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PUBLIC POLICIES FOR PEST CONTROL: TOWARD AN ANALYTICAL FRAMEWORK

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Abstract

In dryland wheat farming in Western Australia, the way in which a particular paddock responds to fertilizer application can vary markedly from year to year. Uncertainty about grain yield arises because inputs which can be controlled by the farmer, such as the rate of applied nitrogen, interact with exogenous factors such as climate, soil physical and chemical factors, and diseases, weeds and pests. Thus, fertilizer decisions have to be based on farmers' subjective beliefs about yield and its determinants.

Farmers may have access to information which reduces production uncertainty before the time of the fertilization decision. For instance, soil tests which measure soil nutrient levels have been available to farmers in Western Australia for several years. While they have been widely adopted in determining rates of phosphorus and potassium fertilizers, their usefulness in making nitrogen fertilizer recommendations is unclear. Recently, it has been claimed by CSBP that nitrogen applied in accordance with soil test results and the CSBP soil testing model was highly profitable, even in areas experiencing poor seasonal conditions (Wesfarmers Ltd Annual Report 1985).

The aim of this paper is firstly to analyse existing opportunities for farmers to make decisions on fertilizer application rates contingent on available information about soil nutrients and seasonal conditions; and secondly to evaluate the potential value of further research on soil chemistry and plant nutrition to improve fertilizer decision making.

To estimate the value of the information on soil nutrient status, it is necessary to compare the value of the optimal strategies, given utilisation of the information with value of the optimal strategies if it is ignored. An appropriate framework for this is Bayesian decision theory (Anderson, Dillon and Hardaker 1985). This theory takes account of the precision of the information that is available, and so is a useful basis for comparing costs and benefits of different sources of information, such as soil test data **vis-à-vis** paddock histories.

Introduction

Pests can be defined as naturally occurring populations of plants or animals which inflict damage on one or more forms of economic activity. In the words of Hueth and Regev (1974), they are a "detrimental renewable resource". The main concern in this paper will be with those pests which raise the costs of agricultural production because of the damage they cause. For convenience such pests will be referred to as agricultural pests.

It is quite common for governments to establish agencies to oversee and/or implement public pest control practices. In Western Australia the agency directly responsible for most aspects of public pest control policy is the Agriculture Protection Board of Western Australia (APB), but other agencies such as the Department of Conservation and Land Management (CALM) also share responsibility for the certain public pest control policies (eg, licensing of kangaroo shooters).

According to Roberts et al (1986), the "APB is responsible for the coordination and administration of the control, prevention and eradication of noxious weeds and vermin in the State." In 1987/88, the APB spent $12.7

million of public funds on pest control in Western Australia (APB, 1988). Three major types of pests fall within the ambit of the APB's responsibility, namely :

Plant Pests (or Weeds)
(eg, skeleton weed, wild oats, doublegee, blackberry, Noogoora burr, Saffron thistle, etc.)
Insect Pests
(eg, weevils, locusts, grasshoppers, european wasps, argentine ants)
Vertebrate Pests
(eg, rabbits, kangaroos, dingoes, foxes, rats, feral pigs, donkeys, camels, and goats, emus, starlings, parrots, cockatoos)

Note that while all three categories of pest inflict damage on agricultural production, a distinctive characteristic of at least some vertebrate pests is the commercial value of harvested animals. For instance, some pests such as kangaroos, goats, and even rabbits are at least partly controlled by professional hunters because their hides and/or carcases command a sufficiently high price to induce commercial harvesting by parties who do not suffer any damage costs from these pests. This alternative control method is not an option for control of plant or insect pests which have no commercial value in their own right. In the absence of government policy, only those agricultural producers who suffer damage from such pests have a private economic incentive to carry out control measures. Irrespective of the type of pest involved, there is no guarantee that the private incentives to undertake control measures will in aggregate result in a level of control which is socially optimal.

The ultimate aim of this research project is to determine for various different types of pest :

(a) What level of pest control is socially optimal? (from the point of view of economic efficiency)--in particular, does the resulting optimal steady-state pest population involve a boundary solution? (Eg, total eradication of an established pest; or alternatively no control at all.)
(b) Whether government intervention in pest control is warranted on grounds of economic efficiency; and if so, then:
(c) What types of public pest control policies are likely to be most efficient? (Ie, what form should government intervention take?)
(d) Where a tax/subsidy policy is indicated, what are the determinants of the optimal level of such policies?

In this paper, we take no more than the first tentative and exploratory steps toward addressing these issues. Specifically, in the next section of this paper, we outline some of the important properties of different types of pests which are relevant to the above questions. Then in the following three sections, we propose three alternative analytical approaches which might be used to further develop an appropriate conceptual framework.

Issues in the Appropriate Role for Government in Pest Control

Pest Growth Rates

Like all biological natural resource stocks, any attempt to manage agricultural pests needs to take account of intertemporal considerations because any pest control measures will have both immediate effects and long term effects due to the so called stock externality. As the work of Clark (1976) shows, the ratio of the discount rate to the intrinsic growth rate of the pest population is an important determinant of private and socially optimal levels of exploitation of any renewable resource.

Pest Mobility

Benefits from controlling agricultural pests cannot be fully appropriated by individual farmers because pests move across farm boundaries. Due to external effects caused by pest mobility, private and social optima diverge with individual farmers likely to apply a lower than socially-optimal level of control. To date, most analytical studies of pest control in the economics literature have made one of two polar assumptions about pest mobility. For pests with relatively low mobility, the pest population has been treated as self-contained (ie, assume zero mobility). This assumption is patently non-sustainable for other pests such as insect pests, and in such cases it has been common to assume that the pest is perfectly mobile (ie, to ignore the stock externality effect and treat the pest population as common-property from the point of view of the individual land owner.

Other Issues

The main concern in this paper will be with the above two issues, and other issues which also are important determinants of optimal pest control policies will be put aside, at least for the time being. Such issues include the nature of damage functions (eg, see Tisdell 1985a), the nature of control cost functions, environmental externalities associated with chemical control methods, optimal management of the public good of pest susceptibility to control measures (see Hueth and Regev 1974), and conservation of genetic diversity as well as of specific wildlife species.

A Bioeconomic Analytical Framework

Probably the most highly developed analytical models to determine policies for the optimal management of naturally-occurring biological resources can be found in the literature on fisheries economics. The basic features of bioeconomic models used in this literature form the starting point for the analytical framework developed in this section.

However, because of the differences discussed above between the harvesting of fish and the control of agricultural pests, bioeconomic models of fishery management need to be modified before they can be applied to the analysis of public pest control policies. In this section, a standard but rather simplistic fishery management model will be adapted to incorporate a damage function reflecting the fact that pest populations cause negative benefits. In addition, the growth function of a self-contained population commonly used in fishery bioeconomic models will be modified so as to incorporate the effects of pest mobility as they affect an individual land holder. Changes also will be made to the conventional assumptions made about cost of effort relationships to make them more applicable to the control of land-based pests.

The bioeconomic model on which this section is based is the widely used but highly simplified Schaefer model of fisheries management. This model is a steady state model which in effect uses the technique of comparative statics to compare net social benefits of alternative sustainable levels of the biological population. In textbooks on fisheries management, this approach is used to illustrate the determination of the steady state fish stock which will maximise sustainable economic rent. However, it has been pointed out, inter alia, by Clark (1976) that the determination of the optimal fish stock should be treated as a problem in capital theory. No such modification to the Schaefer model is presented here because derivation of a general analytical solution for the optimal pest population using capital theory techniques, in conjunction with other modifications described below, has proved to be mathematically difficult, if not intractable. As the purpose of this preliminary exercise is simply to illustrate some of the principles involved, numerical analysis of the simpler standard Schaefer model using a microcomputer spreadsheet was resorted to in order to generate the results presented below.

Following Schaefer (1957), the biological production function is defined by :

$$X = k(1 + ce^{-rt})^{-1} \quad (1)$$

and:

$$dX/dt = rX(1 - X/k) = F(X) \quad (2)$$

where:

X = population stock size

k = environmental carrying capacity (ie the maximum size or "climax" level of the population stock)

r = the intrinsic population growth coefficient

Note that $F(0) = F(K) = 0$, and that $F'(X) > 0$ for $0 < X < K$.

Biologists frequently argue that this simple mathematical equation cannot possibly represent such a complex process as the growth of a biological population in a realistic and comprehensive manner. Unfortunately, more realistic mathematical analogues for actual growth processes tend to be difficult to incorporate into an analytical framework in a mathematically tractable way. However, one caveat that must be acknowledged is the inadequacy of the above compensatory growth function as a description of populations that exhibit depensatory growth. To the extent that a pest population can be exterminated by reducing it below some minimum critical mass, any compensatory growth function, including the above, will over-estimate the marginal cost of reducing the pest population to very low levels. This caveat is more likely to be important for vertebrate pests than for plant and insect pests.

If the above caveats can be disregarded, the Schaefer biological production function might adequately represent growth of a self-contained population, but it is manifestly unsatisfactory as a description of growth of a population subject to exogenous recruitment due to immigration of pests from bordering populations where $F(0) > 0$. To capture pest population growth as perceived by an individual farmer, it was assumed that total recruits to the pest population resident on a particular property comprise two parts. The endogenous component is given by the standard Schaefer biological production function in equation (2) above. In addition the exogenous component is assumed to equal $\alpha.r.(k-X)/4$ where α is a pest mobility coefficient. Note that for a=1, hereafter referred to as "complete" pest mobility, when $X = 0$ this exogenous component $= r.k/4$ (which is the maximum sustainable yield for a self-contained population). This exogenous component also monotonically reduces to zero as X tends to k.

To sum up, growth F(X) of a mobile pest population on an individual property subject to exogenous immigration is assumed to be determined by:

$$F(X) = rX(1 - X/k) + \alpha \cdot r \cdot (k - X)/4 \quad (3)$$

To maintain the pest population at some steady state level, $\hat{X}$, the annual harvest of pests, $\hat{H}$, must equal F(X). If this condition is imposed, then it is possible to use this growth function to determine the optimal level of pest control for an individual farmer, hereafter referred to as the "private optimum". To derive the equivalent "social optimum" level of pest control, the pest mobility coefficient was set equal to zero, thereby assuming away the externality. Whether the above functional form is a realistic representation or not is an empirical question, and further investigation of this issue is planned.

Another unresolved issue is the nature of the relationship between the pest control variable(s) and H, the number of pests harvested. For the purpose of this exercise, it will be assumed that the cost of pest control

is proportional to ϕ, the proportion of total pests (ie extant population plus recruits) harvested as follows :

$$TC = 100 \cdot c \cdot \phi$$
$$= 100 \cdot c \cdot H/(H+X)$$

where:

c = control cost per per-cent kill.

Again the reality of this assumption will be the subject of further investigation. For the moment it suffices that this assumption generates cost functions which are generally in accord with a priori expectations.

Finally, the level of damage caused by the pest was assumed to be proportional to the level of the pest population. While this is a convenient assumption in terms of analytical simplicity, identification of a more general functional form which can encompass actual damage functions for most types of pest clearly ought to be an objective of further research.

Given the above assumptions, the problem can be expressed as: Choose the steady state pest population, $\hat{X}$, so as to maximise:

$$\Pi = p \cdot H - d \cdot X - 100 \cdot c \cdot H/(H + X)$$
$$\text{subject to } H = F(X) .$$

where:

p = returns per head (if any) from harvesting the pest
c = level of damage caused by the pest.

Some preliminary results are presented in Figures 1 to 9 to give some insights into the potential problems and promise of this approach. Figure 1 simply illustrates the difference in the total cost function of controlling a pest which is not mobile ("social cost") with that for one which is perfectly mobile ("private cost"). Note that, in contrast to a self-contained population, the marginal cost of further reductions in the steady state pest population starts to rise sharply as total eradication is approached.

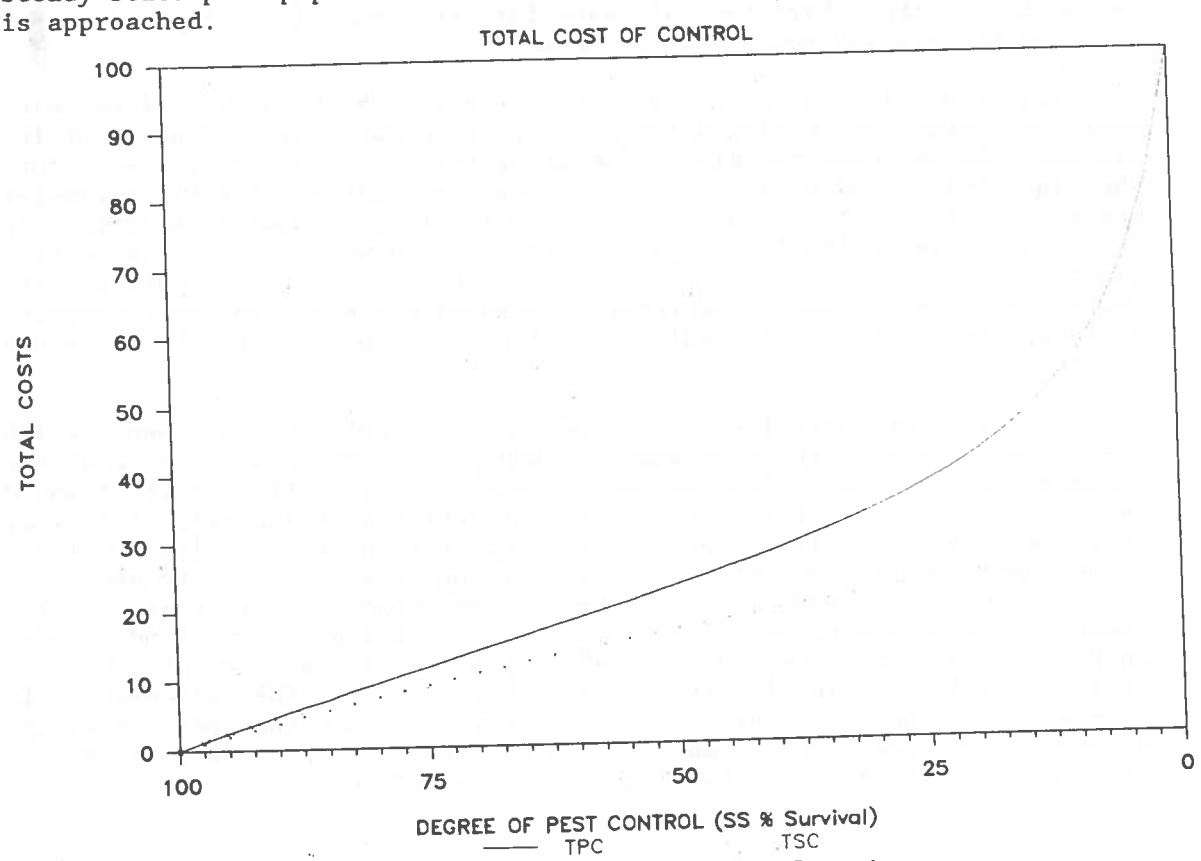

Figure 1: Difference in total cost function

Figures 2 and 4, and 3 and 5 illustrate the shape of sustainable benefit and cost functions for the social and private cases respectively. Figures 2 and 3 apply to "rats", a hypothetical vertebrate pest characterised by a high intrinsic growth rate (200 per cent), a relatively high level of damage ($4 per one-per-cent of climax population level), and zero financial returns from harvesting the pest. Notwithstanding the rising marginal cost to an individual land owner of total eradication, it is both socially and privately optimal to do so. The same relationships are again illustrated in Figures 4 and 5 for "kangaroos", another hypothetical vertebrate pest characterised by a lower intrinsic growth rate (30 per cent), lower damage levels ($0.50 per one-per-cent of maximum population), but positive returns from harvesting ($10 per animal killed).

In this case, interior solutions involving only partial control are both socially and privately optimal. Moreover, the results suggest that a higher level of control would be optimal for a land owner suffering from immigration by a mobile pest than would be the case for a self-contained population. Clearly this result involves a fallacy of composition if the farm in question is representative of other farms in the district, and if there are no pest refuges. On the other hand, where wildlife refuges do exist, it is possible that the rate of immigration is independent of the collective extent of pest control practised by all land owners. Note also that the solution above does not take account of any conservation value placed on kangaroos. The remaining figures only show net social and net private benefits as this suffices to identify optimal levels of pest control. Note that not all of these functions are monotonic, so total rather than marginal functions are depicted.

The only assumed difference between "mice" and "rats" is in the level of damage caused (mice are assumed to cause only $0.50 damage per one-per-cent of the climax population level). From a comparison of net benefits for rats in Figure 6 and net benefits for mice in Figure 7, it can be seen that, whereas eradication of rats is both privately and socially optimal, both the private and social benefits of any control at all of mice fall short of the costs of doing so. Hence, no public pest control policies are called for in these hypothetical cases for rats and mice since in each case the private and social optima coincide.

Figure 8 illustrates the case of "dingoes", which differ from mice only in terms of having a lower intrinsic growth rate (30 per cent for dingoes, 200 per cent for mice). Comparing Figures 7 and 8 reveals that the intrinsic growth rate of the pest population is a key parameter because, although the socially optimal policy is a boundary solution in each case, this optima for dingoes is eradication whereas it is no control for mice. Moreover, in contrast to rats, it will not be optimal for individual land owners to attempt to eradicate dingoes on their property in isolation, even though eradication of a self-contained population would be socially optimal.

A subsidy on control costs is one obvious policy instrument which might be introduced in an attempt to induce all land holders to eradicate dingoes, but it is not clear whether it would be successful or if it would be the most cost effective method of achieving this goal. If it were feasible to effectively convert dingoes into rats by taxing land holders $3.50 per one-per-cent of the dingo-carrying capacity of their property, then eradication should result. The common practice of pest control agencies of declaring certain pests "noxious", and of fining land holders when such pests are detected on their property is a variant on this approach which may involve lower monitoring costs. Another alternative is to remove the root cause of the externality by tackling pest mobility directly. The erection and maintenance of "vermin proof" fences at public expense are practical examples of this policy option.

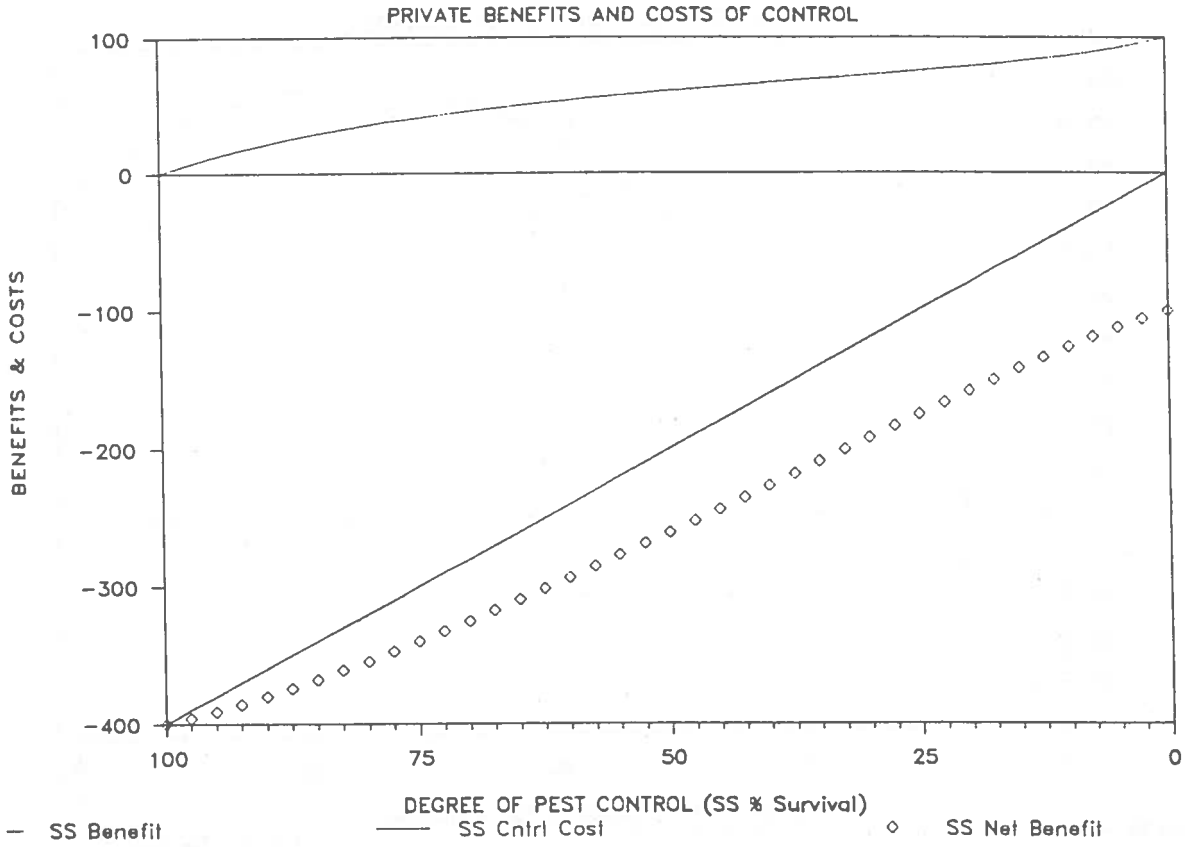

Figure 2: Pest Control--Rats

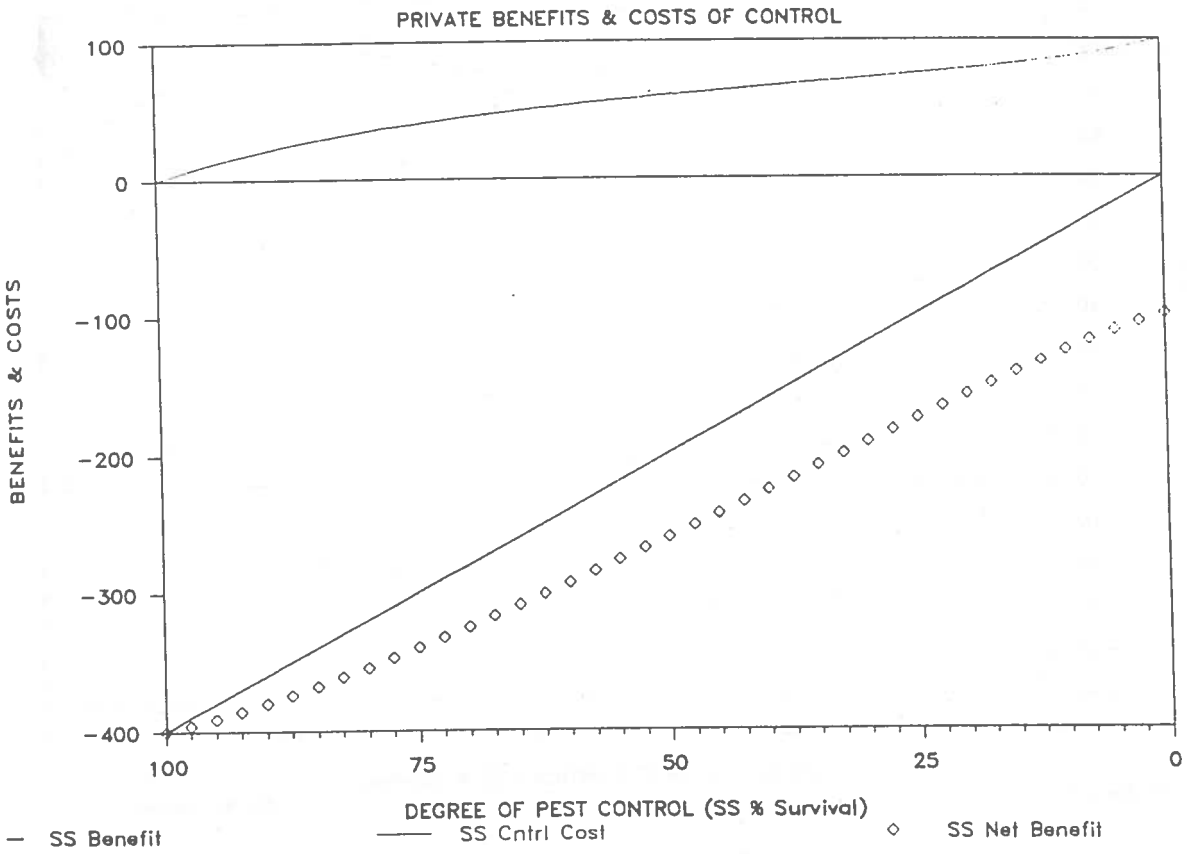

Figure 3: Control of Rats

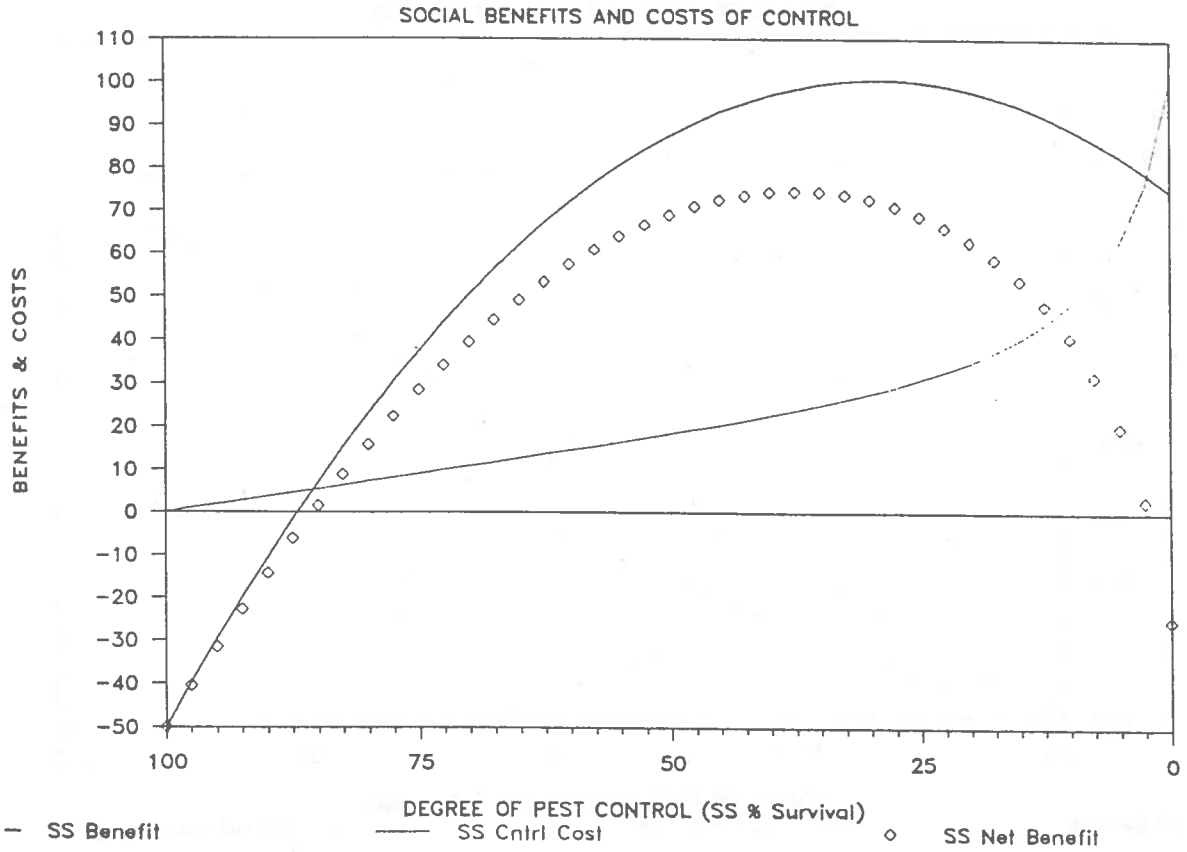

Figure 4: Pest Control--Kangaroos

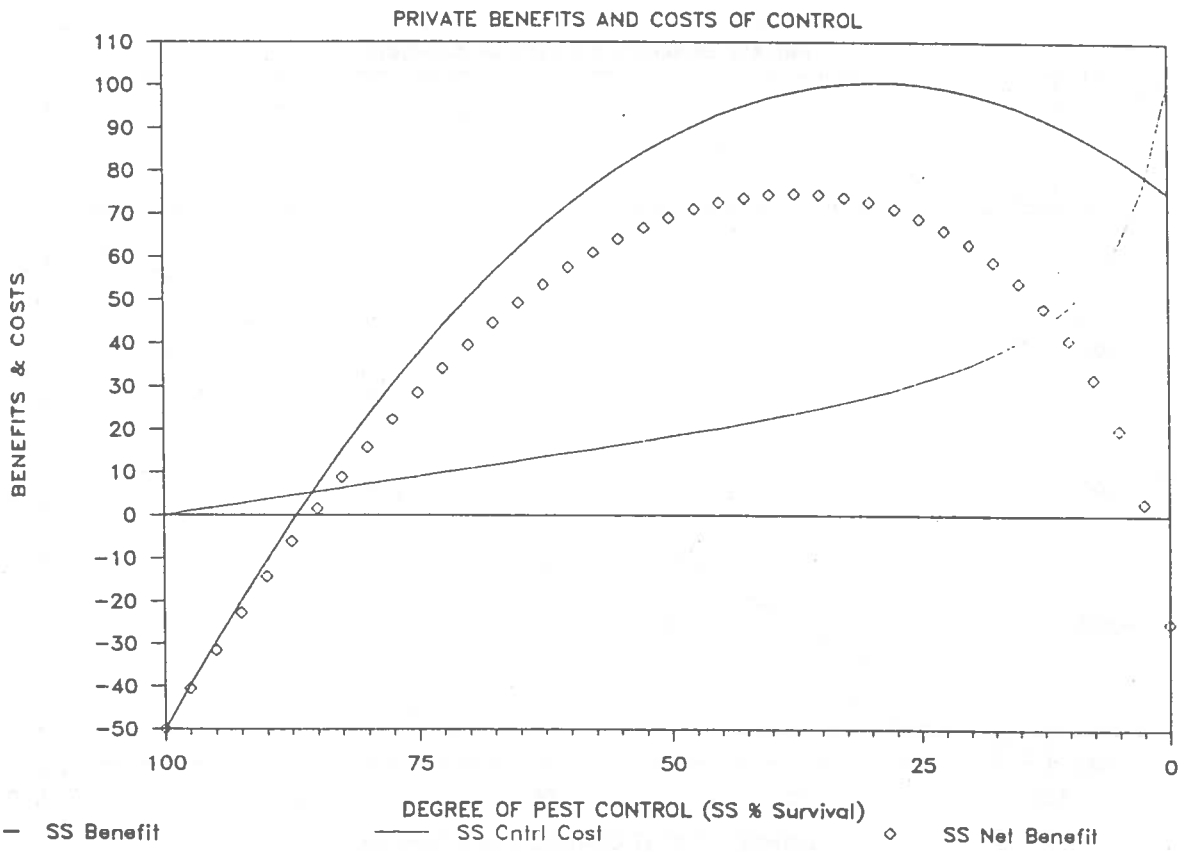

Figure 5: Pest Control--Kangaroos

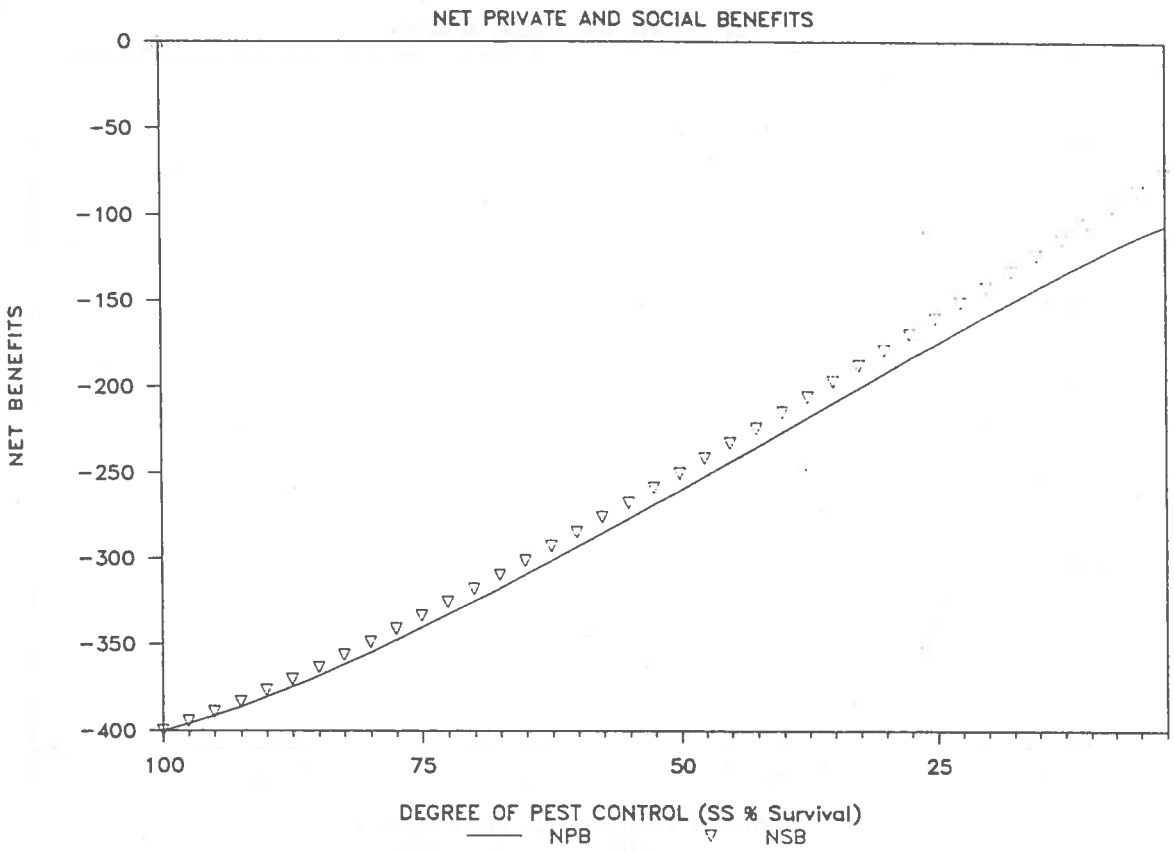

Figure 6: Pest Control--Rats

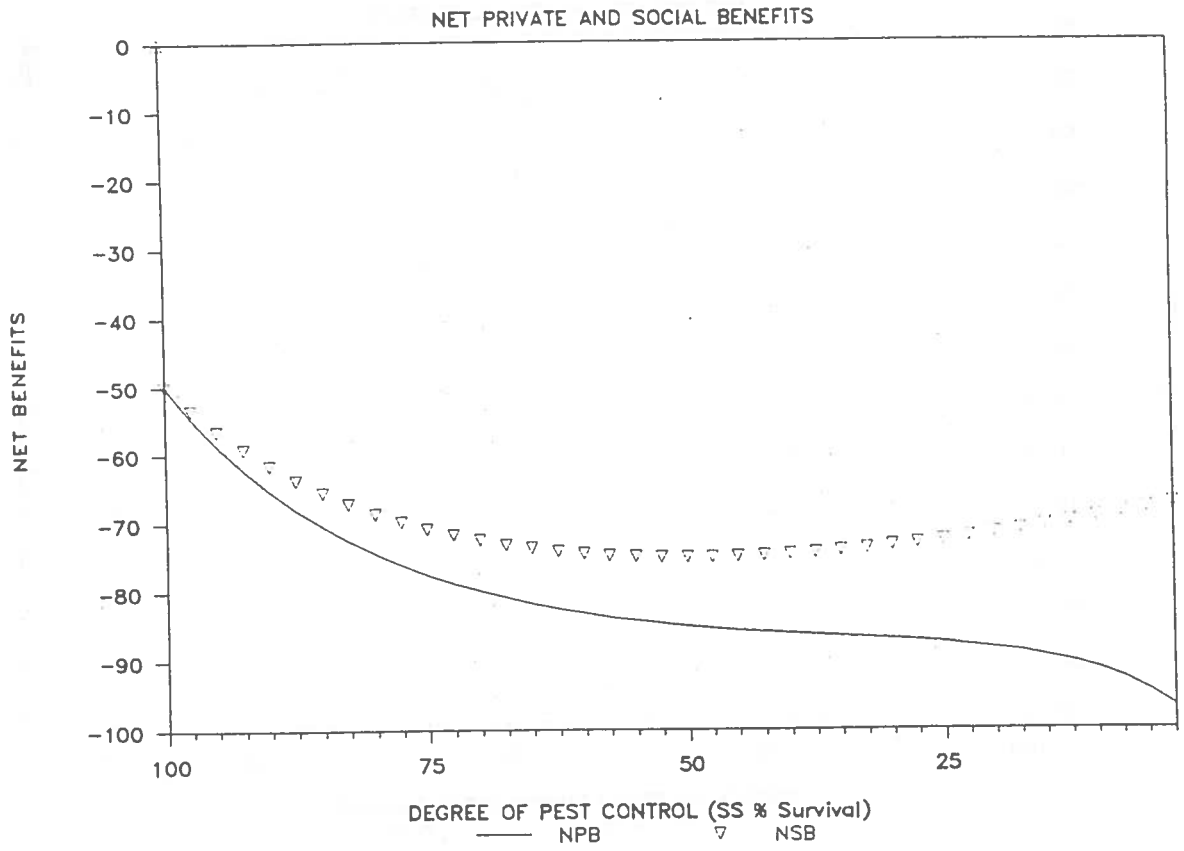

Figure 7: Pest Control--Mice

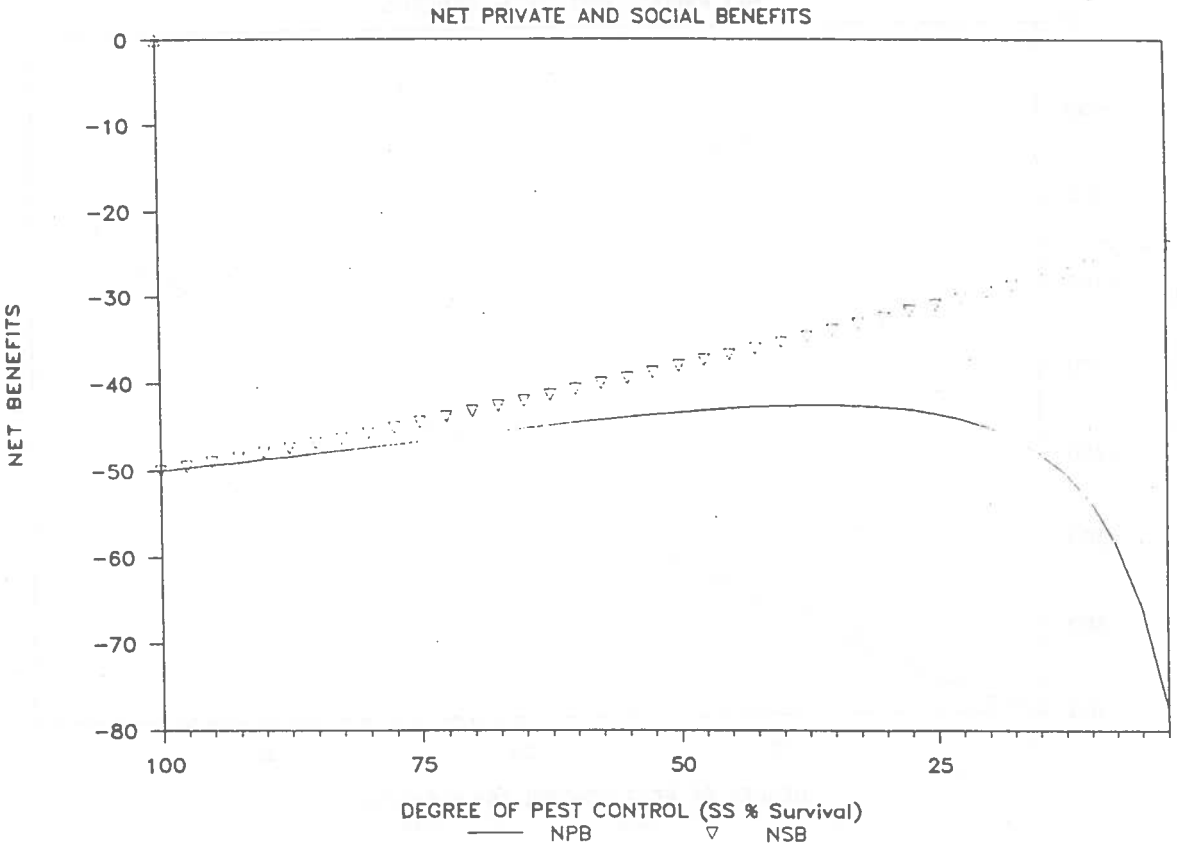

Figure 8: Pest Control--Dingoes

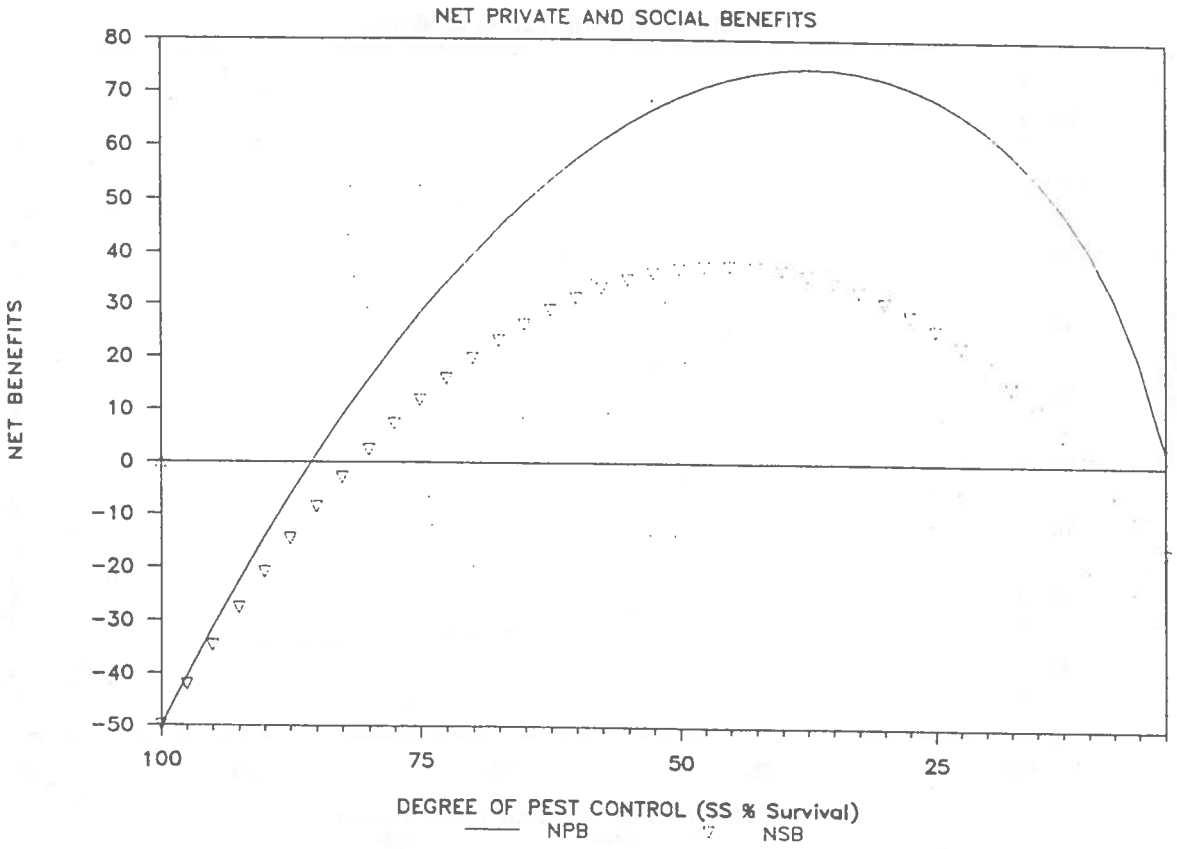

Figure 9: Pest Control--Kangaroos

Finally, in Figure 9 we again return to the case of the kangaroo which is distinguished from dingoes by the commercial value of harvested kangaroos. As noted previously, in this case, while an interior solution (ie, partial control) is both socially and privately optimal, the latter option involves a higher level of control than the former. In addition to the policy instruments discussed above, other options are also available to policy makers to ensure that the social and private optima for kangaroos and similar pests coincide. One is to pay a bounty, or in the above case, levy a tax on all kangaroos killed. Where the private optimal level of control is less than the social optima, another option would be to foster open-access exploitation of the pest population by, for example, giving hunters the right of trespass in order to hunt the pest.

In conclusion, it needs to be stressed that any and all of the above conclusions are at best speculative, and at worst misleading if further research reveals that some of the assumptions from which they ultimately derive are ill-founded in fact.

A Game Theoretic Aanalytical Framework

An alternative approach is to view competition among a few farmers for control of a pest as similar to oligopoly, the competition among a few firms for access to a market. Decisions are interdependent and each farmer must conjecture about the decisions of other farmers in order to make a decision himself. The dissimilarity to an oligopoly is that competition is not over market prices and shares but over stocks of pests.

A farmer manages a proportion of the total pests in his neighbourhood. How much control he can exert depends on the mobility of the pests and the size of his farm relative to the size of the neighbourhood. For a small farmer, the degree of common property will be large. For a large farmer the degree of common property may be small. He seeks to maximise the value of his initial stock of pests which equals the net present value of any direct benefits from harvesting plus indirect benefits of producing crops, minus the costs of the effort expended in harvesting.

$$j(x_0) = \underset{h}{\text{Max}} \int_0^{\infty} e^{-\delta t} \left[p_h h_t + p_y y(x_t) - p_e e(h_t, x_t) \right] dt; \qquad (4)$$

where j is the net present value of the farm; x is the stock of pests on the farm; h is harvest; y is production of crops; e (not to be confused with exponential operator e) is the effort expended on the harvest; p_h, p_y and p_e are prices; and δ is the interest rate.

The corresponding decision problem for neighbouring farmers could be denoted by replacing lower case letters with capital letters in equation (4). The neighbours' stock of pests would be X, for example. Total pests in the neighbourhood would be X + x.

The stock of pests can change over time. The rate at which pests reproduce and grow within a limited carrying capacity depends on population density. The rate at which they migrate from more to less densely populated areas depends on mobility. And the rate at which they are harvested is controlled, of course, by the farmer.

$$\dot{x}_t = g(x_t, r, k) + m(x_t, X_t, k, K, v) - h_t \; ; \qquad (5)$$

where $\dot{x}$ is the change over time in the stock of pests on the farm; g is biological growth; m is the net migration onto the farm; r is the

intrinsic growth rate for a farm with unlimited carrying capacity; k and K are carrying capacities of pests for the farm and neighbouring farms, respectively; and v is the velocity at which the pests migrate.

Migration

Migration has been studied extensively in the mathematical ecology literature. Surveys include Levin (1976) and McMurtrie (1978). For pest populations, migration will take the form:

$$m(x_t, X_t, k, K, v) = 2v[X_t/K - x_t/k] \ . \qquad (6)$$

Any difference in densities is dispersed over the neighbourhood at the rate 2v.

Optimality Conditions

The righthand side of equation (5) is the net quantity of pests eliminated in time t. Growth and migration add to the stock of pests; harvest depletes it. Multiplying the net quantity by an imputed price gives the total cost paid for the pests. This is total user-costs. Subtracting total user-costs from total revenue of harvest plus total revenue of crop production minus total costs of effort gives a dynamic measure of profit at time t.

$$\pi(h_t, x_t, \lambda_t) = p_h h_t + p_y y(x_t) - p_e e(h_t, x_t)$$
$$+ \lambda_t[g(x_t, r, k) + 2v[X_t/K - x_t/k] - h_t] \ ; \qquad (7)$$

where π is dynamic profit at time t and λ is the imputed price or marginal user-cost of pests. π is the current-value Hamiltonian and λ is the current-value costate. Neither is discounted; both are denominated in dollars at time t.

Because, at the optimum, the costate equals the marginal return of future costs saved by harvesting the pests today, dynamic profits capitalised at the interest rate equals the net present value of the farm, $\pi(x_t)/\delta = j(x_t)$. Thus, maximizing the Hamiltonian in each time period is equivalent to maximizing the net present value of the farm in equation (4) subject to the change in the pests population in equation (5).

If functions y and g are concave and e is convex, the Hamiltonian is concave and the optimum is characterised by first-order conditions for harvest, pests and marginal user-costs plus an initial condition on pests and a terminal condition on marginal user-costs.

$$\partial\pi/\partial h_t = 0 = p_h - p_e \partial e/\partial h_t - \lambda_t \ ; \qquad 0 \le t \qquad (8a)$$

$$-\partial\pi/\partial x_t = \dot{\lambda}_t - \delta\lambda_t = -p_y \partial y/\partial x_t + p_e \partial e/\partial x_t$$
$$- \lambda_t\left[\partial g/\partial x_t + 2v(\{dX_t/dx_t\}/K - 1/k]\right]; \ 0 \le t \qquad (8b)$$

$$\partial\pi/\partial\lambda_t = \dot{x}_t = g + 2v[X_t/K - x_t/k] - h_t \ ; \qquad 0 \le t \qquad (8c)$$

$$x_0 \text{ is given} \ ; \qquad (8d)$$

$$\lim_{t\to\infty} \lambda_t = 0; \qquad (8e)$$

where dX_t/dx_t is the conjectural variation: the conjecture by the farmer about his neighbours' variation in pests in reaction to his own changes. Because the pests are owned in common, conjectures about changes in pests, not market prices or market shares, are important.

Condition (8a) equates the marginal revenue from harvesting to the marginal cost of effort plus the marginal user-cost of pests. If there were open access, there would be no social control of the pests and the marginal user-cost would be zero. The harvesting decision would maximise current profits with no regard for the future. If there were partially limited access, the marginal user-cost would be non-zero but less than the full cost of the pests because the future would be discounted too heavily.

Discounting of the future, depending upon the degrees of access to the pest, is described by condition (8b) which can be rearranged into a form somewhat like that of condition (8a).

$$0 = \left[p_y \partial y/\partial x_t - p_e \partial e/\partial x_t\right] / \left[\delta - \dot{\lambda}_t/\lambda_t - \partial g/\partial x_t - 2v(\{dX_t/dx_t\}/K - 1/k\right] - \lambda_t \qquad (8b')$$

The marginal revenue of crops and the marginal cost of effort with respect to pests are capitalised by an appropriate discount rate because a change in the stock of pests affects all future stocks. Hence, the marginal user-cost equals the present value of all these effects. Capital gains, growth and immigration can make pests relatively more costly. The appropriate discount rate is the interest rate less the rate of capital gains, the marginal growth rate and the marginal migration rate.

The marginal migration rate in the denominator of equation (8b') is the key to determining the degree of common property. If the velocity, v, is zero, the pests are private property, the future is not overly discounted, because the marginal user-cost is as large as possible and the pests are optimally managed.

If the velocity is positive, however, there are several possibilities. A farmer who assumes his neighbours will not respond to a change in his stock would set the conjectural variation to zero. A Cournot-Nash equilibrium would result which depends upon the carrying capacity of the farm. If the farm is very large, the pests are again private property. But if the farm is small, the degree of common property can be great. In the limit, open access with a farm size approaching zero drives the discount rate to infinity and the marginal user-cost to zero.

A farmer who assumes his neighbours will reduce their stock as he increases his would set the conjectural variation negative. The degree of common property is exacerbated as the farmer tries to push pest control onto his neighbours.

A farmer who assumes his neighbours increase their stock as he does would set the conjectural variation positive. The degree of common property will be ameliorated. Indeed, an equilibrium equivalent to the private property equilibrium could be achieved if, for example, the farm is one-fifth of the neighbourhood, neighbouring farms are four-fifths and the conjectural variation is set to 4. Further, if the five farms are identical with the same level of stock and if each farmer forms the same conjectural variation, then $\dot{X} = 4\dot{x}$ and the actual variation is $\dot{X}/\dot{x} = 4$. The only conjectural variation consistent with the actual variation is 4 and, conversely, other conjectural variations such as zero are inconsistent.

The fact that consistent conjectures eliminate the common property problem might imply that taxes, subsidies and quotas are unnecessary. All that might be required is to convince each farmer that every other farmer behaves as he does. If he undercontrols the pests, so will they. Unfortunately, the consistent conjectures equilibrium poses a prisoners' dilemma. Even if he controls the pests his neighbours might not and his farm would be reinfested. A public policy to solve the common property problem through a consistent conjecture equilibrium would require a great deal of moral suasion.

From this, it seems reasonable to model the common property problem as a Cournot-Nash equilibrium with zero conjectural variations, as is typical in the natural resources literature. It is still important, however, to model migration and competition among a few farmers to determine the degree of common property. The optimal tax or subsidy is the hypothetical marginal user-cost of privately controlled pests minus the actual marginal user-cost to the farmers. The usual assumption that the marginal user-cost to the farmers equals zero is true only for open access.

A Dynamic Programming Application

Most agricultural pests move across farm boundaries during some part of their life cycle. Thus they possess the characteristics of a negative common property resource. An individual farm firm regards the level of infestation of such pests as exogenous because infestation on an individual farm depends on the level of infestation in the whole region. The objective function of such farm firms may be to maximise profits given the level of infestation. There is little incentive to try to influence the population in the region. However, the joint action of all farm firms affects the population of the pest in the region. Thus the possibility exists for some type of group action over a large geographical region to internalise the 'stock-externality' imposed by each firm on its neighbours.

Where gains from regional coordination are substantial, an appropriate tax/subsidy policy may be implemented to internalise the externality. In this section, the size of such gains is estimated for the case of wild oats in wheat. Instead of making the usual assumption of perfect mobility as in the case of insect pests (Lazarus and Dixon 1984), different rates of spread are assumed. A representative farm approach is used to solve two finite horizon intertemporal decision problems: one for a social solution in which external effects are fully internalised, the other for a private solution in which external effects are only partially internalised. A dynamic programming model is used for deriving the solutions. The number of viable seeds in the soil and the quantity of a post-emergent emergent herbicide are specified as the state and the decision variables in the model.

The social and private solutions for a representative farm over a time horizon of ten years are obtained by applying the dynamic programming model. The detailed specification of the dynamic programming model is discussed by Pandey (1989). To derive the private optimal solution, it is essential to know the size of the externality (X_t) in addition to the level of infestation (x_t) on the farm. However, the size of the externality depends on the collective action of all farm firms. Here, the private solution is derived by using the firm's expectations about the size of the future externalities. The firm is assumed to consider the externality to remain at the present level for all the future years. A ten-year horizon problem is solved by applying the dynamic programming model given constant X_t. In the next period, the level of externality changes as specified in equation (8c) due to joint action of all firms. A nine-year horizon problem is solved assuming the new level of externality

to hold for all future years. The level of externality is again updated. This process is continued to the end of the planning horizon.

The spread of wild oats occurs through redistribution of the newly produced seeds. The net inflow of wild oats seeds into a farm is assumed to be a proportion of the difference between the newly produced seeds in the region and the newly produced seeds in the farm. This proportion is considered here as representing spread rate. When the spread rate is zero, the private solution corresponds to the social solution. The solutions for different spread rates and two initial levels of infestations (or externality) are presented in Figure 10. The present value decreases with an increase in the spread rate for both levels of externality. If the spread rate is 20 per cent, the size of gain from regional coordination is

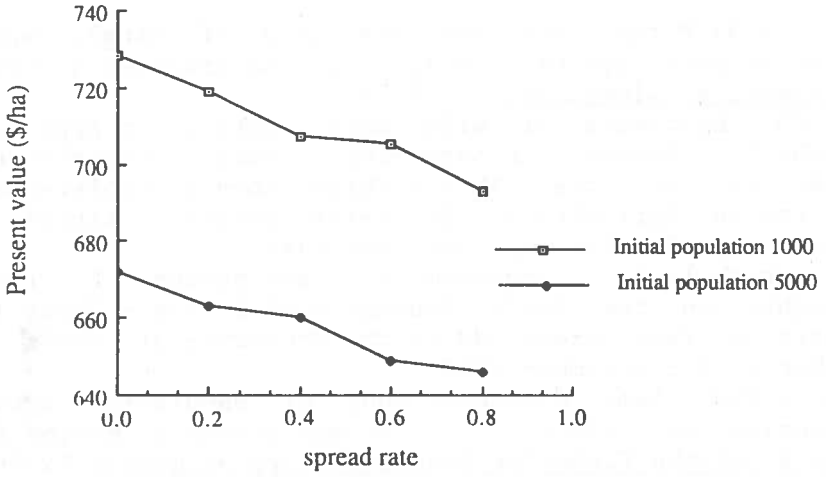

Figure 10: Present Values for Diffelrent Spread Rates and Initial Population

approximately $9/ha for both levels of externality. This level of gain may be considered to be too low to warrant the cost of implementing a tax/subsidy policy for internalising the externality. However, the size of the potential gain from a tax/subsidy policy increases with an increase in spread rate.

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