in the pristine population.

The proportion of insects surviving treatment at time period t can be written as S[Xt,rt/a,b], where survivorship depends not only on insecticide rate, but on the degree of resistance of the rootworm population given by state variable, rt. Hence

$$S[Xt,rt/a,b] = 1 - W[Xt,rt/a,b]$$

Let the genotypic frequencies in the pest population be represented at time t as

r_t - the proportion of resistant homozygotes,
rs_t - the proportion of heterozygotes, and
s_t - the proportion of susceptible genotypes.

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13 Models of pesticide resistance of this form have been used by Tabashnick (1985), Taylor and Georghiou (1979); Comins (1984), Taylor and Headley (1975); and Regev, Shalit and Gutierrez (1983).

At time t, the population survivorship function is a function of insecticide rate, X_t, and the weighted average of survivorship of the population subgroups

$$S[X_t, r_t, s_t] = w_{rr}\ r_t^2 + 2\ w_{rs}\ r_t s_t^2 + w_{ss}\ s_t^2$$

where, w_{rr} is the fitness of the resistant homozygote,
w_{rs} is the fitness of the heterozygote,
w_{ss} is the fitness of the susceptible homozygote,

and the fitness of population subgroups is defined with respect to the agent of selection pressure, such that $0 \leq w_{ss} \leq w_{rs} \leq w_{rr} \leq 1$.

Since $r_t = 1 - s_t$, we can rewrite the population survivorship function as a function of insecticide rate and resistance state variable, r

$$S[X_t, r_t] = r_t^2\ w_{rr} + 2\ r_t(1-r_t)\ w_{rs} + (1-r_t)^2\ w_{ss}$$

Population resistance evolves according to the following equation of motion (Ewens, 1969)

$$r_{t\ 1} = \frac{r_t^2\ w_{rr} + r_t(1-r_t)\ w_{rs}}{r_t^2\ w_{rr} + 2\ r_t(1-r_t)\ w_{rs} + (1-r_t)^2\ w_{ss}},$$

alternatively

$$r_{t\ 1} = \frac{r_t^2\ w_{rr} + r_t(1-r_t)\ w_{rs}}{S[X_t,\ r_t]}.$$

Next period's frequency of the resistant allele, R is therefore a function of previous period's proportion of resistant alleles, the parameters of the fitness functions, and the rate of insecticide application, X.

III.1.3 Crop Production

The crop enterprise for the farm firm is based on a simple corn-soybean model which, in addition to the yield losses attributable to NCR, involves rotational and timeliness effects. Crop rotation is included in the rootworm model for two main reasons. First, rotation is practiced extensively in Minnesota as a form of corn rootworm control. Second, crop rotation confers significant agronomic benefits in a op production system. Leguminous crops are associated with biological nitrogen fixation, and thereby reduce the requirements for nitrogen fertilizers in the subsequent cereal crop. The rotation of crops also improves crop yields by controlling other pests which tend to become a problem in continuous cropping system. The benefits of nitrogen fixation, and of weed and pest control (other than NCR) are incorporated in the crop technology component of the model.

In addition to establishing a set of crop yield potentials for corn and soybeans based on crop history, realized crop yields are also assumed to vary according to the total acreages of each crop planted and a penalty for the timeliness of field operations. This yield loss reflects the compromises in the timely completion of field operations due to limited labor and machine resources (Apland, 1988; Apland *et al* 1989). For example, greater acreages of corn, in conjunction with limited machinery and labor resources leads to preparation and planting operations being conducted later into the year, encroaching upon the crop growing season. Yields 15 percent lower on average have been reported in corn planted in late May rather than late April (Hicks and Peterson, 1978).

Realized crop yields are calculated according to the following functions

$$Y_{i,j,k,t} \qquad F_{i,j,k,t}\left(Z_t, X_t, I_t, \left(\sum_j \sum_k HA_{i,j,k,t}\right)\right), \qquad \forall\ i,j,k,t$$

where $F_{i,j,k,t}(.)$ is the production function for crop i in period t in a field which follows crop j in period t-1 and crop k in t-2.

The following conditions are assumed to hold,

1. $\partial F_{i,j,k,t}/\partial Z_t \geq 0$,
2. $\partial F_{i,j,k,t}/\partial X_t \geq 0$,
3. $\partial F_{i,j,k,t}/\partial I_t \leq 0$,
4. $\partial F_{i,j,k,t}/\partial HA_{i,t} \leq 0$,
5. $\partial^2 F_{i,j,k,t}/\partial X_t \partial Z_t = 0$, and
6. $\partial^2 F_{i,j,k,t}/\partial Z_t \partial X_t = 0$.

Directly productive inputs, Z, and pest abatement inputs, X, increase realized yield, Y (conditions 1 and 2). On the other hand, crop yields decline as infestation increases, (condition 3). Condition 4 reflects the yield penalties associated with timely field operations and states that as area of crop i increases, realized yield declines. Finally, the production function is assumed weakly additive, thus the marginal productivity of the productive input (z) is unaffected by variation in pest abatement input (x), and visa versa (conditions (5 and 6)).

IV.1 Northern Corn Rootworm Management Strategies for the Representative Farmer and the Social Planner - Benchmark Comparisons

Solutions to the RF and SP rootworm control problems were established for a variety of starting values for NCR infestation and the proportion of NCR eggs which undergo extended dormancy. Management strategies for the RF and SP are reported here for initial rootworm infestations of 1000 eggs per row-foot and for diapause proportions of 40 and 50 percent.[14] Infestations of 1000 eggs per row-foot represent moderately heavy infestations whilst diapause proportions of between 40 and 50 percent have been observed in fields with a corn-soybean history.

Period by period choices of insecticide application rate and crop acreages are reported for both the RF and SP in Tables IV.1 to IV.2. These tables also include the paths for pesticide resistance and pest infestation, the discounted period returns, and the value of the decision makers objective function. Table IV.3 summarizes the results obtained for different initial period values and allow a comparison between the pest management choices made by the RF and the SP.

The time path for pest infestation generated in the solutions to the NCR management problem indicates that crop rotation is capable of suppressing the NCR population, without requiring soil insecticide applications (see for example, Table IV.1) In other solutions, with higher initial rootworm infestations, soil insecticide is applied in first-year corn to reduce yield losses (Tables IV.2). However, these applications generally cease after two or three seasons when the rootworm infestation falls below the insecticide application threshold.

Referring to the summary Table IV.3, the potential welfare gains from regional coordination are observed to represent a relatively small proportion of total profit. The potential welfare gains range from $3,974 to $5,696 per farmer or 0.50 to 0.72 percent of total profit. These estimates correspond closely with the earlier estimates by Lazarus and Dixon (1984) who find welfare gains in the order of 0.3 to 0.6 percent and conclude that the benefits of intervention to affect private pest management decisions are unlikely exceed the transaction costs associated with government intervention. However, in contrast to Lazarus and Dixon, who find significant differences in the pest control choices of private and public decision makers, the solutions obtained for the RF and SP in this model of NCR control reveal a close similarity in the choice of soil insecticide rate, although the period by period crop acreages were generally found to differ.

Due to differences in the acreage of treated corn, the total quantity of insecticide applied by the RF was frequently significantly more than the quantities applied in the SP solutions. However, for both decision makers, the overall use of soil insecticide is generally low, and well below the recommended application rate of 8.7 lbs/acre.[15]

The similarity in the rate of insecticide use obtained for the two decision makers may be attributed to two main factors. First, because of the selective technique of soil insecticide application against the rootworm population, selection pressure is not applied to

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14 Diapause proportions of 40 and 50 percent imply, 40 and 50 percent of eggs hatch in the next year (t+1), and the remainder hatch the following year (t+2).

15 Counter® (Terbufos), the soil insecticide used most widely to treat NCR, was selected. Application rates were taken from the Crop Protection Chemicals Reference, 1988.

the overall rootworm population.[16] The reduced selection pressure on resistant genotypes implies a lower user cost associated with insecticide use. Second, crop rotation is found to effectively reduce the NCR population thereby circumventing a dependence on chemical insecticides. The availability of an effective control alternative reduces the value of preserving susceptibility.

Pest managers who confront the problem of NCR infestation and extended diapause have the choice of three management options (Ostlie, 1987). The first is to apply soil insecticides in first year corn, the second is to plant another season of the non-host crop, and the third is to plant first-year corn without soil insecticides.[17] In this model of NCR control, the prevalence of extended dormancy in the NCR population is found to affect the pest management strategies for both the SP and RF. Small amounts of insecticide are applied in first-year corn for rootworm infestations above the threshold of 400 eggs per plant, (where potential corn yield losses of 3.2 percent imply a potential loss of profit of approximately $9.8 per acre). However, the most significant effect of extended dormancy for NCR management is reserved for choice of crop rotation. The general pattern of crop choice is for some proportion of farmland to be replanted to soybeans when the rootworm population is high and for corn acreages to be reduced during this period. The solutions to both the RF's and SP's rootworm management problem indicate it is generally preferable to alter crop rotation to control NCR rather than consistently maintain a corn-soybean rotation and treat infested first-year corn with soil insecticide.[18]

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[16] The moderating effect on resistance development of applying soil insecticide in bands rather than broadcast over fields is discussed in greater detail in Briggs (1989).

[17] The options assume the farmer has previously been following a corn-nonhost rotation.

[18] A less obvious result may be that although the NCR population is eliminated in some solutions within the 10-year period, the subsequent crop choices for the RF and SP may not necessarily be identical. For example, consider the crop choices in the final 4 periods for the RF and SP in Table IV.2. Although the SP's crop choices converge to 300acres corn:300acres soybean each period, the RF's solution establishes a stable 2-year cycle for the corn-soybean rotation. Due to the timeliness penalties on corn production, the RF's rotation in these periods yields slightly less profit than the SP's solution. However, the suboptimal rotation will persist for the myopic RF because the immediate gains from establishing a 300:300 acre corn:soybean rotation do not outweigh the immediate losses.

Table IV.1 Rootworm Control Strategies,
Proportion in Extended Diapause = 0.4, NCRt0 = 1,000.[a]

(a) Representative Farmer

Time Period (t)	Insecticide Rate (lbs/ac)	Acres Corn	Acres Soybeans	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppn)
1	0	300	300	97,956	1,000	0.010
2	0	300	300	93,058	833	0.010
3	0	300	300	88,851	833	0.010
4	0	300	300	84,409	725	0.010
5	0	300	300	80,447	725	0.010
6	0	300	300	76,425	650	0.010
7	0	300	300	72,767	650	0.010
8	0	300	300	69,129	594	0.010
9	0	300	300	65,782	594	0.010
10	0	300	300	62,492	551	0.010

Sum Period Returns = 791,320

(b) Social Planner

Time Period (t)	Insecticide Rate (lbs/ac)	Acres Corn	Acres Soybeans	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppn)
1	0	300	300	97,956	1,000	0.010
2	0	89	511	90,195	833	0.010
3	0	211	389	87,620	833	0.010
4	0	300	300	85,772	0	0.010
5	0	300	300	82,191	0	0.010
6	0	300	300	78,083	0	0.010
7	0	300	300	74,179	0	0.010
8	0	300	300	70,470	0	0.010
9	0	300	300	66,947	0	0.010
10	0	300	300	63,599	0	0.010

Sum Period Returns = 797,016

[a] Initial State Values:
NCR Infestation = 1000 eggs/row-ft
Population Resistance = 0.01

Table IV.2 Rootworm Control Strategies, Proportion in Extended Diapause = 0.5, NCRt0 = 1,000.[a]

(a) Representative Farmer

Time Period (t)	Insecticide Rate (lbs/ac)	Acres Corn	Acres Soybeans	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppn)
1	0.75	300	300	97,249	1,000	0.010
2	0.75	173	427	91,291	913	0.011
3	0.41	212	388	87,522	913	0.011
4	0	214	386	84,329	423	0.011
5	0	173	427	79,321	0	0.011
6	0	313	287	77,299	0	0.011
7	0	291	309	74,094	0	0.011
8	0	309	291	70,513	0	0.011
9	0	291	309	66,902	0	0.011
10	0	309	291	63,633	0	0.011

Sum Period Returns = 792,157

(b) Social Planner

Time Period (t)	Insecticide Rate (lbs/ac)	Acres Corn	Acres Soybeans	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppn)
1	0.75	300	300	97,249	1,000	0.010
2	0.75	71	529	89,662	913	0.010
3	0	229	371	87,825	913	0.011
4	0	300	300	85,920	0	0.011
5	0	300	300	82,191	0	0.011
6	0	300	300	78,088	0	0.011
7	0	300	300	74,179	0	0.011
8	0	300	300	70,470	0	0.011
9	0	300	300	66,947	0	0.011
10	0	300	300	63,599	0	0.011

Sum Period Returns = 796,131

[a] Initial State Values:

NCR Infestation = 1,000 eggs/row-ft
Population Resistance = 0.01
Crop Rotation = 300Ac csc/300Ac scs

Table IV.3 Summary Results: Enterprise Returns and Terminal Period Values for the Systems State Variables: NCRt0 = 1,000.

NCR Eggs in Extended Diapause (ppn)	0.4		0.5	
Decision maker	RF	SP	RF	SP
Terminal Period Values for the State Variables:				
NCR Infestation (eggs/plant)	551	0	0	0
Resistance (ppn)	.01	.01	.011	.011
Total Insecticide Use (lb)	0	0	441	278
Total corn acres[a]	3,000	2,700	2,584	2,700
Total insecticide/ total corn (lb/ac)	0	0	0.171	0.103
Profit ($)	791,320	797,016	792,157	796,131
Potential welfare gain ($)	5,696		3,974	

[a] Total calculated over 10-year period.

IV.2 Northern Corn Rootworm Control and the Commodity Programs

The results establish the importance of crop rotation as an instrument of corn rootworm control. However, not all corn production takes place in a corn-soybean system (CARD, 1988). Furthermore, it has been suggested that the U.S. farm programs provide a disincentive for optimal pest management strategies by mandating large corn acreages, and imposing rigid crop rotations on farms (Taff, 1989). In particular, the conditions of the commodity programs establishes a strong incentive to maintain the farm's "corn base", (Glauber, 1988), the preservation of which may be incompatible with optimal rootworm management. To investigate the possible effects of the farm program on rootworm control strategies, an additional constraint is imposed on the RF's problem which restricts corn acreage to minimums of 50, 75 and 100 percent of total farmland. The results, reported in Tables IV.4 and 5 indicate that the restrictions on crop rotation can lead to a greater use of soil insecticide.

In continuous corn, the pest infestation remains relatively high throughout the 10-year time horizon, lending support to the comment by Sutter (1989) that corn rootworm is a "man made pest" - which have become more prevalent as participants in the Government farm programs grow continuous corn.

The suggestion that the farm program may actually encourage environmentally damaging farm practices and discourage low-input or sustainable agriculture, (Daberkow and Reichelderfer, 1988; Taff, 1989), appears to be supported by the results. The average insecticide application rate increases rapidly as the corn base expands from 50 to 100 percent of total farmland. Moreover, there is an almost 6-fold increase in the terminal period value for population resistance as the corn base expands from 50 to 100 percent. However, the absolute level of population resistance remains relatively small, with less than 7 percent of the NCR larvae population being resistant to the insecticide after 10 years.

To compare solutions for rootworm control in continuous corn, the optimal control problem was solved for both the RF and the SP (Table IV.6).[19] The SP's choice of insecticide rates are influenced not only by current period losses, but by the future crop damage potential of the NCR population. The effect of future losses on the SP's application rate of soil insecticide is most clearly evident in the terminal period insecticide choice. Even accounting for the gradual decline in application rates observed over the time horizon, the final period application rate of 3.99 lbs/acre is less than previous period application rates. The difference in application rates largely reflects the absence of penalties for future losses implied by the next periods pest population and increasing insecticide resistance in the calculation of the optimal final period pesticide rate.

The factors which influence the rate of insecticide application were outlined in more detail elsewhere, (Regev, Shalit and Gutierrez,

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[19] The continuous corn model effectively reduces the pest management problem to a single control variable (insecticide) problem in correspondence with the model developed by Regev, Shalit and Gutierrez (1983) for Alfalfa Weevil control.

1983; Briggs, 1989). There it was found that the question of whether the SP used more or less insecticide than the RF could not be resolved *a priori*. However, it was suggested that in the situation where pesticide applications do not induce rapid resistance development, but that the penalties for future damage implied by the population growth function were sufficiently high, that the SP may use greater amounts of pesticide than the RF. The results obtained for the two decision makers in the control of corn rootworm in continuous corn are summarized in Table IV.7.

The comparison of the soil insecticide application rates for the two decision-makers in continuous corn reveals that the pesticide application rates are higher for the SP. Over the 10-year period, the SP applies 36,504 lbs of soil insecticide compared to 26,172 lbs by the RF, giving an average rate of application over all corn acres of 6.1 and 4.4 lbs/acre, respectively. The terminal period value for NCR infestation is higher for the RF, whereas the terminal value for pesticide resistance is higher for the SP. However, in evaluating pesticide choices, the SP calculates that the benefits of soil insecticide use in suppressing the NCR population exceed the losses implied by the increase in pesticide resistance. This estimation is revealed by the value of the objective function for the SP of $604,985 which is $2,944 higher than the RF's profit function.

This result is probably of most interest because it runs counter to the belief that regional coordination would reduce insecticide use. Not surprisingly, some important caveats apply. First, the RF is assumed to select insecticide applications rates which satisfy the marginal conditions for optimality, and not to obey a discrete "if-then-else" rule for treatment in which case the overall application rates may be different. Second, and perhaps more importantly, the model does not consider the environmental costs of soil insecticides which would tend to reduce the SP's optimal application rate vis a vis the RF's solution. The comparative results obtained for the single control variable model, do however, serve to highlight the importance of problem specific features in determining outcomes of pest management problems.

Table IV.4 Enterprise Returns and Terminal Period Values for the Representative Farmer under Crop Rotation Restrictions, Diapause PPN = 0.4, NCRt0 = 1500.

NCR Eggs in Extended Diapause	0.4			
	Corn Base (%)			
	Free	50	75	100
Terminal Period State Values:				
NCR Infestation (eggs/plant)	142	589	1,054	1,347
Resistance (ppn)	.012	.012	.029	.066
Total Insecticide Use (lb)	676	861	8,842	26,172
Total Corn Acres	2,700	3,000	4,500	6,000
Total Insecticide/ total corn (lb/ac)	0.25	0.29	1.97	4.36
Profit ($)	793,393	786,986	720,410	602,041
Profit in absence of NCR ($)	809,846	809,846	782,638	734,382
Profit loss due to NCR (%)	2.0	2.8	8.0	18.0

Table IV.5 Enterprise Returns and Terminal Period Values for the Representative Farmer under Crop Rotation Restrictions, Diapause PPN = 0.5, NCRt0 = 1,500.

NCR Eggs in Extended Diapause	0.5			
	Corn Base (%)			
	Free	50	75	100
Terminal Period State Values				
NCR Infestation (eggs/plant)	0	371	1,054	1,347
Resistance (ppn)	.013	.018	.03	.066
Total Insecticide Use (lb)	1,199	2,583	9,184	26,172
Total Corn Acres	2,616	3,000	4,500	6,000
Total Insecticide/ total corn (lbs/acre)	0.46	0.86	2.03	4.36
Profit ($)	790,144	778,428	719,839	602,041
Profit in absence of NCR ($)	809,846	809,846	782,638	734,381
Profit loss due to NCR (%)	2.4	3.9	8.0	17.8

Table IV.6 Rootworm Control the Continuous Corn Scenario, NCRt0=1500.[a]

(a) Representative Farmer

Time Period (t)	Insecticide (lbs/ac)	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppm)
1	4.77	73,858	1,500	0.010
2	4.44	71,231	1,378	0.013
3	4.35	67,936	1,345	0.015
4	4.32	64,594	1,336	0.019
5	4.31	61,355	1,334	0.024
6	4.30	58,255	1,335	0.029
7	4.29	55,298	1,337	0.036
8	4.29	52,480	1,339	0.044
9	4.28	49,794	1,343	0.054
10	4.27	47,233	1,347	0.066

Sum Period Returns = 602,041

(b) Social Planner

Time Period (t)	Insecticide (lbs/ac)	Discounted Period Return ($)	NCR Infestation (eggs/plant)	NCR Resistance (ppm)
1	6.57	73,562	1,500	0.010
2	6.53	71,228	1,332	0.013
3	6.50	68,164	1,266	0.016
4	6.48	64,956	1,237	0.021
5	6.45	61,779	1,224	0.026
6	6.40	58,698	1,221	0.033
7	6.30	55,743	1,222	0.042
8	6.07	52,925	1,229	0.053
9	5.55	50,255	1,242	0.066
10	3.99	47,670	1,267	0.083

Sum Period Returns = 604,984

[a] Initial State Values:
NCR Infestation = 1500 eggs/plant
Population Resistance = 0.01
Crop Rotation = 600 ac ccc

Table IV.7 NCR Management Strategies in Continuous Corn - Representative Farmer vs Social Planner.

	RF	SP
Terminal Period Values:		
NCR Infestation	1,347	1,267
Resistance	0.066	0.083
Total Insecticide Use (lbs)	26,172	36,504
Total Corn Acres	6,000	6,000
Average Insecticide Rate (lbs/ac)	4.36	6.08
Present Value of Profit ($)	602,041	604,984

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