The Externalities of Conventional and Organic Pest Management:
When Do Gains to Cooperation Exist?

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During the 1990s, demand for organic products increased on average by 20% each year. This growth in demand fueled growth in organic crop acreage. Between 1992 and 2005, organic cropland more than quadrupled, going from 403,400 acres to just over 1.7 million acres (USDA, 2008). Demand is predicted to increase annually by an additional 9 to 16% through 2010 (Dimitri and Oberholtzer, 2005). This further increase in demand will lead to an additional expansion of organic acreage, increasing the heterogeneity of agricultural regions and increasing the interaction that occurs between conventional and organic farms as they more frequently share the same regional landscape. Sharing the same landscape implies that they share pest and natural enemy populations. The movement of these organisms links farms within a region, potentially causing one grower's pest control decisions to impact other growers. This paper examines these interactions.

The analysis focuses on one organic and one conventional profit-maximizing grower. One pest and one natural enemy population connect the time periods in the model, and the movement of these populations connects the grower's fields, creating a spatial-dynamic model. The analysis compares the privately optimal levels of pest control on the neighboring farms with the socially optimal levels of pest control. This comparison will illuminate situations when private decisions lower the region's total profits via negative externalities created by the movement of insects. The model examines how these externalities differ under different population dynamics.

Background on Pest Control

Pest control is an important part of agricultural production. Crop production systems include the host crop, one or more pests that damage or eat the crop, and one or more predators or parasitoids that eat or lay eggs in, respectively, the pest population(s). These predators and parasitoids, known as natural enemies, provide a natural form of pest control. Growers can introduce other pest control agents, such as pesticides, into the crop production system. When the cost of controlling the pest is less than the revenue lost due to damage, growers maximize profit by choosing the type and level of pest control. The type of pest control chosen in part depends on the type of grower. Conventional growers have the widest range of pest control options available to them while organic regulations restrict organic growers to a subset of the options available to conventional growers. The toxicity of these options to natural enemies falls along a spectrum, ranging from highly toxic to non-toxic.

Synthetic broad spectrum pesticides fall on the highly toxic end of the spectrum. These pesticides are not species-specific, so any individual broad spectrum pesticide is capable of killing multiple pest species and may have lethal and sub-lethal effects on natural enemies.[1] Some approved organic pesticides, such as neem oil and spinosad, may fall next on the spectrum. In laboratory studies, these pesticides have negative impacts on natural enemies, but no evidence of pest resurgences due to lowered enemy populations following the applications has been reported on organic farms (Johnson and Krugner, 2004). This suggests that these organic pesticides are either less toxic to natural enemies than synthetic broad spectrum pesticides or natural enemies are able to withstand the chemicals on organic farms, given the other resources available to them.

Insect pathogens, such as *Bacillus thuringiensis*, have some lethal and sublethal effects on natural enemies, but less than many synthetic broad spectrum pesticides, neem oil, and spinosad (Johnson and Krugner, 2004). Insect growth regulators target specific hormones and interfere with the insect’s development, preventing the individual from becoming a reproductive adult. Each regulator is specific to a group of insects that contain the same hormone (Cornell University Cooperation Extension, 2001), so these will not kill natural enemies as long as the enemies do not contain the targeted hormone.

Pheromones have little toxicity to natural enemies because each pheromone targets only one species of pest. Farmers use these naturally produced chemicals to attract pests into traps or to interfere with mating (Cornell University Cooperative Extension, 2001). Similarly, natural repellants such as herbal teas, plant extracts, and clay or rock powder repel pests with little to no impact on natural enemies (Zehnder et al., 2007).

Not surprisingly, the use of natural enemies also falls at the low toxicity end of the spectrum. Through the provision of habitat, pollen, and nectar, growers can attract natural enemies to their fields and help establish populations large enough to keep pest populations under control. Growers may also provide food for existing populations of predators or hosts for parasitoids when pest populations are low, in order to keep the natural enemies available to help with new pest population booms (Zehnder et al., 2007). If he or she cannot attract adequate quantities of natural enemies, the grower can import predators and parasitoids to release in the fields, a practice that farmers repeat as often as once a week during the growing season, depending on the crop and natural enemy involved (Zehnder et al., 2007).

In addition to the chemical and biological control methods discussed, growers can use cultural controls such as the timing of planting or harvesting, mulching, and planting trap crops. All of these practices have limited impact on natural enemies as well.

Conventional California fruit and nut growers most commonly apply synthetic broad spectrum pesticides, such as organophosphates, carbamates, and, increasingly, pyrethroids (Zalom, Toscano, and Byrne, 2005), despite their high toxicity to natural enemies. Insect growth regulators and pheromones tend to be more expensive than broad spectrum pesticides due to high development and production costs and are most effective at controlling low to moderate pest outbreaks (Welter et al., 2005). Cost analyses performed for strawberry and cabbage show that for these crops, the use of natural enemies can cost thousands of dollars more per acre than conventional pest management involving broad spectrum pesticides (Lundgren, Heimpel, and Bomgren, 2002; Trumble and Morse, 1993). Thus, we find that the use of broad spectrum pesticides is more widespread than the use of more targeted methods among conventional fruit and nut growers.

In contrast, certified organic farms cannot use synthetic broad spectrum pesticides, and must rely on other methods. The use of natural enemies, when viable, can be a low cost alternative to organic pesticides (Zehnder et al., 2007). While the use of locally available natural enemies is a potentially inexpensive and environmentally sound form of pest control relative to other organic methods, conventional pesticide use in nearby fields can make the use of natural enemies more challenging. In the case of citrus crops, vedalia beetles provide excellent control of the cotton cushiony scale, a major pest (University of California Cooperative Extension, 2003), but some organic growers have a difficult time keeping vedalia beetle populations on their farms when located near conventional farms. This problem is exacerbated by the fact that these beetles are not available commercially, so growers cannot augment natural populations with purchased beetles (R. Whitehurst, personal communication, July 1, 2008). According to a supplier of commercially available natural enemies, organic farmers, growing various crops, complain of reductions in, and in some cases complete elimination of, natural enemy populations from conventional pesticide applications on neighboring farms (M. Cherim, personal communication, July 1, 2008).

Previous Work

To date, little work has been done to examine the impact of different pest management systems on each other. There is a limited literature that analyzes pest management in an explicitly spatial context. These models have included multiple farms contained within the same landscape. Levins (1969) examines the optimal timing of pest control among homogeneous farms located in the same region. He finds that synchronized control yields the lowest proportion of infested farms. Ives and Settle (1997) also look at optimal pest control among homogenous farms in the same region. However, they include predators of the pest in their model, look at the levels of the local populations, and consider timing of planting among otherwise homogenous farms. They find that asynchronous planting among growers can yield lower pest levels because such a planting distribution keeps sizable local pest populations present in the region for a longer period of time, which in turn keeps local predator populations high.

Kean et al. (2003) consider only biological control in a 7 by 7 grid of farms. The central farm actively supports natural enemies on its land, while the other farms only passively allow biological control to occur. They find that the natural enemy population increases on the central farm, while its pest population decreases. On farms directly neighboring the central farm, local enemy populations decrease, and local pest populations increase. However, the total system's pest population is lower when the central farm encourages enemies to stay on its land than in the case where no farm encourages natural enemies.

Finally, Sherratt and Jepson (1993) use a spatial model to examine the effects of toxicity of pesticides to both the pest and predators of the pest. They find that as the toxicity of the pesticide to the predator increases relative to its toxicity to the pest, the probably of a pest resurgence following the pesticide application increases.

The literature discussed above considers the population dynamics involved when pests and natural enemies move between farms within the same region. In these models, growers are either assumed to work together cooperatively or to follow a given pest management plan. The model presented here builds on these models by adding a profit-maximization problem to the population dynamics, allowing growers to choose their level of pest control, given the levels of pests and enemies faced.

Model: Economic Basics

This model involves two neighboring fields: one organic field and one conventional field. Organic is denoted by an "o" superscript and conventional denoted by a "c" superscript, $i \in \{c, o\}$. Time is indicated by *t*. One pest, N_t, and one natural enemy of the pest, P_t, move between the two fields. In the absence of the pest, grower *i* could achieve a potential output of $\bar{y}^i$, assuming that pest control decisions are separable from all other grower decisions with regards to output. A portion of the output, $D(N_t^i)$, will be damaged by the pest population on field *i*, and each grower makes use of one pesticide and the natural enemy to control the local pest population.[2] Grower *i* chooses the level of pesticide, X_t^i, which is sold a at a price w^i in order to maximize profit. This level of pest control results in $h^i(X_t^i)$ pests being killed. The pest control provided by the natural enemy enters into the problem through the population dynamics discussed below. Each grower's profit for period *t* equals $p^i\bar{y}^i(1-D(N_t^i))-w^iX_t^i$. The grower's profit maximizing pesticide application choice will depend on the population dynamics of the pest and natural enemy.

Model: Population Basics

The population dynamics connect the farms through time and space. The pest population on field *i* grows through reproduction, $N_t^i r^i(N_t^i)$ where $r^i(N_t^i)$ is the per capita growth rate, and through the dispersal of pests from field *j* to field *i*, $d_N^{ji}(N_t^i, N_t^j)$. This dispersal depends on the relative levels of pests on each farm. Field *i's* pest population declines due to predation or parasitism, $P_t^i\phi(N_t^i, P_t^i)$ where $\phi(N_t^i, P_t^i)$ is the number of pests killed per enemy per time period, the dispersal of pests from the field *i* to field *j*, $d_N^{ij}(N_t^i, N_t^j)$, and pest control, $h^i(X_t^i)$. The change in the pest population on field *i* can thus be written as:

$$(1)\ \frac{\partial N_t^i}{\partial t} = N_t^i r^i(N_t^i) - P_t^i\phi(N_t^i, P_t^i) - h^i(X_t^i) - d_N^{ij}(N_t^i, N_t^j) + d_N^{ji}(N_t^i, N_t^j)$$

The natural enemy population on field *i* increases through reproduction, $P_t^i f[\phi(N_t^i, P_t^i), P_t^i]$ where $f[\phi(N_t^i, P_t^i), P_t^i]$ is the per capita reproduction rate. This rate depends on both its consumption or parasitism of the pest, $\phi(N_t^i, P_t^i)$, and the enemy population. It can also increase through dispersal from field *j* to field *i*, $d_P^{ji}(N_t^i, N_t^j)$. It diminishes through the dispersal of enemies from field *i* to field *j*, $d_P^{ij}(N_t^i, N_t^j)$ and, through deaths resulting from the use of pesticides, $b^i(X_t^i)$. This model assumes that the organic pesticide is non-toxic to enemies, $b^o(X_t^o) = 0\ \forall X_t^o$, while the conventional pesticide is toxic to natural enemies, $b^c(X_t^c) > 0$ and $\frac{\partial b^c(X_t^c)}{\partial X_t^c} > 0$. This model also assumes that predators or parasitoids move from areas of low pest density to areas of high pest density. The change in enemy population on field *i* can thus be written as:

$$(2)\ \frac{\partial P_t^i}{\partial t} = P_t^i f[\phi(N_t^i, P_t^i), P_t^i] - b^i(X_t^i) - d_P^{ij}(N_t^i, N_t^j) + d_P^{ji}(N_t^i, N_t^j)$$

In the discussion of the results that follows, the “appreciation rates” of the pest and natural enemies are important. The enemy appreciation rate on field *i* includes the number of offspring produced by an additional enemy per period and the effects of an additional enemy on the reproduction rate of the enemy population as a whole. In the privately optimal case, the pest appreciation rate on field *i* includes the number of offspring produced by an additional pest per period, the net movement of pests to field *i* induced by an additional pest, and the change in predation or parasitism that occurs by the movement of enemies to field *i* induced by an additional pest. In the socially optimal case, field *i*'s pest appreciation rate will also include changes in the pest population that occur on field *j* due to an additional pest on field *i*. In all cases, the appreciation rate is essentially the contribution of one insect to the next time period's population.

Private Profit Maximizing, Non-Cooperative Equilibrium

Under the assumption of private, non-cooperative profit maximization, both the conventional and organic growers choose a level of pest control to maximize their own profit, without considering the impacts of the decision on the neighboring farm. Growers know the population dynamics and take the other grower's decision as given. Grower *i*'s profit maximization problem is:

$$(3)\quad \max_{X_t^i} \int_{t=0}^{\infty} [p^i \bar{y}^i (1 - D(N_t^i)) - w^i X_t^i] dt$$

subject to:

$$(4)\quad \frac{\partial N_t^i}{\partial t} = N_t^i r^i(N_t^i) - P_t^i \phi(N_t^i, P_t^i) - h^i(X_t^i) - d_N^{ij}(N_t^i, N_t^j) + d_N^{ji}(N_t^i, N_t^j)$$

$$(5)\quad \frac{\partial P_t^i}{\partial t} = P_t^i f[\phi(N_t^i, P_t^i), P_t^i] - b(X_t^i) - d_P^{ij}(N_t^i, N_t^j) + d_P^{ji}(N_t^i, N_t^j).$$

The present valued Hamiltonian is:

(6) $$H = p^i \bar{y}^i (1 - D(N_t^i)) - w^i X_t^i$$
$$\begin{aligned} &+\lambda_{Nt}^i [N_t^i r^i(N_t^i) - P_t^i \phi(N_t^i, P_t^i) - h^i(X_t^i) - d_N^{ij}(N_t^i, N_t^j) + d_N^{ji}(N_t^i, N_t^j)] \\ &+\lambda_{Pt}^i [P_t^i f[\phi(N_t^i, P_t^i), P_t^i] - b(X_t^i) - d_P^{ij}(N_t^i, N_t^j) + d_P^{ji}(N_t^i, N_t^j)] \end{aligned}.$$

To ensure a solution exists, we assume that all functions are continuously differentiable functions of time. In order to ensure that the Hamiltonian is jointly concave in the state and control variables and that we have consequently obtained a maximum, we assume that $\frac{\partial^2 h^i(X_t^i)}{\partial X_t^{i2}} \leq 0$, $\frac{\partial^2 b(X_t^i)}{\partial X_t^{i2}} \geq 0$, $\frac{\partial^2 D(N_t^i)}{\partial N_t^{i2}} \geq 0$, $\frac{\partial^2 r(N_t^i)}{\partial N_t^{i2}} \geq 0$, $\frac{\partial^2 \phi(N_t^i, P_t^i)}{\partial N_t^{i2}} \leq 0$, $\frac{\partial^2 \phi(N_t^i, P_t^i)}{\partial P_t^{i2}} \leq 0$, $\frac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i} \leq 0$, $\frac{\partial f[\phi(N_t^i, P_t^i), P_t^i]}{\partial \phi(N_t^i, P_t^i)} \geq 0$, $\frac{\partial f[\phi(N_t^i, P_t^i), P_t^i]}{\partial P_t^i} \leq 0$, $\frac{\partial^2 f[\phi(N_t^i, P_t^i), P_t^i]}{\partial P_t^{i2}} \leq 0$.[3] None of these assumptions are unrealistic, nor should they drive the results.

The Hamiltonian yields three first order conditions. The first is:

(7) $$\frac{\partial H}{\partial P_t^i} = \lambda_{Nt}^i K_P^i + \lambda_{Pt}^i G_P^i = r\lambda_{Pt}^i - \dot{\lambda}_{Pt}^i$$

where

$G_P^i = f[\phi(N_t^i, P_t^i), P_t^i] + P_t^i \left(\frac{\partial f[\phi(N_t^i, P_t^i), P_t^i]}{\partial \phi(N_t^i, P_t^i)} \frac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i} + \frac{\partial f[\phi(N_t^i, P_t^i), P_t^i]}{\partial P_t^i}\right)$: This is the change in the growth of the enemy population on field *i* in time *t*, excluding dispersal effects, due to an additional enemy on that field. This is also the "appreciation rate" of the natural enemy.

$K_P^i = \phi(N_t^i, P_t^i) + P_t^i \dfrac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i}$: This is the additional number of pests on field *i* killed at time *t* due to one additional enemy on that field.

At the equilibrium, the change in pest and enemy populations is zero implying that the change in their shadows values is also zero. Thus, $\dot{\lambda}_{Pt}^i = \dot{\lambda}_{Nt}^i = 0$

(7) can be used to solve for the value of one additional enemy.

$$\lambda_{Pt}^i = -\lambda_{Nt}^i [\frac{K_P^i}{r - G_P^i}]$$

The value of one extra pest, λ_{Nt}^i, is nonpositive, reflecting the value of crop damages inflicted by the pest, while the value of one extra natural enemy, λ_{Pt}^i, is nonnegative, explaining the negative sign in this relationship. The numerator on the right hand side is the number of pests killed by the additional enemy in each time period plus the effect that the additional enemy has on the per capita kill rate of the other enemies. The denominator represents the discount rate minus the appreciation rate of the additional enemy, G_P^i.[4]

The second first order condition is:

$$(8) \qquad \frac{\partial H}{\partial N_t^i} = -p^i \bar{y}^i \frac{dD(N_t^i)}{dN_t^i} + \lambda_{Nt}^i (G_N^i + M_N^{ji}) + \lambda_{Pt}^i (S_P^i + M_P^{ji}) = r\lambda_{Nt}^i - \dot{\lambda}_{Nt}^i$$

where:

$G_N^i = r^i(N_t^i) + N_t^i \frac{\partial r^i(N_t^i)}{\partial N_t^i} - P_t^i \frac{\partial \phi(N_t^i, P_t^i)}{\partial N_t^i}$: This is the net growth in time *t* of the pest population on field *i*, induced by the addition of one pest on that field, excluding dispersal effects.

$M_N^{ji} = -\frac{\partial d_{ij}^N(N_t^i, N_t^j)}{\partial N_t^i} + \frac{\partial d_{ji}^N(N_t^i, N_t^j)}{\partial N_t^i}$: This is the net movement of pests from field *j* to field *i*, induced by an additional pest on field *i*.

$M_P^{ji} = -\frac{\partial d_P^{ij}(N_t^i, N_t^j)}{\partial N_t^i} + \frac{\partial d_P^{ji}(N_t^i, N_t^j)}{\partial N_t^i}$: This is the net movement of enemies from field *j* to the field *i* due to an additional pest on field *i*.

$S_P^i = P_t^i \frac{\partial f[\phi(N_t^i, P_t^i), P_t^i]}{\partial \phi(N_t^i, P_t^i)} \frac{\partial \phi(N_t^i, P_t^i)}{\partial N_t^i}$: This is the growth of the enemy population on field *i* at time *t* induced by an additional pest on that field.

Substituting the expression for λ_{Pt}^i into (8) yields:

$$\lambda_{Nt}^i = \frac{-p^i \bar{y}^i \frac{\partial D}{\partial N_t^i}}{r - [G_N^i + M_N^{ji} - \frac{K_P^i}{r - G_P^i}(S_P^i + M_P^{ji})]}.$$

The numerator of the shadow value is the value lost on field *i* due to pest damage. The denominator is the interest rate minus the "appreciation" rate of the pest.

Finally, the third first order condition is:

$$(9) \qquad \frac{\partial H}{\partial X_t^i} = -w^i - \lambda_{Nt}^i \frac{dh^i(X_t^i)}{dX_t^i} - \lambda_{Pt}^i \frac{db^i(X_t^i)}{dX_t^i} = 0.$$

Rearranging, at the margin, the grower will use an additional unit of pest control when the marginal benefits exceeds the marginal cost, or when:

$$(10)\ -\lambda_{Nt}^{i}\frac{\partial h^{i}(X_{t}^{i})}{\partial X_{t}^{i}} \geq w^{i} + \lambda_{Pt}^{i}\frac{\partial b^{i}(X_{t}^{i})}{\partial X_{t}^{i}}.$$

The left hand side is the marginal benefit which is the decrease in pest population from an additional unit of pest control multiplied by the damage avoided by killing an additional pest. The right hand side is the marginal cost which has two components: the direct per unit cost of an additional unit of pest control and the indirect cost of an additional unit of pest control due to the negative effect of the pesticide on the enemy population. For the organic grower, an additional unit of pesticide has no direct effect on the enemy population so his marginal cost only contains the direct per unit cost.

From this condition, we see that pest control will be reduced under the following conditions:

- $|\lambda_{Nt}^{i}|$ is small- This implies little pest damage from an additional pest, so there is little need for control.
- $\frac{\partial h^{i}}{\partial X_{t}^{i}}$ is small- This implies that the pest control method is relatively ineffective and few pests die from an additional unit of control.
- λ_{Pt}^{i} is large- This implies that enemies are effective at controlling the pest population, and consequently pest control that kills enemies has a higher indirect cost for the conventional grower. This will lead to a lower level of the toxic pest control used.

- $\frac{\partial b^i(X_t^i)}{\partial X_t^i}$ is large- This implies that many enemies die as a result of an additional unit of pest control. The more toxic the pest control is for natural enemies, the smaller the quantity of the conventional pesticide used.
- w^i is large- When an extra unit of pest control is expensive, the grower will use fewer units of control.

The Socially Optimal Equilibrium

To determine whether or not growers incur a deadweight loss when they do not cooperate, and to determine the distribution of the deadweight loss when it exists, I examine the socially optimal pest control decisions. This model assumes both farms use different management practices, but profit is maximized jointly, taking into account the movement of both pests and enemies across the two fields. The total profits with the socially optimal levels of pest control will then be compared to the total profits with the privately optimal levels of pest control.

The social planner will maximize the combined profits of both the organic and the conventional growers, taking into account the movement of pests and natural enemies. Its optimization problem will be:

$$(11)\quad \max_{X_t^c, X_t^o} \int_{t=0}^{\infty} [p^c \overline{y}^c (1 - D(N_t^c)) + p^o \overline{y}^o (1 - D(N_t^o)) - w^c X_t^c - w^o X_t^o]d$$

Subject to:

$$(12)\quad \frac{\partial N_t^c}{\partial t} = N_t^c r^c (N_t^c) - P_t^c \phi(N_t^c, P_t^c) - h^c (X_t^c) - d_N^{co} (N_t^c, N_t^o) + d_N^o \, (N_t^{cc}, N_t^o)$$

(13) $$\frac{\partial P_t^c}{\partial t} = P_t^c f[\phi(N_t^c, P_t^c), P_t^c] - b(X_t^c) - d_P^{co}(N_t^c, N_t^o) + d_P^o\ (N_t^c, N_t^o)$$

(14) $$\frac{\partial N_t^o}{\partial t} = N_t^o r^o(N_t^o) - P_t^o \phi(N_t^o, P_t^o) - h^o(X_t^o) - d_N^o\ (N_t^c, N_t^o) + d_N^{co}(N_t^c, N_t^o)$$

(15) $$\frac{\partial P_t^o}{\partial t} = P_t^o f[\phi(N_t^o, P_t^o), P_t^o] - d_P^o\ (N_t^c, N_t^o) + d_P^{co}(N_t^c, N_t^o).$$

The present-valued Hamiltonian for the social planner is:

(16) $$\begin{aligned} H = {} & p^c \overline{y}^c (1 - D(N_t^c)) + p^o \overline{y}^o (1 - D(N_t^o)) - w^c X_t^c - w^o X_t^o \\ & + \lambda_{Nt}^c [N_t^c r^c(N_t^c) - P_t^c \phi(N_t^c, P_t^c) - h^c(X_t^c) - d_N^{co}(N_t^c, N_t^o) + d_N^o\ (N_t^c, N_t^o)] \\ & + \lambda_{Pt}^c [P_t^c f[\phi(N_t^c, P_t^c), P_t^c] - b(X_t^c) - d_P^{co}(N_t^c, N_t^o) + d_P^o\ (N_t^c, N_t^o)] \\ & + \lambda_{Nt}^o [N_t^o r^o(N_t^o) - P_t^o \phi(N_t^o, P_t^o) - h^o(X_t^o) - d_N^o\ (N_t^c, N_t^o) + d_N^{co}(N_t^c, N_t^o)] \\ & + \lambda_{Pt}^o [P_t^o f[\phi(N_t^o, P_t^o), P_t^o] - d_P^o\ (N_t^c, N_t^o) + d_P^{co}(N_t^c, N_t^o)]. \end{aligned}$$

Under the assumptions used for the private profit maximization, a maximum will exist for the joint profit maximization because this Hamiltonian is the sum of the two concave Hamiltonians in the private profit maximization.

This Hamiltonian yields the following first order conditions:

(17) $$\frac{\partial H}{\partial X_t^c} = -w^c - \lambda_{Nt}^c \frac{\partial h^c}{\partial X_t^c} - \lambda_{Pt}^c \frac{\partial b}{\partial X_t^c} = 0$$

(18) $$\frac{\partial H}{\partial X_t^o} = -w^o - \lambda_{Nt}^o \frac{\partial h^o}{\partial X_t^o} = 0$$

(19) $$\begin{aligned} \frac{\partial H}{\partial N_t^c} = {} & -p^c \overline{y}^c \frac{\partial D(N_t^c)}{\partial N_t^c} + \lambda_{Nt}^c (G_N^c + M_N^{oc}) + \lambda_{Pt}^c (S_P^c + M_P^{oc}) \\ & + \lambda_{Nt}^o M_N^{oc} + \lambda_{Pt}^o M_P^{co} = r \lambda_{Nt}^c - \dot{\lambda}_{Nt}^c \end{aligned}$$

$$\frac{\partial H}{\partial P_t^c} = -\lambda_{Nt}^c K_P^c + \lambda_{Pt}^c G_P^c = r\lambda_{Pt}^c - \dot{\lambda}_{Pt}^c \tag{20}$$

$$\frac{\partial H}{\partial N_t^o} = -p^o \bar{y}^o \frac{\partial D(N_t^o)}{\partial N_t^o} + \lambda_{Nt}^c M_N^{oc} + \lambda_{Pt}^c M_P^{oc} \tag{21}$$

$$+\lambda_{Nt}^o (G_N^o + M_N^{co}) + \lambda_{Pt}^o (S_P^o + M_P^{co}) = r\lambda_{Nt}^o - \dot{\lambda}_{Nt}^o$$

$$\frac{\partial H}{\partial P_t^o} = -\lambda_{Nt}^o K_P^o + \lambda_{Pt}^o G_P^o = r\lambda_{Pt}^o - \dot{\lambda}_{Pt}^o \tag{22}$$

Rearranging (17) and (18), we find that the social planner's decision rule for each grower has the same form as that grower's rule in the privately managed case.

$$-\lambda_{Nt}^c \frac{\partial h^c(X_t^c)}{\partial X_t^c} \geq \lambda_{Pt}^c \frac{\partial b^c(X_t^c)}{\partial X_t^c} + w^c \tag{23}$$

$$-\lambda_{Nt}^o \frac{\partial h^o(X_t^o)}{\partial X_t^o} \geq w^o. \tag{24}$$

However, the equilibrium shadow values in the social planner's problem are different than in the privately managed case.

Setting $\dot{\lambda}_{Nt}^c = \dot{\lambda}_{Nt}^o = \dot{\lambda}_{Pt}^c = \dot{\lambda}_{Pt}^o = 0$, and rearranging (20) and (22) yields

$$\lambda_{Pt}^c = -\lambda_{Nt}^c \frac{K_P^c}{r - G_P^c} \tag{25}$$

$$\lambda_{Pt}^o = -\lambda_{Nt}^o \frac{K_P^o}{r - G_P^o} \tag{26}$$

Like in the privately optimal case, the socially optimal enemy shadow values are equal to the pest shadow value multiplied by the number of pests killed per time period due to an additional enemy. This is due to the assumption that enemies follow pests and their dispersal does not depend on enemy density. However, the pest shadow values are different in the social planner's problem, making the enemy shadow values different as well.

Substituting the enemy shadow values into (19) and (21) yields the following pest shadow value for field *i*:

$$\lambda_{Nt}^{i}=\frac{\left[-p^{i}\bar{y}^{i}\frac{\partial D(N_t^i)}{\partial N_t^i}\right]+\dfrac{-p^{j}\bar{y}^{j}\dfrac{\partial D(N_t^j)}{\partial N_t^j}M_N^{ji}}{r-(G_N^j+M_N^{ij}-\dfrac{K_P^j(S_P^j+M_P^{ij})}{r-G_P^j})}+\dfrac{-p^{j}\bar{y}^{j}\dfrac{\partial D(N_t^j)}{\partial N_t^j}M_P^{ji}K_P^j}{(r-G_P^j)(r-(G_N^j+M_N^{ij}-\dfrac{K_P^j(S_P^j+M_P^{ij})}{r-G_P^j}))}}{\left[r-(G_N^i+M_N^{ji}-\dfrac{K_P^i(S_P^i+M_P^{ji})}{r-G_P^i}\right]+\dfrac{(M_N^{ji}-\dfrac{M_P^{ji}K_P^j}{r-G_P^j})(M_N^{ij}-\dfrac{M_P^{ji}K_P^i}{r-G_P^i})}{r-(G_N^j+M_N^{ij}-\dfrac{K_P^j(S_P^j+M_P^{ij})}{r-G_P^j})})}$$

As before, the numerator of the pest shadow value equals the value of damages caused by an additional pest on field *i*. The value in the numerator takes into account the damages on field *i* (in square brackets). Unlike before, the value of damages also includes damages on field *j* caused by the additional pest on field *i* (not in square brackets). The damages on field *j* include direct damages caused by pest dispersal as well as indirect damages due to a change in the enemy population caused by the changing pest population. The denominator is again the interest rate minus the "appreciation rate" of the pest except that now this rate includes both the appreciation on the field of interest (in square brackets) as well as the appreciation on the other field (not in square brackets).

Comparing the Private and Social Optima

To see how the socially optimal solution differs from the privately optimal solution and to determine which parameters increase or decrease this difference, we compare the pest shadow values in the two scenarios. If the socially optimal pest shadow value exceeds the privately optimal pest shadow value in absolute value, the social damages of an additional pest exceed the private damages, and a positive externality of pest control exists. Joint profits will be higher if growers increase pest control relative to the privately optimal levels of control. If the privately optimal pest shadow value exceeds the socially optimal pest shadow value, the social damages of an additional pest are less than the private damages, and a negative externality of pest control exists. Joint profits will be higher if growers decrease pest control relative to the privately optimal levels of control.

Looking at the socially optimal shadow value for field *i*'s pest population, the parts in square brackets are the parts contained in both the privately optimal shadow value and the socially optimal shadow value, while the parts outside of the square brackets are only found in the socially optimal shadow value. All terms in the shadow values are evaluated at the optimal levels. While the terms in brackets are found in both the privately and socially optimal shadow values, they are evaluated at different levels of pesticide application and pest and enemy populations. If we assume that the damage function and the various functions included in the population dynamics equations are linear, evaluating these terms at different levels will not change their values. Under these linearity assumptions, the only difference between the privately and socially optimal shadow values will be the terms outside of the brackets. We can then determine how the socially optimal levels of pest control compare to the non-cooperative levels by looking at these additional terms. When these linearity assumptions do not hold, we may not be able to compare the cooperative and non-cooperative pest control levels without applying specific functional forms and parameter values to the population dynamics.

Linearity assumptions are likely unrealistic implying that the value of the terms in brackets will differ when evaluated at the socially and privately optimal levels. Provided the socially and privately optimal solutions do not imply large differences in pesticide, pest, and enemy levels, and provided the functions do not exhibit threshold effects, the addition of the three non-bracketed terms will outweigh differences in the values of the bracketed terms because the values of the bracketed terms will not change significantly. The discussion that follows limits attention to this case. In other cases, the change in the value of the bracketed terms may reinforce the results found here or they may dampen the results.

The specific functional forms of the population dynamics will affect the sign and magnitude of the terms found only in the socially optimal pest shadow value and will consequently affect the difference between the privately and socially optimal shadow values. Two aspects of the population dynamics drive the sign of the difference between the socially and privately optimal pest shadow values: pest dispersal and enemy kill rates. Pest dispersal can be one of three types.

1) $\frac{\partial d_N^{ij}}{\partial N_t^j} < 0, \frac{\partial d_N^{ji}}{\partial N_t^j} > 0$ (or $M_N^{ij} < 0$): Pests move from areas with a high pest population to areas with a low pest population, obtaining a higher level of resources per pest.

2) $\frac{\partial d_N^{ij}}{\partial N_t^j} = \frac{\partial d_N^{ji}}{\partial N_t^j} = 0$ (or $M_N^{ij} = 0$): Pest movement does not depend on the pest population.

3) $\frac{\partial d_N^{ij}}{\partial N_t^j} > 0, \frac{\partial d_N^{ji}}{\partial N_t^j} < 0$ (or $M_N^{ij} > 0$): Pests move towards areas with a high pest population. This would occur if pests do better when surrounded by other pests.

In order to obtain a concave Hamiltonian, we have assumed $\frac{\partial \phi(N_t^j, P_t^j)}{\partial P_t^j} \le 0$ which implies that the rate of predation or parasitism does not increase as the enemy population increases. This suggests a crowding out effect. As a result of this relationship, the movement of an enemy from field *i* has two effects on field *j*.. First, it results in the loss of the pest mortality that that enemy would have inflicted, $\phi(N_t^i, P_t^i)$. Second, it may increase the kill rates of all remaining enemies, leading to an increase in total pest mortality on field *i*, $\left| P_t^i \frac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i} \right|$. If $\phi(N_t^i, P_t^i) > \left| P_t^i \frac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i} \right|$, field *i* experiences a net decrease in enemy-induced pest deaths when an enemy leaves its field. If $\phi(N_t^i, P_t^i) < \left| P_t^i \frac{\partial \phi(N_t^i, P_t^i)}{\partial P_t^i} \right|$, field *i* experiences a net increase in enemy-induced pest deaths when an enemy leaves its field.

With these different population dynamics in mind, we will examine the three terms found only in the socially optimal pest shadow value. First, the "direct effect,” $\dfrac{-p^i \bar{y}^i \dfrac{\partial D(N_t^i)}{N_t^i} M_N^{ji}}{r-(G_N^j + M_N^{ij} - \dfrac{K_P^j(S_P^j + M_P^{ij})}{r-G_P^j})}$, is the direct effect felt by grower *j* from an additional pest on grower *i*’s field. The additional pest on grower *i*’s field induces movement of pests. If pests move onto grower *j*’s field (pest dispersal type 1), the direct effect represents increased damage on farmer *j*’s field. If the additional pest induces a movement of pests onto grower *i*’s field (pest dispersal type 3), this direct effect represents damages avoided on field *j*. If there is no density dependent movement of pests (pest dispersal type 2), an increase in pests on field *i* does not cause any direct damages on field *j*.

Second, the “indirect effect”, $\dfrac{-p^j \bar{y}^j \dfrac{\partial D(N_t^j)}{\partial N_t^j} M_P^{ji} K_P^j}{(r-G_P^j)(r-(G_N^j + M_N^{ij} - \dfrac{K_P^j(S_P^j + M_P^{ij})}{r-G_P^j}))}$, is the indirect effect felt by grower *j* from an additional pest on grower *i*’s field. In this model, enemies follow the pests, so the additional pest on field *i* induces a shift of enemies from field *j* to field *i*. The decrease in enemies on field *j* increases the kill rate per enemy. If $\left| P_t^j \dfrac{\partial \phi(N_t^j, P_t^j)}{\partial P_t^j} \right| > \phi(N_t^j, P_t^j)$, implying $K_P^j < 0$, the increase in kill rate is high enough to offset the loss of the predation or parasitism that emigrated enemies would have caused on field *j* had they not emigrated. If this holds, the indirect effect will represent damages avoided due to increased killing by natural enemies. If the increase in kill rate does not offset the decrease due to enemy emigration, the indirect effect represents increased damages. Notice that the pest dispersal type does not impact the indirect effect.

Third, the "appreciation rate effect," $\dfrac{(M_N^{ji} - \dfrac{M_P^{ji} K_P^j}{r - G_P^j})(M_N^{ij} - \dfrac{M_P^{ji} K_P^i}{r - G_P^i})}{r - (G_N^j + M_N^{ij} - \dfrac{K_P^j (S_P^j + M_P^{ij})}{r - G_P^j})}$, represents the appreciation rate of field *i*'s additional pest that takes place on field *j*. Since an additional pest induces movement of pests and enemies, an additional pest on field *i* changes the number of future pests on field *j*. The two parenthesized terms contained in the numerator both contain the same population dynamics terms except the pest dispersal, kill rate, and enemy growth terms refer to different fields. If the two fields were identical, the numerator would be a square number, and thus, positive. When the population dynamics on both fields are similar, both parentheses will have the same sign, making this term positive. Since it is subtracted off of the denominator, this component increases the absolute value of the socially optimal pest shadow value relative to the privately optimal pest shadow value. If the kill rates and enemy growth rates differ considerably across fields, as we might expect if conventional pesticides have sublethal effects on enemies, this term will be negative, lowering the absolute value of the socially optimal pest shadow value relative to the privately optimal pest shadow value.

To determine how the socially optimal pest shadow value differs from the privately optimal pest shadow value, all three parts must be combined. However, in certain situations, they work in opposite directions. Table 1 provides an outline of the results discussed below. The middle three columns indicate which conditions must hold for each of the three dispersal types to lead to the given difference between the social and private damages. A positive sign in column (A) indicates that the increase in kill rate induced by a reduction in enemies offsets the pest deaths the lost enemies would have caused, while a negative sign indicates the reverse. A positive sign in column (B) indicates that the direct effect on field *j* from an additional pest on field *i*, $\dfrac{-p^i\bar{y}^i\dfrac{\partial D(N_t^i)}{N_t^i}M_N^{ji}}{r-(G_N^j+M_N^{ij}-\dfrac{K_P^j(S_P^j+M_P^{ij})}{r-G_P^j})}$ exceeds the indirect effect on field *j* from an additional pest on field *i*, field $\dfrac{-p^j\bar{y}^j\dfrac{\partial D(N_t^j)}{\partial N_t^j}M_P^{ji}K_P^j}{(r-G_P^j)(r-(G_N^j+M_N^{ij}-\dfrac{K_P^j(S_P^j+M_P^{ij})}{r-G_P^j}))}$ while a negative sign indicates the reverse. A positive sign in column (C) indicates that the change in the numerator outweighs the change in the denominator, or $-p^j\bar{y}\dfrac{\partial D(N_t^i)}{\partial N_t^i}>M_N^{ij}-\dfrac{M_P^{ji}-K_P^i}{r-G_P^j}$ while a negative sign indicates the reverse. In the table, all scenarios assume that both fields have similar population dynamics. In the event of differing population dynamics, any of the following cases could result in lower social damages relative to private damages if the differences are dramatic enough.

For most scenarios involving a movement of pests from the field with a higher pest population to the field with the lower pest population, social damages from an additional pest exceed private damages, implying that it is socially optimal for both growers to increase their pest control. Under this pest dispersal assumption, a grower would not unilaterally decrease pest control because doing so would cause an increase in the number of pests moving from his neighbor's field onto his own. If both growers agree to increase their pest control simultaneously, they will achieve a decrease in crop damages that more than compensates for the increase in pest control costs.

Under the assumption that pests move from the field with the high pest population to the field with the low pest population, it is also possible that the social damages are lower than the private damages if the indirect effect outweighs the direct effect and the appreciation rate effect. This implies that when grower *i* keeps his pest level high and induces a movement of enemies from field *j* to field *i*, the kill rate on field *j* increases enough to more than compensate for the increase in pests that result from the dispersal of pests from field *i* to field *j*.

When pest dispersal does not depend on the relative levels of the pest populations on the two fields, the indirect effect and appreciation rate effect still occur because a change in pests induces movement of the natural enemies. When a movement of enemies from field *j* to field *i* only has a small effect on the kill rate, social damages from an additional pest on field *i* exceed private damages. If the movement of enemies from field *j* to field *i* has a large effect on the kill rate, private damages from an additional pest on field *i* exceed social damages since the movement of enemies away from field *j* increases the effectiveness of the remaining enemies, allowing *j* to benefit from *i*'s high pest population.

When pests move from the field with the low pest population to the field with the high pest population, social damages may be greater than or less than private damages.

When the change in kill rate is small and the direct effect dominates, the social damages are lower than the privately optimal damages, and growers should decrease their pest control. In this case, when growers act unilaterally, they use a very high level of pest control to prevent an influx of pests from the other field. When growers cooperate, they can decrease their pest control levels without facing an increase in pests from the other grower's field. When the change in kill rate is small, and the appreciation rate effect dominates, social damages exceed private damages.

When the pest has a similar effect on conventional and organic crops and when natural enemies have a similar effect on pests on conventional and organic farms, the shadow values for the two types of growers will move in the same direction when going from the privately optimal equilibrium to the socially optimal equilibrium. However, it may be the case that enemies have lower kill rates on conventional fields due to sublethal effects of conventional pesticides. In this case, the indirect effect contained in the socially optimal organic pest shadow value will be smaller than in the socially optimal conventional pest shadow value; the loss of enemies from the conventional field to the organic field will have a minimal impact on the conventional pest population. Similarly, if the organic grower plants a variety that is more pest resistant in response to not being able to use conventional pesticides, the damages inflicted on the organic farm from pests originating on the conventional farm may be small, decreasing the divergence between the socially and privately optimal levels of conventional pest control. Additionally, if the organic crop receives a price premium, the socially optimal conventional pest shadow value will diverge from the privately optimal pest shadow value more than the corresponding organic divergence. The impact of additional pests will have a larger monetary impact on the organic farm.

The socially and privately optimal levels of pest control will only coincide if there is no density dependent movement of pests or natural enemies. For any other possible case, the two will diverge. When maximizing joint profits, the social planner has the privately optimal pest control levels available as options. When the socially optimal pest control levels diverge from the privately optimal levels, this must occur because these levels increase joint profits relative to joint profits using the privately optimal levels of pest control. When both growers make changes in pest control levels in the same direction and of the same magnitude, the distribution of profit gains will be similar. When the magnitude or direction of changes diverges, the distribution of profit gains will differ. Given the form of the solutions here, these distributional effects cannot be analyzed.

Adding Natural Enemy Augmentation

While some growers may be able to establish populations of natural enemies on their farms at negligible cost, others may need to create habitat or provide supplemental resources to attract and sustain viable enemy populations. In cases where the farm is too small to sustain a population or when the regional level of enemies is too low, the grower may need to purchase commercially available enemies to release in the field. This is known as augmentation.

To account for possible augmentation, the organic grower can choose the level of augmentation effort, α_t. This corresponds to an increase in the enemy population equal to $s(\alpha_t)$. In the case where the grower provides resources for the enemy, $s(\cdot)$ represents how this effort translates into enemies. In the case where the grower purchases enemies to apply, $s(\cdot)$ represents how the number bought translates into effective enemies. Some enemies may die in the transportation and application process, and imported enemies may be of lower quality than native enemies due to how they are reared in captivity and how they are stored and shipped (Hajek, 2004).

This model assumes the conventional grower will not choose augmentation both because conventional pesticides will kill the imported enemies, and because the use of augmentation will likely be more expensive than conventional methods. This implies that the privately optimal conventional decisions are identical with and without organic grower augmentation.

The organic grower's private optimization problem becomes:

$$(27)\ \max \int_{t=0}^{\infty} [p^o \bar{y}^o (1 - D(N_t^o)) - w^o X_t^o - v\alpha_t] dt$$

subject to:

$$(28)\ \frac{\partial N_t^o}{\partial t} = N_t^o r^o(N_t^o) - P_t^o \phi(N_t^o, P_t^o) - h^o(X_t^o) - d_o^N(N_t^c, N_t^o) + d_{co}^N(N_t^c, N_t^o)$$

$$(29)\ \frac{\partial P_t^o}{\partial t} = P_t^o f[\phi(N_t^o, P_t^o), P_t^o] + s(\alpha_t) - d_o^P(N_t^c, N_t^o) + d_{co}^P(N_t^c, N_t^o).$$

The present-valued Hamiltonian is:

$$(30)\ H = p^o \bar{y}^o (1 - D(N_t^o)) - w^o X_t^o - v\alpha_t$$

$$+\lambda_{Nt}^o [N_t^o r^o(N_t^o) - P_t^o \phi(N_t^o, P_t^o) - h^o(X_t^o) - d_o^N(N_t^c, N_t^o) + d_{co}^N(N_t^c, N_t^o)]$$

$$+\lambda^{o}_{Pt}[P^{o}_{t} f[\phi(N^{o}_{t},P^{o}_{t}),P^{o}_{t}]+s(\alpha_{t})-d^{P}_{o}(N^{c}_{t},N^{o}_{t})+d^{P}_{co}(N^{c}_{t},N^{o}_{t})]$$

which yields the following first order conditions:

$$(31)\qquad \frac{\partial H}{\partial X^{o}_{t}}=-w^{o}-\lambda^{o}_{Nt}\frac{\partial h^{o}}{\partial X^{o}_{t}}=0$$

$$(32)\qquad \frac{\partial H}{\partial \alpha_{t}}=-v+\lambda^{o}_{Pt}\frac{\partial s}{\partial \alpha_{t}}=0$$

$$(33)\qquad \frac{\partial H}{\partial N^{o}_{t}}=-p^{o}\overline{y}^{o}\frac{\partial D(N^{o}_{t})}{\partial N^{o}_{t}}+\lambda^{o}_{Nt}(G^{o}_{N}+M^{co}_{N})+\lambda^{o}_{Pt}(S^{o}_{P}+M^{co}_{P})=r\lambda^{o}_{Nt}-\dot{\lambda}^{o}_{Nt}$$

$$(34)\qquad \frac{\partial H}{\partial P^{o}_{t}}=-\lambda^{o}_{Nt}K^{o}_{P}+\lambda^{o}_{Pt}G^{o}_{P}=r\lambda^{o}_{Pt}-\dot{\lambda}^{o}_{Pt}\,.$$

Here, the organic grower will apply the organic pesticide if its marginal benefit exceeds its marginal cost, which occurs when:

$$(35)\quad -\lambda^{o}_{Nt}\frac{\partial h^{o}}{\partial X^{o}_{t}}\geq w^{o},$$

and he will augment the enemy population when augmentation's marginal benefit is at least as large as its marginal cost, which occurs when:

$$(36)\quad \lambda^{o}_{Pt}\frac{\partial s}{\partial \alpha_{t}}\geq v$$

Rates of augmentation will be higher if the cost of augmentation is low, damages are high, predation or parasitism rates are high, and enemy appreciation is high. The enemy appreciation rate depends in part on the region's enemy population which is influenced by the movement of the enemies and the actions of the neighbor.

From (34), we see that the enemy shadow value takes the same form as in the scenario without augmentation:

$$(37)\ \lambda_{Pt}^{o} = -\lambda_{Nt}^{o} \frac{K_P^o}{r - G_P^o}$$

Let:

$$(38)\ \beta = \frac{K_P^o}{r - G_P^o}$$

This implies that:

$$(39)\ \lambda_{Pt}^{o} = -\lambda_{Nt}^{o} \beta$$

And the organic grower will use an additional unit of augmentation if:

$$(40)\ -\lambda_{Nt}^{o} \beta \frac{\partial s}{\partial \alpha_t} \geq v$$

Since the augmentation variable does not enter into OA.3 and OA.4 and will not enter into the corresponding first order conditions of the socially optimal model, the private and social pest shadow values retain the same form as the problem without augmentation. The organic grower's pest shadow value for the privately optimal case is:

$$(41)\ \lambda_{Nt}^{o,PO} = \frac{-p^o \overline{y}^o \dfrac{\partial D}{\partial N_t^o}}{r - [G_N^o + M_N^{co} - \dfrac{K_P^o}{r - G_P^o}(S_P^o + M_P^{co})]},$$

while the organic grower's pest shadow value for the socially optimal case is:

$$(42)\quad \lambda_{Nt}^{o,SO}=\frac{-p^{o}\overline{y}^{o}\frac{\partial D(N_t^o)}{\partial N_t^o}+\frac{-p^{c}\overline{y}^{c}\frac{\partial D(N_t^c)}{\partial N_t^c}M_N^{co}}{r-(G_N^c+M_N^{oc}-\frac{K_P^c(S_P^c+M_P^{oc})}{r-G_P^c})}+\frac{-p^{c}\overline{y}^{c}\frac{\partial D(N_t^c)}{\partial N_t^c}M_P^{co}K_P^c}{(r-G_P^c)(r-(G_N^c+M_N^{oc}-\frac{K_P^c(S_P^c+M_P^{oc})}{r-G_P^c}))}}{r-(G_N^o+M_N^{co}-\frac{K_P^o(S_P^o+M_P^{co})}{r-G_P^o}+\frac{(M_N^{co}-\frac{M_P^{co}K_P^c}{r-G_P^c})(M_N^{oc}-\frac{M_P^{co}K_P^o}{r-G_P^o})}{r-(G_N^c+M_N^{oc}-\frac{K_P^c(S_P^c+M_P^{oc})}{r-G_P^c})})}\ .$$

Again, we see the socially optimal pest shadow value contains three terms not contained in the privately optimal pest shadow value.

As was the case without augmentation, the decision rules governing the socially optimal level of pesticide use and augmentation,

$$(43)\quad -\lambda_{Nt}^{o}\frac{\partial h^o}{\partial X_t^o}\geq w^o$$

$$(44)\quad -\lambda_{Nt}^{o}\beta\frac{\partial s}{\partial \alpha_t}\geq v\ ,$$

have the same form as the rules governing the privately optimal levels, but these rules contain the pest shadow value for the socially optimal case which is quantitatively different that of the privately optimal case.

The socially optimal first order conditions governing the organic grower's use decisions can be written as:

$$(45)\quad -(\lambda_{Nt}^{o,PO}+\lambda_{Nt}^{o,Diff})\frac{\partial h^o}{\partial X_t^o}\geq w^o$$

$$(46)\quad -(\lambda_{Nt}^{o,PO}+\lambda_{Nt}^{o,Diff})(\beta^{PO}+\beta^{Diff})\frac{\partial s}{\partial \alpha_t}\geq v$$

where $\lambda_{Nt}^{o,Diff}=\lambda_{Nt}^{o,SO}-\lambda_{Nt}^{o,PO}$ and $\beta^{Diff}=\beta^{SO}-\beta^{PO}$.

(45) is of the same form as the corresponding expression in the socially optimal case in the absence of augmentation. Thus, the results in Table 1 also represent the direction of change moving from the privately optimal to the socially optimal levels of organic pesticide use with augmentation, assuming the direct, indirect, and appreciation rate effects dominate any changes in the levels of components found in both the socially and privately optimal pest shadow values.

When considering (46), it is important to remember that $\beta = \beta(N_t^o, P_t^o)$, so the value of this term can be different in the socially optimal solution relative to the privately optimal solution. Considering the case where the socially optimal enemy population is greater than the privately optimal one, we know that the marginal value of an additional enemy is lower at the social optimum than at the private optimum given our assumptions. This implies β^{Diff} is negative.

If β^{Diff} has the same sign as λ^{Diff}, augmentation use will move in the same direction as organic pesticide use when moving from the private optimum to the social optimum. This implies that augmentation complements organic pesticides. Intuitively, in this case, pesticides decrease the source of food or hosts for the enemy, which in turn will decrease the enemy population. The use of augmentation provides a steady stream of enemies to replace those lost due to a lack of pests, and can compensate for low regional levels of enemies. For the cases listed in table 1 where the social damages from an additional pest exceed private damages, λ^{Diff} is also negative, implying that augmentation and organic pesticides and augmentation are complements. Thus, when the social damages exceed the private damages, growers increase both types of pest control in the cooperative case.

For the cases listed in table 1 where social damages are less than private damages, λ^{Diff} is positive and is of the opposite sign as β^{Diff}, implying that augmentation and organic pesticides are complements. When moving to the social optimum, growers shift from one type of pest control to the other and decrease the levels of both types of pest control.

Conclusions

The results of this theoretical model show that under most circumstances, growers will affect other growers in their region through their pest management decisions. In regions where growers are homogenous, the impacts on one another will be similar. In regions containing crop-pest-enemy systems where pests move from areas of high pest density to areas of low pest density, a positive externality of pest control will likely exist. In those areas where enemies have much higher kill rates at low levels of the enemy population, a negative externality of pest control will likely exist.

In regions where growers are heterogeneous, such as agricultural regions containing both organic and conventional growers, the impacts are likely to be asymmetric, although the degree of asymmetry will depend on the specific crop-pest-enemy system. Those systems in which conventional growers use pesticides with significant sublethal effects on enemies will contain large asymmetries because enemies will have very low kill rates on conventional fields relative to their kill rates on organic fields. Similarly, large asymmetries will exist for crops where the organic product receives a high price premium over the conventional product. The damages inflicted on organic fields induced by an additional pest located on the conventional field will be more highly valued than similar damages inflicted on the conventional field.

Analysis of specific crop-pest-enemy systems can illuminate ways by which specific types of growers impact each other so that these impacts can be addressed. Such internalization of externalities may be addressed by pest management districts, a phenomenon that has appeared to combat pests, such as the olive fruit fly and mosquitoes, where cooperation of all stakeholders is crucial for control.

The current model illustrates how asymmetries between population dynamics on different fields can result in different adjustment to the social optimum for different growers. It shows how sublethal effects of synthetic broad spectrum pesticides can result in the conventional grower adjusting his pest control more than the organic grower. It cannot, however, adequately address all issues regarding toxicity because the modeled conventional grower only has one pesticide available, making an analytical solution possible. Future work will simulate scenarios where the conventional grower has pesticides of varying toxicities available at varying prices and with varying efficacies to determine how the socially optimal level and type of pest control differ from the privately optimal type and level.

Table 1. Social Versus Private Damages Resulting from an Additional Pest on Field *i* with Symmetric Population Dynamics.

	(A) $\left\| P_t^j \frac{\partial \phi}{\partial P_t^j} \right\| -$ $\phi(N_t^j, P_t^j)$	(B) Direct Effect - Indirect Effect	(C) Numerator Effect - Denominator Effect	Social Damages Relative to Private Damages
$\frac{\partial d_N^{ij}}{\partial N_t^j} < 0,$ $\frac{\partial d_N^{ji}}{\partial N_t^j} > 0$ (or $M_N^{ij} < 0$)	-	+/-	+/-	Higher
	+	+	+/-	Higher
	+	-	+	Lower
	+	-	-	Higher
$\frac{\partial d_N^{ij}}{\partial N_t^j} = 0,$ $\frac{\partial d_N^{ji}}{\partial N_t^j} = 0$ (or $M_N^{ij} = 0$)	-	+/-	+/-	Higher
	+	+/-	+	Lower
	+	+/-	-	Higher
$\frac{\partial d_N^{ij}}{\partial N_t^j} > 0,$ $\frac{\partial d_N^{ji}}{\partial N_t^j} < 0$ (or $M_N^{ij} > 0$)	-	+	+	Lower
	-	+	-	Higher
	-	-	+/-	Higher
	+	+/-	+	Lower
	+	+/-	-	Higher

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[1] Sublethal effects include reductions in reproduction rates and lifespans, interference with the enemies' ability to locate prey or hosts, and suppression of predators' appetites. All of these sublethal effects decrease the natural enemies' supply of pest control (Dresneux et al, 2007).

[2] By reducing the problem to only one pesticide option per grower, the model assumes that the grower has chosen the most profitable form of pest control and now must choose the level to apply. Implicitly, the grower's application level does not alter the relative profitability of his chosen pest control method.

[3] The Hamiltonian may still be jointly concave if some of these assumptions are relaxed as long as the relative magnitudes of its components still ensure negative semidefiniteness of the Hessian matrix.

[4] This shadow value and the shadow value that will be derived for the local pest population closely mirror the shadow value one finds in a traditional capital investment problem. In this kind of problem, if profit can be written as $\pi(K)$, if capital appreciates at a rate of ρ, and if the discount rate is *r*, then $\lambda_{Kt} = \frac{\partial \pi(K) / \partial K}{r - \rho}$

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