Selective vs. Broad-Spectrum Pesticides:
When Do Private Decisions Differ from Socially Optimal Decisions?

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Abstract

This paper examines the spatial externalities of conventional and organic pest control methods to determine if, and how, the two types affect each other. These interactions make the problem more complicated than the usual analysis of a single externality. The numerical simulation model includes one organically managed and one conventionally managed field. One pest and one predator of the pest move between the two fields over five seasons. In each season, the conventional grower has the option of applying a broad-spectrum pesticide that kills the predator a selective pesticide that has no adverse effects on the predator but is either more expensive or less effective than the broad-spectrum pesticide. The organic grower can apply an organic pesticide, augment the predator population, or both. The simulation model identifies the socially optimal pest control decisions and the Nash equilibrium decisions of both growers over the five growing seasons. The relative price and efficacy of the selective pesticide, the type of predator, and the type of pest introduction all influence whether or not either or both growers make inefficient decisions. Under certain conditions, regional pest management, equivalent to coordination of pest control across growers, could increase total regional profits.

Key Words: spatial-dynamic games, spatial externalities, non-cooperative games, organic agriculture, biological control, agricultural policy
JEL Codes: C61, C72, Q18, Q52, Q57

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1. Introduction

The ever-rising demand for organic products has and will continue to increase organic acreage in the United States. This increase in acreage will increase the frequency of interactions between conventional and organic farms as they more often share the same regional landscape.[1] Sharing the same landscape implies that they share spatially dispersed pest and beneficial insect populations. The movement of these organisms links farms within a region, potentially causing one grower's pest control decisions to affect other growers. This paper examines these interactions in a spatial-dynamic framework.

The model includes two representative profit-maximizing growers. One utilizes organic production methods on one field, and, on the neighboring field, the other utilizes conventional methods. Both growers manage an insect pest that moves freely between the two fields. Their pest management decisions directly and/or indirectly affect the region's population of a predator of the pest, and this predator provides naturally occurring pest control. The movement of the pest and the separate movement of the predator link the growers' fields spatially, while the generations of the pest and predator link the fields temporally. The analysis compares the growers' privately optimal pest control decisions that maximize their individual profits to the socially optimal decisions that maximize the total profit obtained by the two growers. This comparison identifies situations where a grower's private choices over pest control lower the region's total profits via negative externalities created by the movement of organisms.

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[1] During the 1990s, demand for organic products increased an average of 20% annually. This growth in demand fueled growth in organic crop acreage. Between 1992 and 2005, organic cropland more than quadrupled, increasing from 403,400 acres to just over 1.7 million acres (USDA, 2008). Prior to the current recession, demand was predicted to increase annually by an additional 9 to 16% through 2010 (Dimitri and Oberholtzer, 2005). Since the beginning of the recession, total sales have continued to increase, but at a slower rate (California Certified Organic Farmers, 2009).

Interestingly, the model shows that, even when externalities exist, they need not result in inefficiencies. This is due, in part, to the discrete choice nature of the problem and, in part, due to the interactions of the externalities. The presence of interacting externalities can either mitigate or exacerbate the effects of the externalities. This paper will demonstrate how pesticide attributes affect the presence of inefficiencies, and it will show that the type of pest pressure and the type of predator are important determinants of whether or not inefficient decisions are made.

2. 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 pest control. Growers can introduce other pest control agents, such as pesticides or commercially purchased natural enemies, into the crop production system. Additionally, they can use cultural controls such as adjusting planting or harvesting times, choosing pest-resistant varieties, improving field sanitation, or managing water and nutrients. When the cost of controlling the pest is less than the revenue lost due to pest damage, growers maximize profit by choosing a pest control method. The type of pest control chosen in part depends on the type of production used by the grower. Conventional growers have a wider range of pest control options than organic growers; organic regulations restrict organic growers to a subset of the options available to conventional growers.

Pest controls kill, harm, or repel insect pests, and they can also negatively affect beneficial insects like natural enemies. The toxicity of all pest control options to natural enemies falls along a spectrum, ranging from highly toxic to non-toxic.

Pesticides with a broad range of targeted pests tend to fall at the highly toxic end of the spectrum. All synthetic broad-spectrum pesticides (BSPs), such as organophosphates, carbamates, and pyrethroids, fall at this end. These pesticides are not species-specific, so any particular BSP is capable of killing multiple pest species and may have lethal and sub-lethal effects on natural enemies.[2] Neem oil and spinosad, two products with organically approved formulations, may fall next on the spectrum, although evidence is mixed. In laboratory studies, they have negative effects on natural enemies, yet in the field, no evidence of pest resurgences due to lowered enemy populations after applications has been reported (Johnson and Krugner, 2004). This may be due to laboratory conditions that differ considerably from field conditions.

Pest controls that have short-lived residues and/or only target a small range of insects fall in the moderately toxic range. Insect pathogens, such as *Bacillus thuringiensis* (*Bt*), have some lethal and sublethal effects on natural enemies, but less than many synthetic BSPs, neem oil, and spinosad, due to short-lived residues (Johnson and Krugner, 2004)[3]. Like neem oil and spinosad, some formulations of insect pathogens are approved for organic use. Insect growth regulators target specific hormones that 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, so these will not kill natural enemies that do not contain the specific hormone (Cornell University Cooperation Extension, 2001). Since insect growth regulators are synthetic materials, only conventional growers can apply them.

Pheromones have little toxicity to natural enemies because each pheromone targets only

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[2] 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 services (Dresneux et al, 2007).

[3] The residue length refers to *Bt* that is applied to fields, not *Bt* produced by genetically modified organisms. In the latter case, *Bt* is constantly present.

one species of pest. Growers use these naturally produced chemicals to attract pests into traps or to interfere with mating (Cornell University Cooperative Extension, 2001). Some application methods and formulations of pheromones are approved for organic use. Organically approved natural repellants such as herbal teas, plant extracts, and clay or rock powder repel pests with little to no effect on natural enemies (Zehnder et al., 2007).

Cultural and biological controls fall at the non-toxic end of the spectrum. While biological control occurs naturally when beneficial insects are present, growers can also encourage increased biological control. They can provide habitat, pollen, and nectar to attract natural enemies to their fields and may be able to establish populations large enough to keep pest populations under control (Zehnder et al., 2007). If augmentation through resource provision does not establish sufficient natural enemies, the grower can purchase commercially available natural enemies to release in the field. Growers may make releases 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, which have limited effects on natural enemies.

Despite their high toxicity to natural enemies, many growers still rely on BSPs. In 2007, the three most commonly applied insecticide active ingredients were chlorpyrifos and acephate, organophosphates, and aldicarb, a carbamate. Thirty-five percent of all pounds of insecticide applied in 2007 were organophosphates (Grube et al. 2011). More selective controls such as insect growth regulators and pheromones tend to be more expensive than BSPs 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 BSPs (Lundgren et al., 2002; Trumble and Morse, 1993). Thus, the use of BSPs is more widespread than the use of selective methods due to both efficacy and cost considerations.

In contrast, certified organic farms cannot use synthetic BSPs 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 on nearby fields can make the use of natural enemies more challenging. A respondent to a 2010 California citrus grower survey wrote that the pesticides used by a neighboring strawberry grower killed predatory insects and resulted in reduced predatory insect populations on his own fields. According to a supplier of commercially available natural enemies, organic growers 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, Green Methods, personal communication, July 1, 2008). This pest control problem is economically significant since the less expensive and/or more effective conventional method imposes an externality on the organic grower.

At the same time, organic practices can be less effective than conventional practices (Tamm et al., 2004), which can lead to a negative externality imposed on nearby conventional growers. Additionally, as will be shown below, higher pest levels on organic farms may drive the movement of the natural enemy population, altering the negative externality imposed by the conventional grower. Finally, augmentative releases of natural enemies can yield a positive externality because the released natural enemies can provide pest control for neighboring growers as well.

Previous literature has examined components of the problem we address. Work has been done on optimal management strategies for multiple growers who act cooperatively and are linked by the movement of insects (Ives and Settle, 1997; Levins, 1969). Keane et al. (2003) model the effects experienced on surrounding farms when one grower unilaterally alters his pest control, and all growers follow a given pest management plan. Finally, several model the choice among different types of pest control strategies, but they do not incorporate cross-grower effects (Liu et al., 2005 and Reichelderfer and Bender, 1979). We include such effects in my model. To the best of my knowledge, our work is the first to model the choice of pest control strategies by individual profit-maximizing heterogeneous growers whose fields are linked by the movement of pests and natural enemies.

3. Economic Model

We model two adjacent and equally sized fields, an organic field, *o*, and a conventional field, *c*. Field sizes are normalized to 1. Each field is managed by a profit-maximizing grower. Time is indicated by *t*. One pest, with population N_t, and one predator of the pest, with population P_t, move between the two fields. In the absence of the pest, grower *i*, $i \in \{c, o\}$, could achieve a potential output of $\overline{y}^i$, assuming that pest control decisions are separable from all other grower decisions with respect to output. While for some real-world cases this is a strong assumption, it greatly simplifies the problem at hand. The pest population on field *i* will damage a portion of the output, $\frac{N_t^i}{K}$, where *K* is the pest carrying capacity per field. In total, we consider four pest control methods: three pesticides whose type will be indexed by k = o (organic), S (selective), and B (BSP), and predator augmentation (A).

The conventional grower chooses between two pest control methods: a selective pesticide (SP) application, X_t^S, and a BSP application, X_t^B. Pesticide type k kills $\beta_t^k X_t^k$ pests. We model pesticide use on a per-acre basis; that is, we normalize the recommended application rates such that $X^B = X^S$.[4] We specify that $\beta^B \geq \beta^S$, implying that the effectiveness of the SP is less than or equal to the effectiveness of the BSP. The SP, representing a selective conventional option such as an insect growth regulator, does not kill or impair the predator, allowing the predator to provide the conventional grower with pest control. In contrast, the BSP kills $\sigma^B X^B$ predators, where σ^B is the number of predators killed per unit of BSP applied. The BSP also impairs all surviving predators, preventing them from consuming pests in the time period of the application. The price per unit of pesticide type k is w^k, where $w^B \leq w^S$, implying that the SP is at least as expensive as the BSP. The conventional grower's profit for period t is $p^c \bar{y}^c \left(1 - \frac{N_t^c}{K}\right) - w^k X_t^k$, where k is the conventional grower's choice of pesticide for period t.

The organic grower chooses among three pest control options each period. He can apply an organic pesticide, X_t^o, with a unit price of w^o; release natural enemies, A_t, with a unit price of *v*; or do both. Like the conventional grower, the organic grower uses recommended application rates. The organic pesticide application rate is normalized to be the same as the recommended selective and BSP application rate per acre. The organic pesticide, representing a selective method like a plant extract or pheromone trap, is more expensive than the BSP, and it is assumed to be half as effective as the BSP. The predators released by the grower are assumed to have the same effect on the pest population as naturally occurring ones, although in reality, the former type of predator may not be as effective as the latter. When used in combination, the total control

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[4] Normalizing application rates to be equal across pesticide types allows us to focus on the cost and effectiveness of an application per acre (or field) instead of a pound of pesticide per acre. Growers commonly follow recommended application rates, so representing the grower's pest management decision as a choice of method is more accurate than representing it as a choice of method and, contingent on that method, a pounds per acre choice.

provided by augmentation and the organic pesticide does not exceed the efficacy of the conventional BSP in a given season. The organic grower's profit for period *t* equals $p^o \bar{y}^o \left(1 - \frac{N_t^o}{K}\right) - w^o X_t^o - vA_t$. Both growers' profit maximizing pest control choices will depend on the population dynamics of the pest and predator.

4. Population Model

The population dynamics connect the fields through time and space. We use the population models and parameter values specified in the analysis of natural enemy enhancement by Kean et al. (2003), an article from the entomological literature that examines the pest control benefits of biological control. We chose to utilize their work because of the realism embedded in the population dynamics; both the pest and predator populations face limits to their growth. Field i's pest population grows through reproduction, $R^i N_t^i \left(1 - \frac{N_t^i}{K}\right)$, where R^i is the maximum per capita growth rate possible. Field *i's* pest population declines due to predation. Each natural enemy searches for the pest at a rate of a^i, attacks pests that it finds at a rate of f^i, and kills $\frac{a^i f^i N_t^i}{f^i + a^i N_t^i}$ pests in each time period, making the total number of pests killed in time *t* by field i's natural enemy population $\frac{a^i f^i N_t^i}{f^i + a^i N_t^i} P_t^i$ pests. Pesticides kill $\beta^k X_t^k$ pests in each time period.

Movement between fields also affects the pest populations. The net gain in pests on field i is $\mu_N\left(N_t^j - N_t^i\right)$ where *j* represents the other field. A certain portion of the difference in populations, μ_N, moves between the fields. If $\mu_N > 0$, then pests disperse in order to obtain a greater quantity of resources per individual, and if $\mu_N < 0$, then pests aggregate. When $\mu_N = 0$, there is no density dependence of movement. This analysis will focus on the case where pests diffuse ($\mu_N > 0$) since this is a common assumption in the pest control literature.

We consider two types of pest pressure. The first assumes that a certain number of pests, N_0, is introduced onto each field prior to the first production period, but after this initial introduction or infestation of the pests, no more pests enter the two field system ("initial pest introduction"). Under these conditions, if N_0 is a small to moderate introduction, the growers are capable of eliminating the pest during the time periods modeled. Once the pest is eliminated, the growers no longer need to apply control. The second type of pest pressure assumes that in each time period $\overline{N}$ pests move onto each field from outside of the two-field system ("recurrent pest introductions"). Under these conditions, the growers cannot eliminate the pest. In this analysis, we assume that $\overline{N}$ is constant for all time periods, $\overline{N} = N_0$ and $\overline{N}$ in period 1 will be denoted N_0 in order to represent the dynamics for both types of pest pressure within the same equation.

Although in reality pests often move between neighboring fields during the growing season, this model implicitly assumes they move only between growing seasons due to the discrete time aspect of this problem and the small number of time steps used for simplicity in the numerical analysis. The pest population on field *i* in time *t* can thus be written as:

$$(1)\ N_t^i = N_{t-1}^i + N_{t-1}^i R^i\left(N_{t-1}^i\right)\left(1 - \frac{N_{t-1}^i}{K}\right) - \frac{a^i f^i N_{t-1}^i}{f^i + a^i N_{t-1}^i} P_{t-1}^i - \beta^k X_t^k + \mu_N\left(N_{t-1}^j - N_{t-1}^i\right) + \overline{N},$$

where $\overline{N}$ will equal zero for all *t* for the case of only an initial introduction of pests and will equal a positive constant when $t \in \{2,3,4,5\}$ for the case of recurrent pest introductions.[5] If the conventional grower applies the BSP in period *t*, then the BSP eliminates the predator's ability to locate the pest ($a^i = 0$) and/or attack the pest ($f^i = 0$). With these effects present, the predator does not kill any pests, and the pest population in time *t* reduces to:

$$(2)\ N_t^c = N_{t-1}^c + N_{t-1}^c R^c(N_{t-1}^c)\left(1 - \frac{N_{t-1}^c}{K}\right) - \beta^c X_t^c + \mu_N(N_{t-1}^o - N_{t-1}^c) + \overline{N}.$$

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[5] When t = 1, $N_{t-1}^i = N_0$, which is set equal to the same positive constant as $\overline{N}$.

The predator population on field i increases by $\gamma^i \frac{a^i f^i N_{t-1}^i}{f^i + a^i N_{t-1}^i} P_{t-1}^i$ through reproduction where γ^i is the number of preadtors that result from consuming a pest. The natural death rate of the predator, g, results in $\frac{P_t^i}{g}$ predator deaths each period. We consider two types of predators, and the type determines the predator dispersal function. For the first type, we assume that the predator moves from the field with a lower pest population to the field with a higher pest population. If $N_t^i > N_t^j$, field i will receive $P_t^j \frac{N_t^i - N_t^j}{\left(N_t^i + N_t^j\right)/2}$ predators. Conversely, if $N_t^i < N_t^j$, field i will lose $P_t^i \frac{N_t^j - N_t^i}{\left(N_t^i + N_t^j\right)/2}$ predators. This sort of movement is associated with specialist predators who only consume a small number of insect species. As a result of their specialization, they actively seek out the pest species (Hajek, 2004). This is in contrast to generalist predators who consume a wide range of insect species and, consequently, move from areas of higher predator density to areas of lower predator density to obtain a higher level of resources per individual instead of actively seeking out the pest species (Hajek, 2004). In this case, field i will receive $\mu_P(P_t^j - P_t^i)$ predators from field j where $\mu_P > 0$. If $P_t^j > P_t^i$, there will be a net loss of predators from field i to field j. For simplicity, the predator dispersal will be represented as $\phi(P_t, N_t)$, where P_t and N_t are vectors of the two grower's predator and pest populations. The functional form used will be the one that represents the type of predator being modeled.

Finally, pest control can affect the predator population. The BSP kills $\sigma^B X^B$ in any time period when it is applied, and augmentation adds A_t predators. The selective and organic pesticides have no direct effect on the predator population. If the conventional grower uses the SP, then the predator population in time t is:

$$(3)\ P_t^c = P_{t-1}^c + \gamma^c \frac{a^c f^c N_{t-1}^c}{f^c + a^c N_{t-1}^c} P_{t-1}^c - \frac{P_{t-1}^c}{g} + \phi(P_t, N_t)$$

If the conventional grower uses the BSP, any predators that survive the application become too impaired to attack the pest population, and without consuming the pest, the predators cannot reproduce. Consequently, the population in time *t* becomes

$$(4)\ P_t^c = P_{t-1}^c - \frac{P_{t-1}^c}{g} + \phi(P_t, N_t)$$

The organic grower's predator population in time period *t* is

$$(5)\ P_t^o = P_{t-1}^o + \gamma^o \frac{a^o f^o N_{t-1}^o}{f^o + a^o N_{t-1}^o} P_{t-1}^o - \frac{P_{t-1}^o}{g} + \phi(P_t, N_t)$$

Combining the economic and population models creates a bioeconomic simulation model. Table 1 contains a summary of all variables used in the simulations, their definitions, and their numerical values or ranges.

The simulation model contains five growing seasons, $t \in \{1,2,3,4,5\}$. The use of five growing seasons allows the insects to move four times, and consequently allows growers to affect each other four times. However, this number of time periods is small enough to keep the problem a manageable size for the optimization methods that will be described below. Additionally, a relatively short time horizon is appropriate in the context of pest management. With invasive species bringing new pest problems, pesticide companies introducing new pesticides on the market, and changing weather patterns changing pest conditions, one can reasonably assume that growers do not plan their pest control on a long-term time horizon as they might do for decisions such as long-term investments in equipment. However, growers who are interested in utilizing natural enemies will likely think beyond one growing season since populations of beneficials generally build up over time. Consequently, the choice of five time periods allows for the possibility that growers consider multiple periods without assuming that they have pest management decisions planned for the next twenty years.

5. Two Optimization Problems

To identify cases where private decisions lead to inefficient outcomes, we compare the privately optimal and socially optimal decisions. We solve for the private optimum as a Nash equilibrium between two non-cooperative growers, as recommended by Horowitz et al. (1996). Each grower maximizes his own profits over the five time periods without considering how his actions affect his neighbor. However, each grower considers how the neighbor's pest management choices may affect his own profits and chooses his best response. We assume that in the social optimum, joint profits are maximized over the five time periods, taking into account how the growers' decisions affect each other's profits.[6] When the two solutions diverge, inefficiencies will exist. In such cases, the growers would benefit from an intervention that encourages cooperation or induces the socially optimal decisions. In many cases, even though pest control externalities are present, the Nash equilibrium decisions align with the socially optimal decisions.

5.1. Private profit maximization

In the private profit maximization problem, the organic and conventional growers simultaneously maximize profits subject to the same set of pest and predator population dynamics. The organic grower's optimization problem is

$$(6)\ \max_{d_t^o, d_t^A} \sum_1^5 \left[p^o \overline{y}^o \left(1 - \frac{N_t^o}{K}\right) - d_t^o w^o X_t^o - d_t^A v A_t\right] \frac{1}{(1+r)^{t-1}}$$

subject to

$$(7) N_t^o = N_{t-1}^o + N_{t-1}^o R^o(N_{t-1}^o)\left(1 - \frac{N_{t-1}^o}{K}\right) - \frac{a^o f^o N_{t-1}^o}{f^o + a^o N_{t-1}^o} P_{t-1}^o - d_t^o \beta^o X_t^o + \mu_N (N_{t-1}^c - N_{t-1}^o) + \overline{N}$$

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[6] While pesticides may generate negative externalities that occur off-farm, such as surface water contamination or indoor air pollution, we focus only on externalities that occur within the two-field system.

(8) $N_t^c = N_{t-1}^c + N_{t-1}^c R^c(N_{t-1}^c)\left(1 - \frac{N_{t-1}^c}{K}\right) - d_t^S \frac{a^c f^c N_{t-1}^c}{f^c + a^c N_{t-1}^c} P_{t-1}^c - d_t^S \beta^S X_t^S - (1 - d_t^S)\beta^B X_t^B +$

$\mu_N(N_{t-1}^o - N_{t-1}^c) + \bar{N}$

(9) $P_t^o = P_{t-1}^o + \gamma^o \frac{a^o f^o N_{t-1}^o}{f^o + a^o N_{t-1}^o} P_{t-1}^o - \frac{P_{t-1}^o}{g} + \phi(P_t, N_t) + d_t^A A_t$

(10) $P_t^c = P_{t-1}^c + d_t^S \gamma^c \frac{a^c f^c N_{t-1}^c}{f^c + a^c N_{t-1}^c} P_{t-1}^c - \frac{P_{t-1}^c}{g} + \phi(P_t, N_t) - (1 - d_t^S)\sigma X_t^B$

where $d_t^o = \begin{cases} 1 \; if \; X_t^o > 0 \\ 0 \text{ otherwise} \end{cases}$, $d_t^A = \begin{cases} 1 \; if \; A_t > 0 \\ 0 \text{ otherwise} \end{cases}$, and $d_t^S = \begin{cases} 1 \; if \; X_t^S > 0 \\ 0 \text{ otherwise} \end{cases}$.[7]

The conventional grower's optimization problem is:

(11) $\max_{d_t^S} \sum_1^5 \left[p^c \bar{y}^c \left(1 - \frac{N_t^c}{K}\right) - d_t^S w^S X_t^S - (1 - d_t^S) w^B X_t^B\right] \frac{1}{(1+r)^{t-1}}$

subject to (7) though (10).

To eliminate affects of terminal condition assumptions, we assume that the ending populations of the pest and predator do not affect the growers' profit calculations. This would occur if growers switched to a different crop after five years that has different pests and predators, if the growers converted or sold their land to a non-agricultural use, or if growers simply do not know conditions well enough that far into the future to determine the value of pests and predators. This assumption, however, does make the growers less likely to conserve the predator in the final period.

To solve for the Nash equilibrium, we use Matlab to simulate every possible combination of decisions (7,776 combinations) and then determine the combination that is each grower's best response.

5.2. Social optimum

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[7] We assume that each grower's field is homogenous, implying that the grower would not choose to apply one method for a portion of the field and another method for the remaining portion.

The social planner's optimization problem is:

$$(12)\ \max_{d_t^S, d_t^A, d_t^o} \sum_1^5 \left[p^o \overline{y}^o \left(1 - \frac{N_t^o}{K}\right) + p^c \overline{y}^c \left(1 - \frac{N_t^c}{K}\right) - d_t^o w^o X_t^o - d_t^A A_t - d_t^S w^S X_t^S - (1 - d_t^S) w^B X_t^B \right] \frac{1}{(1+r)^{t-1}}$$

subject to (7) through (10). As we do to identify the Nash equilibrium, we simulate joint profits under all combinations of decisions and determine the combination that maximizes joint profits.

6. Effects of Relative Conventional Pesticide Attributes with a Specialist Predator

In some cases, SPs are less effective at controlling the pest than BSPs are, while in other cases the price of SPs may exceed the price of BSPs. These two negative attributes could also be present in the same SP. In order to determine how the price and efficacy of the SP affect any divergence between the social optimum and Nash equilibrium, we vary these two attributes of the SP, holding all other parameters constant. For each level of efficacy and price, we evaluate the difference in the growers' socially optimal and Nash equilibrium pest management decisions, and we calculate the welfare gains that would be achieved if the social optimum were reached. The nature of the problem leads to natural bounds on the range of relative efficacies and prices that we examine. We begin by specifying that the SP is equally as effective as the BSP, $\beta^S = \beta^B$, and then reduce its effectiveness in increments of 10% of the effectiveness of the BSP until it is half as effective as the BSP. At that point, its effectiveness equals that of the organic pesticide. For relative price, we begin by specifying that the price of the SP is equal to \$6, the price of the BSP. We increase the price of the SP in increments of \$2 from \$6 to \$18. The selective and BSPs are assumed to be twice as effective as the organic pesticide that has a unit price of \$9. At a price of \$18, the SP's price per unit of efficacy is equal to the organic pesticide's price per unit of efficacy. If the SP's price rises above \$18, the conventional grower will choose the organic pesticide instead of the SP, if avoiding the BSP is optimal. In total, we examine 7 prices and 6 efficacies, resulting in 42 price and efficacy combinations.

We conduct this comparison for the two types of pest pressure previously described: the initial pest introduction and recurrent pest introductions. For each relative efficacy and price combination, we vary the size of the initial, N_0, or recurrent, $\overline{N}$, pest introduction(s) from 100 pests per field to the field carrying capacity of 5,000 pests per field in increments of 100 pests per field, yielding 50 populations levels for each SP attribute combination.

Figures 1 through 4, discussed below, have the same basic structure, so this will be discussed here. For each graph, the origin is at (100,6). At this point, the SP is equally as effective as the BSP and has the same price as the BSP. As the plot moves right along the x-axis, the relative efficacy of the SP decreases. As the plot moves up along the y-axis, the price of the SP increases. As the plot moves northeast from (100,6), the relative efficacy decreases and the price increases simultaneously. All of the graphs in Figures 1 and 3 have the same scale on the z-axis for comparison purposes. The color scale, however, varies for each panel to ensure clarity in the surfaces. Similarly, all of the graphs in Figures 2 and 4 have the same scale on the z-axis for comparison purposes, while having different color scales for clarity. Finally, each value plotted on the z-axis represents the value summed or averaged over the range of 50 pest introduction levels for the given price and efficacy combination.

6.1. Initial pest introduction only

Figure 1 depicts the presence of inefficient decisions as the price and efficacy of the SP vary. Panels a and b pertain to the initial pest introduction only. Panel a plots the number of pest introduction levels (out of 50 levels) for which the organic grower's Nash equilibrium decisions are not socially optimal for each SP price and efficacy combination. The right-hand panel plots the number of pest introduction levels for which the conventional grower's Nash equilibrium decisions are not socially optimal for each price and efficacy combination.

For the conventional grower, if the five-period decision includes the use of the SP in some periods, and the BSP in others, he always begins with the SP. Beginning with the BSP and switching to the SP would not be optimal because the early season broad-spectrum application would reduce the predator population and greatly reduce the benefit of conserving it in later periods. Inefficient decisions occur in the Nash equilibrium when the conventional grower chooses to apply the BSP in an early period when the use of the SP is socially optimal. For the initial pest introduction only and the specialist predator, the conventional grower's inefficient decisions only differ from the socially optimal decisions in one growing season, either the first or the second season.

In Figure 1, panel b, there are two noteworthy trends in the conventional grower's inefficient decisions. First, as the SP's price increases, there are more introduction levels for which the conventional grower's decision is inefficient. As the price of the SP increases, the negative externality avoided by applying the SP remains the same, but the private cost of applying the SP increases. Consequently, we see that the conventional grower is less likely to choose the SP even though it is socially optimal to do so. On the other hand, as the relative efficacy of the SP decreases, the net positive externality decreases. This occurs because even though the use of the SP conserves the predator, it also causes more pests to remain after the application than would remain had the conventional grower applied the BSP. Consequently, we see that initially, as SP efficacy decreases, inefficient decisions increase, but after about 70% relative efficacy, the inefficient decisions begin to decrease. At lower levels of efficacy, the BSP is socially optimal.

The organic grower's inefficient Nash equilibrium decisions all involve cases where the organic grower chooses to apply just the organic pesticide in at least one season when it is socially optimal to apply the organic pesticide and make an augmentative release of the predator in the same season. The augmentative release generates a positive externality for the conventional grower in two ways. First, it adds additional pest control on the organic field, decreasing the total number of pests present in the two-field system. Second, some of the predators and/or their offspring may eventually move onto the conventional grower's field, increasing the quantity of biological control occurring on that field. However, given the assumption of a specialist predator here and that the less effective organic controls will result in elevated pest populations on the organic field, the net movement of predators will be from the conventional field to the organic field. This will largely eliminate the second positive externality.

Indeed, we see that the organic grower makes few inefficient decisions in this situation, and almost half of the price, efficacy, and pest introduction level combinations that yield inefficient decisions are combinations for which the conventional grower's decisions are also inefficient and involve the use of the BSP. For these cases, both growers would benefit from a move to the social optimum.

In Figure 2, panels a-c, we plot the percent welfare gains achieved by reaching the social optimum. The graphs plot the percent increase in profits relative to a case without any pest control averaged over the fifty introduction levels for each price and efficacy combination. For those introduction levels where the Nash equilibrium decisions are socially optimal, the gain is zero, and these zero gains are included in the averages presented. Although the prevalence of the conventional grower's inefficient decisions varies considerably over the parameter space, there is little variation in welfare gains. This implies that even though inefficient decisions occur, the magnitude of the welfare loss is small on average.

6.2 Recurrent Pest Introductions

Changing the nature of the pest introduction from an initial introduction only to recurrent introductions changes the prevalence of both the organic grower and the conventional grower's inefficient decisions. With recurrent pest introductions, the predator's food source persists at a stable level throughout the five growing seasons. This allows the predator population to increase over time. With only an initial pest introduction, the food source declines over time, and so the predator population also declines over time. Additionally, the predation rate per predator decreases as the pest population decreases. Recurrent introductions have two effects on the possible externalities. First, the negative externality generated by a BSP application increases because such an application kills predators that had the potential to have more offspring and higher predation rates compared to predators killed by the BSP with an initial pest introduction only. Second, the positive externality generated by an augmentative release increases. Each of the released predators can potentially provide increased control of the pest because of the continuous, stable food source.

Indeed, we see in Figure 1, panel c that for all price and efficacy combinations, the organic grower makes inefficient decisions for more introduction levels than he did with only the initial introduction, depicted in panel a. The overall trend in the organic grower's inefficient decisions is a reduction in inefficient decisions as the SP's relative efficacy decreases. As the relative efficacy decreases, the conventional grower provides less pest control for the two-field system when he applies the SP. This lowered control lessens the organic grower's incentive to utilize too little pest control, and results in the organic grower using the socially optimal combination of the organic pesticide and augmentation.

For the conventional grower, we still find that at low efficacy levels, the BSP is often socially optimal, and inefficient decisions taper off. However, we see an increase in introduction levels for which the conventional grower makes inefficient decisions for cases where the SP's price is from $6 to $12. This is due to the increased negative externality generated by a BSP application that makes the SP socially optimal under this type of pest introduction.

Figure 4, panels d-f plot the average welfare gains from achieving the social optimum. We see that the organic grower can gain an average of almost 6% in profits if the social optimum is reached when the price of the SP is $14 and the efficacy of the SP is 90% of the efficacy of the BSP. We see that for the conventional grower, achieving the social optimum results in welfare losses when the SP is about 70% as effective as the BSP or when the SP is relatively expensive with high efficacy. Overall, achieving the social optimum yields the highest percent gains in profits when the SP is between 70 and 80% as effective as the BSP, and when the SP is relatively expensive but effective.

We see greater welfare gains with recurrent introductions than with only the initial introduction because the type of introduction increases the magnitude of the possible externalities.

7. Effects of Pesticide Attribuites with a Generalist Predator

Thus far, we have assumed that predators follow the pest population and move to the field with a higher pest population. As discussed in section 3, this type of predator movement characterizes a specialist predator. Because the organic pest control methods are less effective than the conventional BSP, the organic field tends to have more pests remaining at the end of each growing season, which causes predators to migrate there from the conventional field. Consequently, the externalities associated with using the BSP in later periods will be lower than in early periods because fewer predators will remain on the conventional field. While the assumed movement lessens the negative externality of using the BSP in later growing seasons, it also decreases the conventional grower's incentive to apply the SP. Doing so conserves predators, but a portion of these predators will move to the organic field. These two impacts counteract each other. The first suggests that the specialist dispersal function will decrease the number of inefficiencies relative to alternative specifications, while the second suggests that it will increase the number of inefficiencies relative to alternative specifications.

In order to understand the factors that determine the net effect, we also consider a generalist predator implying a dispersal function such that predators move from the field with a higher predator population to the field with the lower predator population. The less effective organic pesticide results in a higher pest population and hence a higher predator population on the organic field. This will result in a net movement of predators to the conventional field. As was the case for the specialist predator dispersal function, there are two offsetting effects. From a social perspective, this movement increases the externality associated with the use of the BSP because an application of the BSP will increase the predator population gradient between the two fields. From the conventional grower's perspective, this movement increases his incentive to apply the SP because a portion of his conserved predators no longer emigrates to the organic field.

7.1. Initial pest introduction only

With an initial pest introduction and a generalist predator, we see more introduction levels for which the conventional grower's decisions are inefficient when the SP is relatively close in price to the BSP but with efficacy between 60% and 80% of that of the BSP relative to the scenario with an initial introduction and a specialist predator (Figure 3). This change in inefficient decisions resembles the change seen when moving from an initial introduction only to recurring introductions with a specialist predator. Both changes in scenario involve increasing the magnitude of the negative externality generated by the BSP. With an initial introduction and generalist predator, we also see an increase in the number of introduction levels that lead to inefficient decisions by the conventional grower when the price of the SP is relatively highly. Again, this is driven by the increased negative externality generated by the BSP. We do not see increases in inefficient decisions when efficacy is quite low because at 50% efficacy, the BSP is often socially optimal.

The organic grower's pattern of inefficient decisions is similar to the case with an initial introduction and a specialist predator except that the inefficient decisions are slightly more concentrated at higher SP prices. This is likely driven by the conventional grower's inefficient decision to apply the BSP instead of the targeted pesticide, which decreases the organic grower's incentive to augment the predator population in addition to applying the organic pesticide.

As we saw for the case of a specialist predator and an initial introduction only, the welfare gains obtained by reaching the social optimum are small for the case of a generalist predator and an initial introduction only (Figure 3, panels a-c).

7.2. Recurrent pest introductions

As discussed earlier, with recurrent pest introductions the externality generated by a BSP increases relative to the case with only an initial introduction because predators in the former scenario have a higher reproductive potential. Combining this increase in externality with the increase that occurs due to a generalist predator would seem to imply that this scenario would result in many more pest introduction levels for which the conventional grower makes inefficient decisions than the previous scenarios. On the contrary, there are fewer introduction levels for which the conventional grower makes inefficient decisions in this scenario compared to the case with an initial introduction with a generalist predator and recurrent introductions with a specialist predator. This reduction in inefficient decisions occurs because in this scenario, even though the potential externality is the greatest, the incentive to conserve predators for his own use is also the greatest. For many price, efficacy, and introduction level combinations, the effects of this incentive on the conventional grower's decision outweigh the effects of the negative externality. Most of the conventional grower's inefficient decisions occur when the SP is about 70% as effective as the BSP. For efficacies greater than this, the conventional grower tends to choose the socially optimal applications involving the SP, and for efficacies lower than 70%, the BSP is often socially optimal.

The organic grower also makes fewer inefficient decisions in this scenario relative to the case of recurrent introductions and a specialist predator. In the latter scenario, predators move, on net, towards the organic field, allowing the organic grower to free-ride off of the conventional grower's predators and making him less likely to augment the predator population. With the generalist predator, the net movement is towards the conventional grower. This means that augmentative releases have a larger positive externality, but it also means that the organic grower has a smaller incentive to free-ride and use too little pest control. We see that as the SP efficacy decreases, the organic grower's inefficient decisions decrease, due to a smaller incentive to apply too little pest control.

While the potential welfare gains from achieving the social optimum were small for the case of an initial pest introduction and a generalist predator, they are larger for the case of a generalist predator and recurring pest introductions, particularly for the organic grower (Figure 3, panels a-c). While the conventional grower makes fewer inefficient decisions in this scenario, when those inefficient decisions are made, they have a large effect on the organic grower due to the increase in magnitude of the negative externality generated by BSP applications. The organic grower could achieve an average of up to a 9.4% increase in profits relative to the case without pest control if the social optimum is achieved when the SP is 80% as effective as the BSP and three times its price ($18). The maximum average total welfare gain from achieving the social optimum is about 2.7%.

It is important to note that the higher pest population on the organic field (which generates a negative externality) relative to the conventional field drives the net movement of predators, under either dispersal function. With a specialist predator, a larger pest population on the organic field attracts more predators from the conventional field, decreasing the negative externality generated by BSP applications occurring in later seasons. With a generalist predator, higher pest levels on the organic field lead to a larger net movement toward the conventional field, increasing the externality generated by BSP applications in later periods. This is an interesting case of one externality altering the magnitude of another externality.

8. Comparison of the Effects of Differing Population Dynamics

The type of pest introduction and type of predator have substantial effects on the number of introduction levels and SP attribute combinations for which either the organic or conventional grower or both growers make inefficient decisions. For each introduction and predator type combination, 42 price and efficacy combinations were considered, and the simulations were run for 50 introduction levels for each price and efficacy combination yielding a total of 2,100 simulation runs. Table 2 presents the percent simulations for each introduction and predator type combination for which the organic grower makes inefficient decisions, for which the conventional grower makes inefficient decisions, and for which at least one grower makes inefficient decisions. The last column presents the percent of simulations for which both the organic and conventional growers make inefficient decisions. These simulations are included in the numbers for the individual growers.

The first important thing to note is that for every introduction and predator combination, less than 28% of the simulations result in inefficient decisions. For every simulation, both positive and negative externalities exist, yet the growers make efficient decisions most of the time. This is in part due to the discrete choice nature of the decision. Thus far, little has been discussed about the pest introduction levels at which the growers are making inefficient decisions, and this detail sheds light on why we find so many cases of efficient decisions. As we vary the magnitude of the initial or recurrent pest introductions, inefficient decisions tend to occur in the middle range of the number of pests introduced when the SP is less effective than the BSP, holding its price equal to that of the BSP. This is the case regardless of whether the introduction is an initial introduction or recurrent. For low initial and recurrent pest introductions, pest pressure is low enough that the conventional grower can control the pest with the SP despite its decreased efficacy. As the number of pests introduced increases, the conventional grower switches to the more effective BSP in the Nash equilibrium, but, in doing so, he impedes the organic grower's use of the predator population and reduces social welfare. In this range, inefficiencies occur. For high pest introductions, larger numbers of pests remain after treatment with the less effective SP. The total cost of damages incurred by both growers from these remaining pests outweighs the total benefits of damages prevented by predators conserved by using the SP, so the conventional grower's choice of the BSP is socially optimal.

When the SP is more expensive than the BSP, but of equal efficacy, inefficient decisions also tend to occur in the middle range of the number of pests introduced, regardless of whether the introduction is only an initial one or occurs every period. For low initial and recurrent pest introductions, the pest pressure is low enough that both the organic and conventional growers can control the pest without the help of the predator. The BSP is both privately and socially optimal for low initial pest populations. The organic grower's pesticide is less effective than the conventional pesticides, so as the initial or recurrent pest introduction increases, the organic grower will reach a range of pest introduction levels in which he is unable to completely control the pest without the help of the predator, but the conventional grower continues to apply the BSP. In this range, inefficiencies occur. For high pest introduction levels, a larger predator population can be supported, and the pest control provided by this population outweighs the increased costs of the SP. Consequently, the conventional grower chooses the socially optimal SP for high levels of pest introductions.

When the SP is both more expensive and less effective than the BSP, both of the two tradeoffs occur simultaneously, but there are still cases where the conventional grower chooses the socially optimal SP in the Nash equilibrium, and cases where the BSP is socially optimal. In these cases, externalities are present, but the decisions are efficient.

The second important thing to note is that both the organic grower and the conventional grower make inefficient decisions. While organic might be considered a "better" type of agricultural production by some, the organic grower can also make inefficient decisions by not combining their organic pesticide with augmentation, resulting in a lower total amount of pest control utilized than is socially optimal. For three of the four introduction and predator type combinations, fewer simulations resulted in the organic grower making inefficient decisions than the conventional grower making inefficient decisions. However, with recurrent pest introductions and a specialist predator, 19.7% of the simulations result in the organic grower making an inefficient decision. This is almost six percentage points higher than the conventional grower's maximum number of inefficient decision runs. The organic grower’s inefficient decisions occur for more simulations with a specialist predator and recurrent pest introductions because of the incentives these population dynamics give the organic grower to free-ride. The organic grower’s inefficient decisions all involved not making an augmentative release. With a specialist predator, the predators moved on net towards the organic grower. Making the release would have resulted in fewer pests remaining on the organic field, which would decrease the number of predators leaving the conventional field for the organic field and would also decrease the number of pests moving from the organic field to the conventional field. By not augmenting, the organic grower receives more predators from the conventional field later on, and the organic grower free-rides off of the conventional grower’s predators while also increasing the conventional grower’s pest population. With recurrent pest introductions, the predators immigrating from the conventional grower’s field have a higher pest control potential than they would with only an initial pest introduction, increasing the organic grower’s incentive to free-ride.

The incentives created by a specialist predator occur with an initial introduction only as well, but that type of pest introduction dampens the effect of the specialist predator. With an initial introduction, a specialist predator results in 2.4% of simulation runs where the organic grower’s decisions are inefficient while with a generalist predator, only 1.8% of simulations have this result. However, this difference in proportion is not statistically significant. With only an initial introduction, the potential pest control provided by predators emigrating from the conventional field is smaller.

For the organic grower, a specialist predator results in more simulations where inefficiencies occur compared to a generalist predator and a recurrent pest introduction results in more simulations where inefficiencies occur compared to an initial introduction. For the conventional grower, however, the two population dynamics components do not yield these same patterns. With an initial introduction only, there are more simulations for which the conventional grower makes inefficient decisions when the predator is a generalist than when the predator is a specialist. With an initial introduction, the increase in the negative externality generated by a BSP application that occurs when switching from a specialist to a generalist predator outweighs the increase in the incentive for the conventional grower to conserve his predator population. For recurrent pest introductions, however, the conventional grower makes fewer inefficient decisions when the predator is a generalist than when the predator is a specialist. With recurrent introductions and the resultant increase in potential biological control provided by the predator, the increase in the incentive to conserve the predator outweighs the negative externality generated by the BSP.

When considering the effects of the type of pest introduction, a change from initial to recurrent pest introductions with a specialist predator increases the percent of simulations for which the conventional grower makes inefficient decisions due to the increase in magnitude of the negative externality generated by the BSP. However, when considering a generalist predator, a change from initial to recurrent pest introductions decreases the simulations for which the conventional grower makes inefficient decisions due to the increase in magnitude of the incentive for the conventional grower to conserve the predator population.

In total, the largest number of simulations with inefficient decisions occurs with recurrent pest introductions and a specialist predator. This is also the combination that yields the highest percentage of simulations where a prisoner’s dilemma type solution is found; both growers make inefficient decisions in the Nash equilibrium, and both growers would benefit from achieving the social optimum. The lowest percentage of simulations with inefficient decisions occurs with an initial introduction and a specialist predator.

Interestingly, even though recurrent introductions and specialist predator lead to the most number of simulations with inefficient decisions, the average welfare loss averaged over all simulations for a given introduction and predator type combination is highest for recurrent introductions and a generalist predator (Table 3), and this difference is statistically significant. This is driven by the large negative externality that results in this scenario from the BSP. Even though the conventional grower does not choose it as often in the Nash equilibrium as he does with a specialist predator, when he does choose the BSP inefficiently, the resulting welfare loss felt by the organic grower is large. One will also note that the expected welfare loss is rather small for all scenarios. This is due to the fact that for the majority of simulations, even though externalities are present, the growers make efficient decisions in the Nash equilibrium. In general, the organic grower benefits more from obtaining the social optimum. Even though total welfare gains are small, if there are other positive externalities associated with organic production that are not included in this model, policies that help achieve the social optimum with respect to the pest control decisions considered here will increase organic profits and improve the viability of organic production.

9. Summary, Conclusions, and Policy Implications

This paper shows that the movement of pests and predators creates spatial externalities in pest control, and that these externalities sometimes, but not always, lead to inefficient pest control decisions. For all cases, the inefficiencies tend to occur in the middle range of the number of pests introduced for both initial or recurrent pest introductions. At both ends of the introduction size, the private and social net benefits of the SP are either both positive or both negative, and, consequently, the conventional grower's decisions are efficient in these ranges. At intermediate levels, the net private and social benefits of the SP change signs, but not at the same initial or recurrent pest introduction level. Inefficient decisions made by the conventional grower occur in the interval between the introduction levels where the two types of net benefits change signs.

Interestingly, although the externalities from both the organic and conventional pest controls are always present, under many sets of parameter values, the externalities are small enough that growers still make efficient pest control decisions. Under these conditions, there will be no benefits to cooperation. Social welfare may even decrease as a result of cooperation if sufficiently large transaction costs are present. Similarly, if efficient pest control occurs in spite of the existence of externalities, regulation cannot improve social welfare.

These observations have two important policy implications. First, from both an individual grower's perspective and society's perspective, the development of effective SPs is paramount for increasing the adoption of SPs since ineffective SPs are frequently not socially optimal. Second, for a given relative efficacy, the development of inexpensive SPs will decrease the occurrence of inefficient pest control decisions by increasing the conventional grower's incentive to apply them.

The type of pest introduction is an important determinant of how often the Nash equilibrium diverges from the social optimum. With only an initial introduction of the pest, the pest population gets smaller in each time period and can potentially be eliminated. As the pest population decreases, the predator population decreases as does the amount of control each predator provides. With recurrent pest introductions, new pests enter the fields in each time period, keeping the predator population high and increasing the number of pests killed per predator each period. Consequently, the value of predators conserved and the value of predators augmented or received through dispersal is higher with recurrent pest introductions, and the magnitudes of the positive and negative externalities is greater. This implies that cooperation will be more beneficial for recurrent pest introductions.

In reality, most crops face a variety of pests. Some species achieve economic importance every year, requiring treatment every season. Others achieve economic importance only sporadically. These two cases can be interpreted in terms of initial and recurring pest introductions. For example, the California red scale, a major citrus pest, requires treatment almost every year in California's San Joaquin Valley while the citrus bud mite is only occasionally found and treated (Ewart et al., 2003). The simulation results suggest that many more inefficiencies will occur in the control of the red scale than in the control of the citrus bud mite. The results apply to invasive pests as well. Pest control used to treat invasive pests that spread rapidly and quickly re-colonize areas after treatment will lead to more inefficiencies than pest control used to treat invasive pests that move more slowly and take more time to re-colonize after treatment.

The type of predator movement also influences the occurrence of inefficient decisions, but the effect differs by pest introduction type. Movement associated with generalist predators and parasitoids leads to more pest introduction levels that result in inefficiencies than movement associated with specialist predators with only an initial pest introduction. Specialist predators lead to more pest introduction levels that result in inefficiencies when there are recurrent pest introductions. Commercial producers of natural enemies tend to favor production of generalist species due to the larger potential market. For pests with recurrent introductions, this practice may help reduce inefficient decisions, but for initial introductions only, it may increase inefficients.

While many of the inefficiencies identified here are due to the conventional grower's choice of pesticides, there are cases where the organic grower makes inefficient pest control decisions. Specifically, there are cases where augmentation has a positive externality that is large enough to warrant an augmentative release even when it is not profitable for the organic grower. In such cases, subsidizing natural enemy releases could help align the Nash equilibrium with the social optimum.

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Tables and Figures

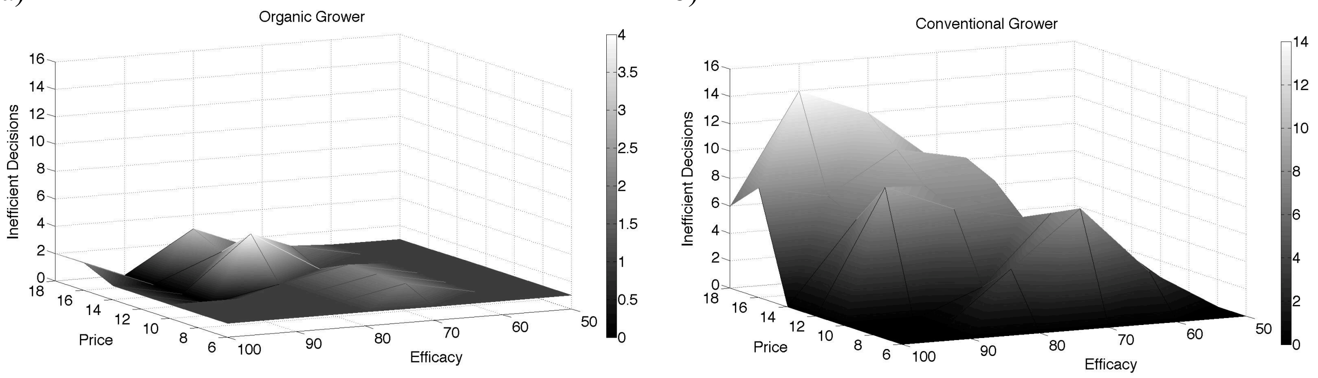
Table 1. Variables and Parameter Values: Base Case

Variable	Definition	Value/Range	
		Organic	Conventional
N_0	Initial Pest Introduction per Field	0-5,000	0-5,000
$\overline{N}$	Recurrent Pest Introduction per Field	0-5,000	0-5,000
P_0	Initial Enemy Population per Field	200	200
$\overline{y}$	Maximum Possible Output	1,000	1,000
P	Unit Price of Output	\$2.50	\$2.00
w^B	Unit Price of BSP		\$6
w^S	Unit Price of SP		\$6-18
w^o	Unit Price of Organic Pesticide	\$9	
v	Unit Price of Augmentation	\$5	
r	Interest Rate	0.05	0.05
β^B	Number of Pests Killed per Unit of BSP		100
β^S	Number of Pests Killed per Unit of SP		50-100
β^o	Number of Pests Killed per Unit of Organic Pesticide	50	
a	Enemy Search Rate	0.001	0 or 0.001
f	Enemy Attack Rate	10	0 or 10
γ	Number of Enemies that Result from Eating/Parasitizing a Pest	0.01	0.01
g	Enemy Death Rate	50	50
K	Pest Carrying Capacity per Field	5,000	5,000
R	Maximum Pest Per Capita Growth Rate	0.2	0.2
μ_N	Proportion of the Difference in Pest Levels that Emigrates	0.5	0.5
σ	Number of Enemies Killed by 1 Unit of BSP		100
X^k	Recommended Units of Pesticide Type k	15	15
A	Recommended Number of Natural Enemies Released	25	

Figure 1. Number of Initial or Recurrent Introduction Levels for which the Organic Grower and Conventional Grower Make Inefficient Decisions in the Nash Equilibrium.

Initial Introduction

a) b)



Recurrent Introductions

c) d)

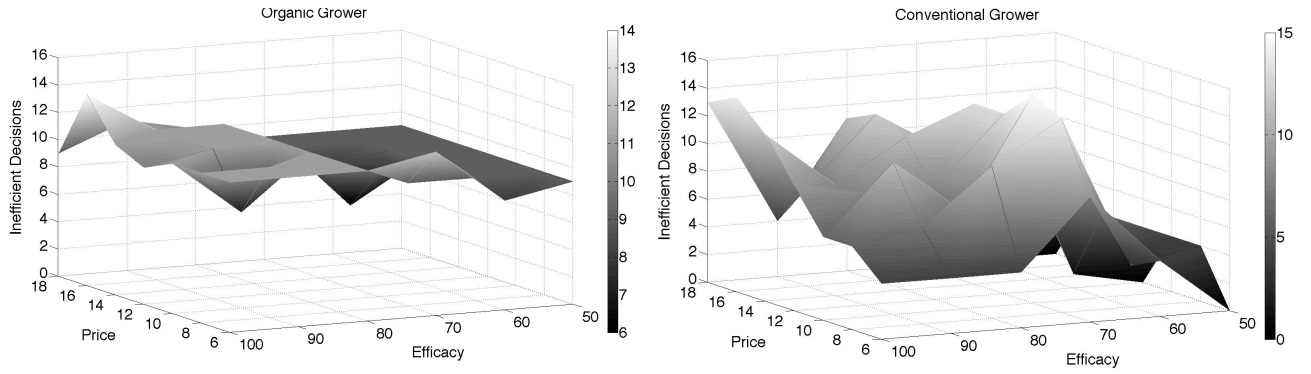
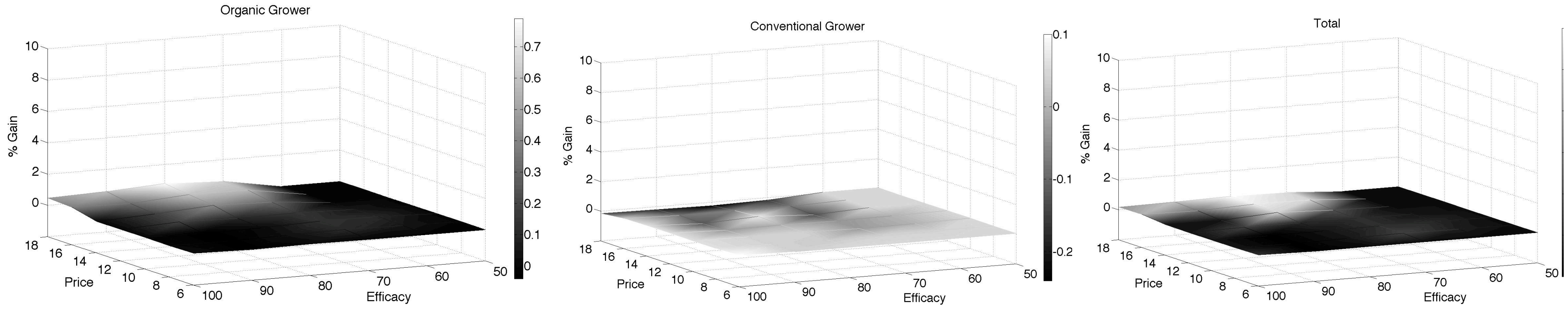


Figure 2. Percent Welfare Gains from Achieving the Social Optimum for the Organic Grower, the Conventional Grower, and Both Growers Averaged over All Introduction Levels

Initial Introduction

a) b) c)



Recurrent Introductions

d) e) f)

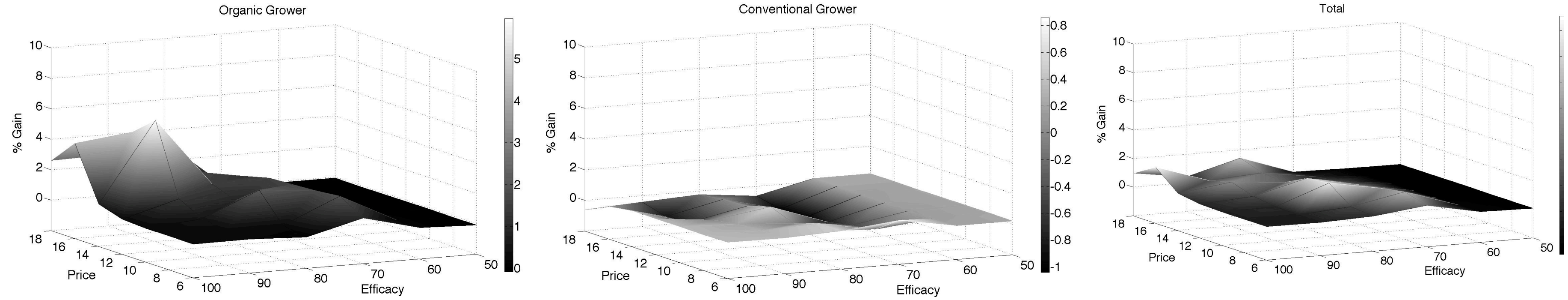
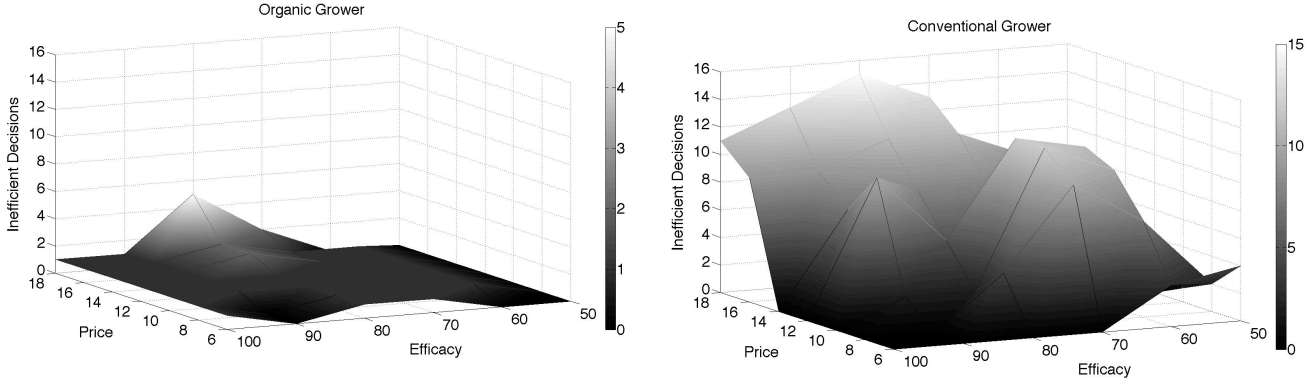


Figure 3. Number of Initial or Recurrent Introduction Levels for which the Organic Grower and Conventional Grower Make Inefficient Decisions in the Nash Equilibrium with a Generalist Predator.

Initial Introduction Only

a) b)



Recurrent Introductions

c) d)

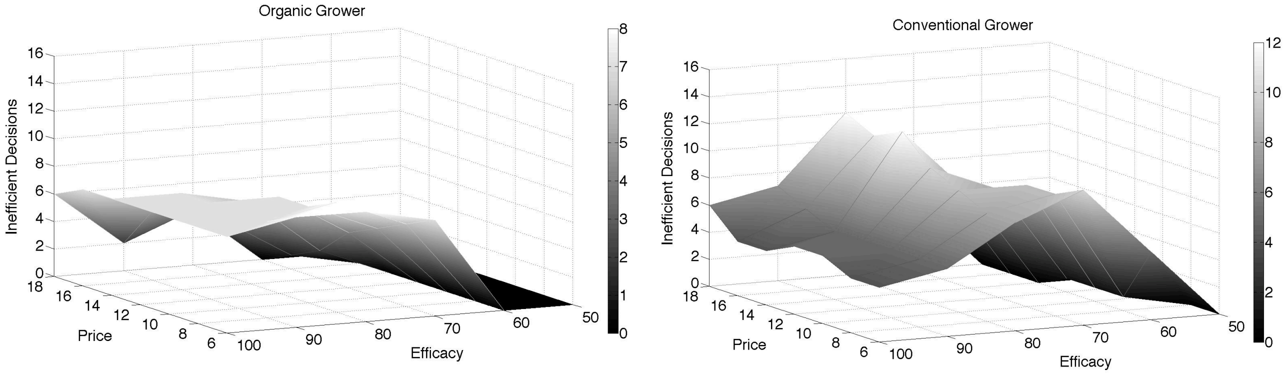
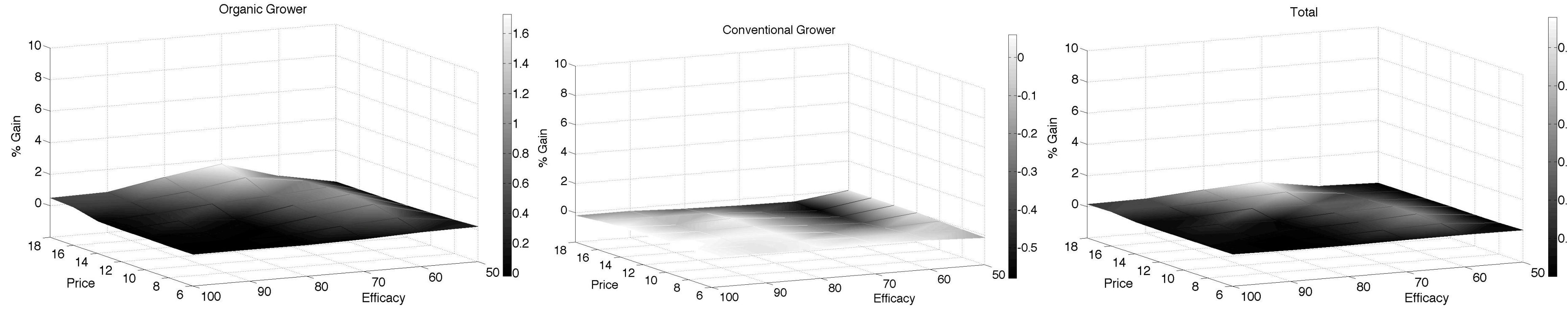


Figure 4. Percent Welfare Gains from Achieving the Social Optimum for the Organic Grower, the Conventional Grower, and Both Growers Averaged over All Introduction Levels with a Generalist Predator

Initial Introduction


a) b) c)

Recurrent Introductions

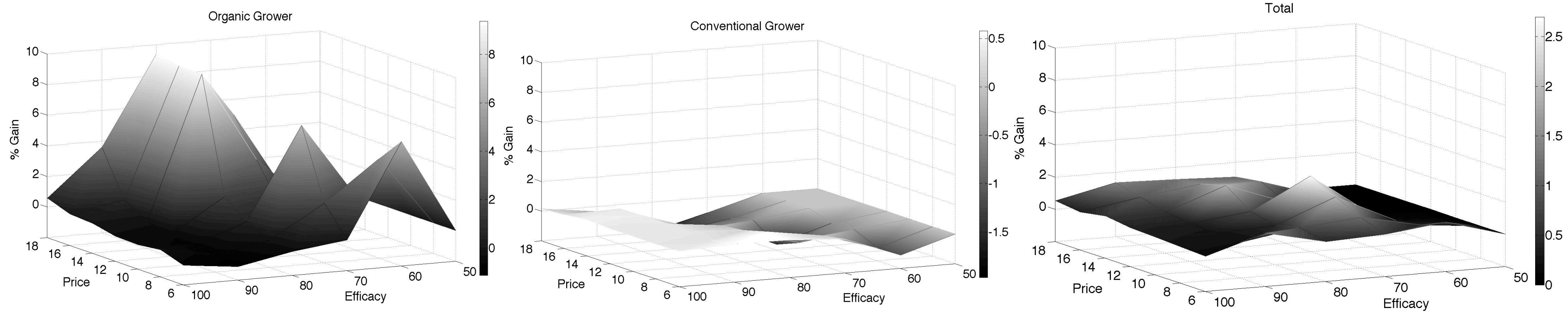

d) e) f)

Table 2. Percent of Pest Introduction Levels for with the Organic and/or Conventional Growers Make Inefficient Decisions in the Nash Equilibrium[1]

Pest Introduction	Predator Type	Organic	Conventional	Total with Inefficiencies	Subset that is Prisoner's Dilemma
Initial Only	Specialist	2.38	7.05***	8.38***	1.05
Initial Only	Generalist	1.81	11.19*	11.71***	1.29
Recurring	Specialist	19.67***	13.95***	27.33***	6.29***
Recurring	Generalist	7.62***	9.67*	15.43***	1.86

*, **, and *** indicate a statistically significant rejection of the hypothesis of pair-wise equality with each of the other proportions in the column at the 10%, 5%, and 1% level, respectively, for a two-tailed test.

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[1] We examine 42 combinations of price and efficacy and run the simulations for 50 introduction levels for each combination leading to 2,100 introduction levels for each of the four introduction and predator type combinations.

Table 3. Minimum, Mean, and Maximum Percent Profit Gains (Relative to No Pest Control) Possible by Achieving the Social Optimum for the Organic Grower, Conventional Grower, and Both Growers Combined[1]

Pest Introduction	Predator Type	Organic Min	Organic Mean	Organic Max	Conventional Min	Conventional Mean	Conventional Max	Total Min	Total Mean	Total Max
Initial Only	Specialist	-0.04	0.14***	0.79	-0.24	0.00	0.10	0.00	0.08***	0.30
Initial Only	Generalist	-0.02	0.38***	1.73	-0.58	-0.11***	0.06	0.00	0.14***	0.68
Recurring	Specialist	-0.08	1.02***	5.97	-1.04	0.01	0.86	0.07	0.53***	1.91
Recurring	Generalist	-1.13	1.57***	9.38	-1.97	-0.16***	0.58	0.00	0.61***	2.70

*, **, and *** indicate a statistically significant rejection of the hypothesis of pair-wise equality with each of the other means in the column at the 10%, 5%, and 1% level, respectively, for a two-tailed test with known variance.

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[1] The minimum, maximum, and mean are based on the percent profit gains averaged over 50 pest introduction levels for each SP price and efficacy combination. Consequently, the percent gain for a specific pest introduction level and price and efficacy combination may be lower than the minimum listed here or higher than the maximum listed here. These statistics are generated from the averages for each price and efficacy combination because for some of the higher pest introduction levels, profits for both the Nash equilibrium and social optimum were very small, and divergences between the two equilibria lead to large percent gains with small absolute gains.