When Ignorance Is Not Bliss:
Pest Control Decisions Involving Beneficial Insects

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Abstract: Recent survey data revealed that many California citrus growers did not know whether or not important beneficial insects were found on their fields while other growers were relying heavily or even entirely on these insects for pest control. Some pesticides are toxic both to the targeted pest and the predaceous or parasitic insect that could provide pest control. Alternative pesticides with fewer or no negative effects on the beneficial insect often exist but can be more expensive. Additionally, some beneficial insects are commercially available and can be purchased and released in the field. This paper models the pest control decisions of a grower who optimally utilizes a pesticide and a predaceous insect to control the crop pest and compares these decisions to that of a grower who does not know that the predaceous insect exists. The results show that the latter grower will drive the predator population to zero and will overutilize chemical control. The optimal decisions involve entirely mitigating the negative effects of the pesticide as well as releasing additional predators.

Keywords: beneficial insect, dynamic optimization, pest control, pesticide

1. Introduction

Between 2000 and 2008, expenditures on pesticides increased by 37.6% in the United States, and 2008 nationwide expenditures on pesticides were 5.8% of the total nationwide expenditures on commercial agricultural inputs (USDA, 2009). Since pest control expenditures are a significant and growing share of production costs, achieving efficient pest control will significantly benefit growers.

In addition to expenditures on pesticides, the use of pesticides can have a variety of negative agricultural, environmental, and health effects. These damages total an estimated $12 billion for the United States alone (Pimental, 2009). A reduction in pesticide use would necessarily reduce these damages.

While many growers rely on chemical pest control, growers can also make use of biological and cultural controls. Biological control involves the use of organisms, often insects, to control the crop pests. Common biological controls include predators and parasitoids of crop pests, which provide natural pest control services through their trophic interactions with the pest. Unfortunately, many common pesticides are toxic to beneficial insects. Growers can conserve naturally occurring populations of these beneficial insects by avoiding pesticides that are toxic to them and can support the populations through the provision of habitat and supplemental resources. Additionally, some of these insects are commercially produced, allowing growers to purchase and release them on their fields. Cultural controls include planting pest resistant varieties, altering planting and/or harvesting times, and adjusting crop spacing to create less hospitable conditions for crop pests.

A recent survey of California citrus growers revealed that only about 58% of respondents with *Aonidiella aurantii* (California red scale) on their fields knew whether or not *Aphytis melinus*, a parasitic wasp that provides control of *A. aurantii*, was present on their fields (Grogan and Goodhue, 2012b). Only about 51% of all respondents knew whether or not *Rodolia cardinalis*, the primary form of pest control for *Icerya purchasi* (cottony cushion scale) was present, and only about 43% knew whether or not *Euseius tularensis*, a predator of *Panonychus citri* and *Scirtothrips citri*, was present (Grogan and Goodhue, 2010).

This lack of knowledge about the presence of beneficial insects raises an important question: How do growers' pest management decisions differ from the optimal decisions if they are unaware that predaceous or parasitic insects are present? Using a dynamic bioeconomic model, this paper addresses this question and shows that a lack of knowledge in almost all cases results in local extinction of the beneficial insect and consequently leads to complete elimination of the associated pest control services. Since these services are both free and cause little to no external damages, these lost services are economically significant.

This work fits within a larger body of literature that considers optimal pest control decisions in a dynamic framework. Some of the earlier work in this body of literature uses dynamic models to analyze the effects of the pest's growing resistance to the pesticide on the optimal use of the pesticide over time (Plant et al. 1985, Regev et al. 1983). More recent work focuses on optimal management of invasive species across time and space (Brown et al. 2002, Ceddia et al. 2009). Some work has added a predaceous insect population, but without considering the possibility of pesticide toxicity to the predator (Marsh et al. 2000, Schumacher 2006).

Several papers outside of the economics literature consider the effects of pesticide toxicity on the predator in agricultural systems. Trumper and Holt (1998) and Sherratt and Jepson (1993) use landscape level models to determine the effect of pesticide toxicity to the predator on pest populations. They find that pest resurgences after pesticide applications increase as the pesticide's toxicity to the predator increases. Increased predator dispersal helps to dissipate this effect and helps enable the predator to persist in the system despite applications of the pesticide.

In the economics literature, three previous papers address the question at hand. Previous work by Harper and Zilberman (1989) and Harper (1991) examine pesticide use decisions for static and dynamic models, respectively, that include a primary pest, a secondary pest, and a predator of the secondary pest which is negatively affected by the pesticide used to control the primary pest. They find that growers who ignore the effect of the pesticide on the predator will overuse the pesticide. Feder and Regev (1975) examine pesticide use decisions using a model containing one pest and one predator. They compare optimal decisions made by a central decision maker who considers environmental effects as well as population dynamics to decisions made by an individual who only considers one period at a time. The latter decisions are inefficient due to both stock and environmental externalities.

The model that follows differs from previous work in several ways. First, the model here allows the grower to mitigate the effect of the pesticide on the predator and even allows the grower to augment the predator population, allowing for a more thorough analysis of possible optimal solutions. Second, this paper considers three types of decisions: pest control without the predator present, pest control with the predator present but with its pest control services attributed to an unknown factor, and pest control with a known predator. Harper and Zilberman (1989) compare the first and third cases, but do not consider the intermediate case. Harper (1991) considers a case myopic case where the predator is present and consumes the secondary pest, but the grower does not consider the damage caused by the secondary pest in their optimization problem. This essentially eliminates the predator from the optimization problem. Lastly, the analysis presented here thoroughly examines how varying economic and biological parameters affects the divergence between the optimal and the myopic solutions, and to the best of my knowledge, is the first to demonstrate that field-level beneficial insect populations will be driven to zero under most circumstances when growers are unaware of their presence.

This paper proceeds as follows. First, the bioeconomic model is presented. A discussion of the optimal pest management decisions follows. This is followed by a discussion of the myopic decisions that do not account for pest control services to the predator and the decisions for the case with no predator population. Next, the decisions for a wide variety of possible parameter values are considered, and finally, conclusions and policy implications are provided.

2. Methods

The model that follows combines a biological model with an economic model to form a bioeconomic model of pest control decisions and pest and predator populations.

2.1. Biological Model

The model contains one pest and one predator of the pest. Unlike previous work, this analysis does not contain a secondary pest. Previously, conventional thought assumed that chemical control was used to control primary pests and biological control was only used for secondary pests, as demonstrated in Harper and Zilberman (1989) and Harper (1991). Now, biological control is also being used for primary pests, making such analysis relevant (Grogan and Goodhue, 2012a). The interaction of the pest and predator is modeled using a Lotka-Volterra predator-prey model with logistic pest growth, following the population modeling work by Trumper and Holt (1998)'s analysis of pesticide toxicity on predator populations. In the absence of human intervention, the pest and predator growth functions are:

$$\dot{N}_t = \gamma N_t(1 - (N_t/K)) - \mu P_t N_t \tag{1}$$

$$\dot{P}_t = \alpha\mu P_t N_t - \beta P_t \tag{2}$$

where N_t and P_t are the pest and predator populations in time period *t*, respectively, γ and α are the pest's and predator's intrinsic growth rates, respectively, K is the pest's carrying capacity, μ is the predation rate, and β is the predator death rate.

In the absence of human intervention, this system reaches an equilibrium where $\dot{N}_t = \dot{P}_t = 0$, which occurs when:

$$N_t = \beta/\alpha\mu \tag{3}$$

$$P_t = (\gamma/\mu)(1 - (\beta/(\alpha\mu K))) \tag{4}$$

For the predator to persist in equilibrium, it must be the case that $\beta/(\alpha\mu K) < 1$. Since K is likely to be large and β is less than one, the predator will persist in most cases.

2.2. Economic Model

Following the model format of previous literature, the grower produces a crop that, in the absence of the pest, could achieve an output of $\bar{y}$, but the pest damages a proportion of the crop, N_t/K (Brown et al. 2002, Ceddia et al. 2009, Marsh et al. 2000). To control the pest, grower has a range of pest control options. The base pesticide, which will be referred to as level of chemical effort, E_t, has a unit price of w. This is the grower's least expensive option, but it is toxic to the predator. The grower can mitigate this toxic effect by substituting more expensive but less toxic pesticides (with respect to the predator) that have equal pest control efficacy as the base pesticide. The level of mitigation chosen, M_t, has a unit price of v in addition to the cost of the chemical effort. The price of mitigation can be thought of as the price differential between the base pesticide and more selective options. The grower can partially mitigate the effect on the predator ($M_t < E_t$), completely mitigate the toxic effect on the predator ($M_t = E_t$), or can choose mitigation such that the toxic effect is entirely mitigated and more predators are added to the system through the purchase and release of additional predators ($M_t > E_t$). While M_t can differ from E_t, only the level of E_t determines the effect of chemical control on the pest. This situation is similar to the case of California red scale control in citrus. Growers can apply an inexpensive pesticide such as chlorpyrifos to control the scale, but this pesticide is toxic to *A. melinus*. Growers can choose to apply more expensive insect growth regulators, which have no effect on *A. melinus*. Growers also have the option to apply the insect growth regulator and purchase and release *A. melinus* (Grafton-Cardwell, 2009).[1] The grower's profit in each time period is:

$$\pi_t = p\bar{y}(1 - (N_t/K)) - wE_t - vM_t \tag{5}$$

2.3. Bioeconomic Model

With the introduction of pest control, equations (1) and (2) become:

$$\dot{N}_t = \gamma N_t(1 - (N_t/K)) - \mu P_t N_t - qE_t N_t \tag{6}$$

$$\dot{P}_t = \alpha\mu P_t N_t - \beta P_t - \phi(E_t - M_t)P_t \tag{7}$$

where q is the toxicity of the pesticide to the pest and ϕ is the toxicity of the pesticide to the predator. The assumption of linear kill functions, $-qE_tN_t$ and $-\phi(E_t - M_t)P_t$, follows previous literature (Marsh et al. 2000, Harper 1991). When $M_t > E_t$, ϕ can be thought of as the rate at which released predators contribute to the total population. The shipping and releasing process may lead to a less than 1-to-1 correspondence between released predators and viable, effective predators.

3. Three Pest Management Cases

The analysis considers three pest management cases: optimal pest management that considers the pest control services provided by the predator, myopic pest management that does not consider

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[1] The grower could also potentially rely entirely on *A. melinus* for control. I assume that this is not the case for the model's pest. This assumption holds for cases where the biological equilibrium with augmentation exceeds the threshold population level at which growers apply a pesticide.

the pest control services provided by the predator, and pest management in the absence of a predator population. Each case has its own optimization problem.

3.1. Optimal Pest Management

The optimization problem that determines the optimal pest control decisions is:

$$\max_{E_t,M_t} \int_0^{\infty} (p\bar{y}(1-(N_t/K)) - wE_t - vM_t)\, e^{-rt} dt \tag{8}$$

subject to equations (6) and (7).

The Hamiltonian becomes:

$$H = p\bar{y}(1-(N_t/K)) - wE_t - vM_t + \lambda_{Nt}(\gamma N_t(1-(N_t/K)) - \mu P_t N_t - qE_t N_t) + \lambda_{Pt}(\alpha\mu P_t N_t - \beta P_t - \phi(E_t - M_t)P_t) \tag{9}$$

Since the optimization problem is linear in the control variables, the solution entails a "most rapid approach" to the singular path, by choosing either the maximum or minimum possible values for the control variables. Upon reaching the singular path, the optimal solution is to remain on the singular path forever (Hartl and Feightinger 1987). This is a good approximation of pest control decisions where growers often do nothing until a threshold population level is reached, at which point they apply the optimal level of control. For large infestations, growers will apply the maximum possible pest control until the population has been reduced to an economically acceptable level. The maximum possible level of pest control is generally the maximum application rate allowed for the given pesticide.

The Hamiltonian yields the following first order conditions:

$$E_t = \begin{cases} 0 \; if \; w + \lambda_{Pt}\phi P_t > -\lambda_{Nt} q N_t \\ E^{SS} \; if \; w + \lambda_{Pt}\phi P_t = -\lambda_{Nt} q N_t \\ E_{max} \; if \; w + \lambda_{Pt}\phi P_t < -\lambda_{Nt} q N_t \end{cases} \tag{10}$$

$$M_t = \begin{cases} 0\, if\ v > \lambda_{Pt}\phi P_t \\ M^{SS}\, if\ v = \lambda_{Pt}\phi P_t \\ M_{max}\, if\ v < \lambda_{Pt}\phi P_t \end{cases} \tag{11}$$

$$-\partial H/\partial N_t = p\bar{y}/K - \lambda_{Nt}(\gamma - 2\gamma(N_t/K) - \mu P_t - qE_t) - \lambda_{Pt}\alpha\mu P_t = \dot{\lambda}_{Nt} - r\lambda_{Nt} \tag{12}$$

$$-\partial H/\partial P_t = \lambda_{Nt}\mu N_t + \lambda_{Pt}(\alpha\mu N_t - \beta - \phi(E_t - M_t)) = \dot{\lambda}_{Pt} - r\lambda_{Pt} \tag{13}$$

where E^{SS} and M^{SS} are the singular solutions defined in (16) and (17) below, E_{max} is the maximum possible effort level dictated by the maximum allowed application rate for the particular pesticide, and M_{max} is the maximum possible augmentation rate which will be dictated by the maximum number of predators that the system can absorb. In equation (10), $-\lambda_{Nt}qN_t$ represents the present discounted value of crop damages avoided by one more unit of chemical effort. The grower will apply no control if the cost of the control (both unit price as well as the value of the negative effects on the predator population) exceeds the present discounted value of crop losses prevented by the pesticide. Conversely, the grower applies the maximum control when the cost of doing so is less than the value of damages prevented. When the cost and damage prevented are equal, the grower applies the singular level of control. The cost and benefit of mitigation similarly determine the level of mitigation chosen.

Equation (10) has interesting implications for pest eradication. As N_t goes to zero, the marginal value of chemical control, $-\lambda_{Nt}qN_t$, also goes to zero.[2] Consequently, unless chemical control is free, the pest level at which the grower switches to no control will be positive. Thus, the grower will never eradicate the pest with chemical control alone. This is observed in reality frequently; primary pests are present in every season and never fully eradicated.

The steady state solution to this problem can be derived from the first order conditions

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[2] The marginal damage of a pest is constant, so λ_{Nt} does not go to negative infinity as N_t goes to zero.

(please see the supplementary Appendix for derivations and stability analysis of the solution):

$$N^{SS} = r\phi K(w+v)/[p\bar{y}q\phi - \gamma\phi(w+v) - v\alpha\mu qK] \tag{14}$$

$$P^{SS} = rvq/[\mu\phi(w+v)] \tag{15}$$

$$E^{SS} = \frac{\gamma}{q}\left(1 - \frac{r\phi(w+v)}{p\bar{y}q\phi - \gamma\phi(w+v) - v\alpha\mu qK}\right) - \frac{rvq}{\phi(w+v)} \tag{16}$$

$$M^{SS} = \frac{\gamma}{q}\left(1 - \frac{r\phi(w+v)}{p\bar{y}q\phi - \gamma\phi(w+v) - v\alpha\mu qK}\right) - \frac{rvq}{\phi(w+v)} - \frac{1}{\phi}\left(\frac{\alpha\mu r\phi K(w+v)}{p\bar{y}q\phi - \gamma\phi(w+v) - v\alpha\mu qK} - \beta\right) \tag{17}$$

From (14), the steady state pest population could be positive or reach a corner solution at 0, which would imply eradication of the pest. This eradication would be a result of the combination of biological and chemical control, given the conditions determining the level of chemical control. If the pest population is positive in the steady state, the predator population will always be positive. For relevant parameter ranges, discussed below, the optimal steady state pest population always has an interior solution. The steady state values will be discussed further in section 4.

3.2. Myopic Pest Management

In the myopic pest management case, the predator exists and provides pest control, but the grower does not associate the pest control provided with the predator. The grower may instead believe that that portion of the reduction in the pest population is part of the pest's natural death rate (i.e.- deaths due to disease, weather, environmental stress, etc.). This implies that the predator remains in the optimization problem (unlike in previous work), but the grower does not optimize with respect to the predator population and the grower does not mitigate the effect of the pesticide, due to a lack of knowledge.

The optimization problem that determines the myopic pest control decision is:

$$\max_{E_t} \int_0^{\infty} (p\bar{y}(1 - (N_t/K)) - wE_t)\, e^{-rt} dt \tag{18}$$

subject to:

$$\dot{N}_t = \gamma N_t(1-(N_t/K)) - \mu P_t N_t - qE_t N_t \tag{19}$$

$$\dot{P}_t = \alpha\mu P_t N_t - \beta P_t - \phi E_t P_t \tag{20}$$

The Hamiltonian becomes:

$$H = p\bar{y}(1-(N_t/K)) - wE_t + \lambda_{Nt}\big(\gamma N_t(1-(N_t/K)) - \mu\overline{P}_t N_t - qE_t N_t\big) \tag{21}$$

where $\overline{P}_t$ is determined by (20) but $\mu\overline{P}_t N_t$ is viewed by the grower as deaths attributed to other natural causes.

This yields the following first order conditions:

$$E_t = \begin{cases} 0 \; if \; w > -\lambda_{Nt} q N_t \\ E^{SS} \; if \; w = -\lambda_{Nt} q N_t \\ E_{max} \; if \; w < -\lambda_{Nt} q N_t \end{cases} \tag{22}$$

$$-\partial H/\partial N_t = p\bar{y}/K - \lambda_{Nt}\big(\gamma - 2\gamma(N_t/K) - \mu\overline{P}_t - qE_t\big) = \dot{\lambda}_{Nt} - r\lambda_{Nt} \tag{23}$$

Equation (22) indicates that the grower only considers the market cost of chemical control, not the (unknown to the grower) external cost of the control on the predator population.

From the first order conditions, we can derive the steady state pest population:

$$N^{SS} = rKw/[p\bar{y}q - \gamma w] \tag{24}$$

For an interior steady state, it must be that $p\bar{y}q > \gamma w$.

The pest population in (24) is the myopic grower's optimal steady state pest population, but this level could be reached with or without the predator population, and the first order conditions do not yield a myopically optimal predator population. Consequently, the predator population can only be determined by considering the pest and predator equations of motion. In a steady state with both the pest and predator present, $\dot{N}_t = \dot{P}_t = 0$. From $\dot{P}_t = 0$, we can solve for E^{SS} for the case where $P^{SS} > 0$. If this derivation yields a negative E^{SS}, it must be the case that the grower eliminated the predator population en route to the steady state because a negative

E^{SS} implies adding pests to the field. Since $\dot{P}_t = 0$ was used to solve for the negative E^{SS}, it would imply that the grower is adding pests and predators to the field in order to force an equilibrium with both the pest and predator present. Thus, when this method yields a negative E^{SS}, $\dot{N}_t = 0$ is used instead to determine E^{SS}. This is now a viable option because $\dot{N}_t$ will not be a function of P_t when the predator has been driven to extinction. These calculations yield:

$$E^{SS} = \begin{cases} (\alpha\mu rKw/(p\bar{y}q - \gamma w) \ - \beta)/\phi & if\ P^{SS} > 0 \\ (\gamma/q)(1 - (rw/(p\bar{y}q - \gamma w))) & if\ P^{SS} = 0 \end{cases} \tag{25}$$

When $N^{SS} > 0$ and $P^{SS} > 0$, it follows that:

$$P^{SS} = \frac{1}{\mu}\left(\gamma\left(1 - \frac{rw}{p\bar{y}q - \gamma w}\right) - \frac{q}{\phi}\left(\frac{\alpha\mu rKw}{(p\bar{y}q - \gamma w)} - \beta\right)\right) \tag{26}$$

From (26), the first major difference between the socially optimal and the myopic solution is apparent; the predator population can be locally extinct in the myopic steady state even with a positive pest population whereas the predator is always present in the optimal steady state. This has important implications for regional pest control. If predator populations are eliminated on some growers' fields, and if the species needs a minimum amount of space with which to support a thriving regional population, myopic growers may hinder the use of the predator on the fields of growers who are aware of the services the predator provides.

The difference between the optimal and myopic steady state pest populations is given by:

$$N_O^{SS} - N_M^{SS} = (rvqK)(\phi p\bar{y} - w\alpha\mu K)/[(\phi p\bar{y}q - \gamma\phi(w + v) - v\alpha\mu qK)(p\bar{y}q - \gamma w)] \tag{27}$$

The denominator of (27) will be positive if both steady state pest levels are positive, implying that difference depends on the sign of $\phi p\bar{y} - w\alpha\mu K$. For the base parameter values discussed below, this term is positive, implying that the optimal steady state pest population exceeds the myopic steady state pest population. The effect of varying parameter values on this difference will be analyzed below. The difference in steady state effort levels is less concise and depends on the presence of the predator population, so this difference will be analyzed graphically below.

3.3. Pest Management in the Absence of a Predator

In this pest management case, the predator does not exist. With many invasive species, the pest invades, but the predator from its native region does not co-invade. This leads to a pest whose only growth limit is the carrying capacity of the field.

The optimization problem for the optimal pest control decisions in the absence of a predator is:

$$\max_{E_t} \int_0^{\infty} (p\overline{y}(1-(N_t/K)) - wE_t)\, e^{-rt} dt \tag{28}$$

subject to:

$$\dot{N}_t = \gamma N_t(1-(N_t/K)) - qE_tN_t \tag{29}$$

The Hamiltonian becomes:

$$H = p\overline{y}(1-(N_t/K)) - wE_t + \lambda_{Nt}(\gamma N_t(1-(N_t/K)) - qE_tN_t\,) \tag{30}$$

This yields the following first order conditions:

$$E_t = \begin{cases} 0 \; if \; w > -\lambda_{Nt}qN_t \\ E^{SS} \; if \; w = -\lambda_{Nt}qN_t \\ E_{max} \; if \; w < -\lambda_{Nt}qN_t \end{cases} \tag{31}$$

$$-\partial H/\partial N_t = p\overline{y}/K - \lambda_{Nt}(\gamma - 2\gamma(N_t/K) - qE_t) = \dot{\lambda}_{Nt} - r\lambda_{Nt} \tag{32}$$

Equation (31) matches the corresponding first order condition for the myopic case.

From the first order conditions, the steady state pest population is:

$$N^{SS} = rKw/[p\overline{y}q - \gamma w] \tag{33}$$

This steady state pest population is the same as the myopic case. However, in the case where the predator remains in the myopic steady state, the effort level for the case without a predator will be greater than that of the myopic case because the myopic grower still receives pest control services even though he does not know that the predator exists. Without a predator, steady state effort is:

$$E^{SS} = (1/q)\big(\gamma(1 - (rw/(p\bar{y}q - \gamma w)))\big) \tag{34}$$

4. Results: Comparison of Pest Management Decisions

Previous work has calculated the solutions to their specific models but has not thoroughly analyzed how their myopic solutions diverge from their optimal solutions. To analyze the divergences between the steady state solutions, the base population parameter values used are those used in Trumper and Holt (1998) in their model of pest resurgences due to applications of pesticides that are toxic to the predator of the pest. The base economic values are such that in the steady state, growers approximately achieve per acre revenues (\$5,100) and incur per acre pest control costs (\$200) that coincide with the median per acre revenues and control costs found for a sampling of American producers of fruits, vegetables, and nuts (USDA, 2008a-c, UC Davis, 2012). Table 1 lists the starting values. The range of parameters used were obtained from the same sources. Trumper and Holt provide a meta-analysis of population parameters and the USDA and UC Davis resources contain a wide range of crops providing a range of feasible economic parameters.

Since the case without a predator nests within the myopic case when the predator is not present in the myopic steady state, and since it will be demonstrated that the predator rarely exists in the myopic steady state, the comparison focuses on the optimal and myopic solutions.

4.1 Comparative Dynamics

Table 2 displays the sign of the effect of varying parameters on the steady state levels of pests, chemical effort, predators, and mitigation for the optimal and myopic cases. For some parameters the sign of the comparative dynamic is the same for all parameter values. For others, the sign depends on the parameter values. The reported sign is the sign for the base parameter values for this latter group of parameters and noted as such.

When looking at the effects of parameters on the steady state level of the pest population, the first thing to note is that the myopic grower's steady state pest level does not depend on mitigation price, the predation rate, and the toxicity of the pesticide to the predator, while an increase in all three of the parameter values increases the optimal steady state level of pests.

Interestingly, when the myopic grower conserves the predator population in steady state, the effects of varying parameters has the opposite sign than in the optimal case for the majority of parameters. As will be demonstrated below, the predator will only remain in steady state for cases where the pesticide is highly ineffective and the predator is highly effective. In this case, the myopic grower relies predominantly on the predator while the optimal grower still uses a considerable amount of chemical effort in addition to the predator. Consequently, seemingly perverse comparative dynamics result. For example, an increase in output price results in a decrease in pesticide use by the myopic grower. One would expect more pest control used for a higher valued crop, and indeed, the myopic grower is using more control, but in the form of biological control. A reduction in pesticide use allows for a larger predator population, and more total control for the case when the pesticide is ineffective and the predator is highly effective. Since the optimal grower can mitigate the effect of the chemical control on the predator, price has the hypothesized positive effect on this steady state level of chemical effort.

When the predator remains in the myopic steady state, the only parameter that does not have an effect on the myopic level of chemical effort is the mitigation price. Unlike for the myopic pest population, the predator's parameters have effects on the myopic chemical control, even though the myopic grower does not know that the predator exists. The pressure exerted by the predator is enough to influence the pest control decisions, indirectly.

When the predator is driven to extinction before reaching the myopic steady state, those parameters that have an effect on the myopic steady state chemical effort level all have the same qualitative effect as the optimal steady state. However, when the predator is driven to extinction, the pest's carrying capacity, mitigation price, and all predator biological parameters have no effect on the myopic level of chemical effort. This is not surprising since the predator does not exist.

Interestingly, several parameters have no effect on the optimal steady state level of predators while they do have an effect on the myopic steady state level of predators (when the predator exists in steady state). Output price, output quantity, pest carrying capacity, the pest and predator growth rates, and the predator death rate have no effect on the optimal steady state predator population. The optimal grower adjusts the effective predator population and level of predation by adjusting mitigation, so the steady state level of predators remains unchanged by a variety of parameters. For the myopic grower, they must adjust the level of predation by adjusting the steady state predator population.

4.2 Steady State Predator Population

It has already been demonstrated that the predator population will persist in steady state if the pest remains in steady state for the optimal case. The question remains as to which parameter values will allow the predator to remain in the myopic steady state. As discussed earlier, the predator persists in the myopic steady state if setting the predator equation of motion equal to zero yields a positive level of chemical effort. From (25), this will occur when:

$$((\alpha\mu rwK)/(p\bar{y}q + \delta w)) - \beta > 0 \tag{35}$$

For the base parameter values, (35) equals -0.1906. Increasing α, μ, r, and K, or decreasing β, p, $\bar{y}$, q, or δ by large enough magnitudes from their base values will lead to a positive predator population. However, this is only meaningful if the parameter values are within realistic ranges. The value of (35) could be calculated repeatedly over all combinations of logical ranges for the parameters of interest. Doing so, however, creates an unwieldy 8-dimensional parameter space. Consequently, pairs of parameters are varied while holding all other parameters at their base values. The parameters were only varied in the direction that increases the likelihood that the predator remains in steady state. This process was done for five pairs of parameters: w and p (since p and $\bar{y}$ always enter the optimization as $p\bar{y}$, only p is varied here and is done so to yield a per acre revenue that represents the minimum found in the literature), α and β, α and δ, K and p, and μ and q. These pairs were chosen because they are economic or biological pairs that represent a logical tradeoff. The ranges were determined by looking at minimum and maximum possible values reported in the literature, and the upper or lower bounds are shown in Table 1 for the parameters of interest (Trumper and Holt, 1998; USDA, 2008a-c, UC Davis, 2012).

All five pairs of parameters yielded a zero predator population over the whole range of parameters considered. The citrus grower survey mentioned earlier suggested that there might be a case where a high predation rate coinciding with a low efficacy pesticide would allow the predator to persist in the myopic steady state as appears to be the case with the vedalia beetle, a predaceous insect that controls cottony cushion scale. To test this hypothesis, μ and q were considered, and μ was increased until a positive predator population was found. The maximum value for μ found in Trumper and Holt's (1998) review of the literature was approximately 0.04.

The predator population does not remain in the myopic steady state until μ reaches 0.24 with q equal to 0.1 (Figure 1). In this case, the pesticide is very ineffective, while the predator is highly effective. While no predation rates could be found for the vedalia beetle, when first introduced, its "voracious feeding activities … were visible and impressively dynamic, and the beneficial results were instantly apparent" (Caltagirone and Doutt, 1989). This suggests that the vedalia beetle might be an outlier with regards to predation, allowing it to persist even though growers are not aware of its presence. Additionally, chemical controls are not very effective at controlling cottony cushion scale, indicating a low value for q and placing the vedalia beetle/cottony cushion scale case in the range where the predator might persist (Grafton-Cardwell, 2012).

Harper (1991) finds that the predator population will be reduced by the application of the pesticide but leaves the model unparameterized and does not demonstrate that the predator will be driven to extinction for realistic ranges of the parameters. Additionally, Harper does not explicitly solve for the optimal predator population and so does not determine that the optimal case always conserves the predator.

4.3. Steady State Pest Population

It was demonstrated above that the difference in steady state pest populations would depend on the parameter values. Mathematically, it is possible for the myopic steady state to exceed the optimal steady state pest population if $\phi p\bar{y} < w\alpha\mu K$. At the base parameter values, the socially optimal pest population exceeds the myopic pest population by about 14 pests per acre. From the base parameter values, decreasing $\phi, p,$ or $\bar{y}$ and/or increasing $w, \alpha, \mu,$ or K could lead to a higher myopic pest population relative to the optimal pest population. However, since all of these parameters are also in the denominator of the difference in pest populations, movements of these parameters in the specified directions does not imply a decrease in the value of (27). Indeed, the first derivatives of the difference with respect to each of these parameter values is of indeterminate sign and depends on the parameter values. As was done to determine when the predator might persist in the myopic steady state, pairs of parameters are varied from their base parameter value in the direction that might lead to a higher myopic pest population. The maximum or minimum values used coincide with the maximum or minimum values found in the literature and are displayed in Table 1. The parameter pairs are p and w, p and K, ϕ and μ, and ϕ and α.

Over the entire ranges of p and w, ϕ and μ, and ϕ and α, the socially optimal pest population exceeds the myopic pest population (Figure 2). When looking at p and K, there is a small parameter range for which the myopic pest population exceeds the socially optimal pest population; it is the narrow quadrilateral in the top left of the Figure 3. In this range, price is less than \$0.60 (or per acre revenue less than \$600) and carrying capacity is greater than 8,550 pests per acre.

From this analysis, one can conclude that the socially optimal pest population exceeds the myopic pest population in most cases. As will be shown below, the optimal grower relies heavily on the predator population for pest control. In order to do so, there must be a large enough pest population to support the predator population each season. The predators then consume the pests, preventing damage, and providing a stock of predators for the next growing season.

These results differ from previous work. Harper and Zilberman (1989) find that in the myopic case, the secondary pest, which is controlled by the predator, increases and the primary pest which is not controlled by the predator, decreases. This increase in their secondary pest relative to the optimal case is likely due to the static nature of their model. In a dynamic model, the current pest population effects both the future pest population as well as the future predator population. The optimal pest population will be lower in a static model than in a dynamic model because the predator has no value after the first period, making a source of food for the predator no longer valuable.

4.4 Steady State Chemical Effort and Mitigation

The next question of interest pertains to the relative steady state levels of chemical effort. The equations for optimal and myopic effort can be written as a function of the pest and predator populations to yield:

$$E_O^{SS} = (\gamma/q)(1 - (N_O^{SS}/K)) - \mu P_O^{SS} \tag{36}$$

$$E_M^{SS} = (\gamma/q)(1 - (N_M^{SS}/K)) \text{ if } P_M^{SS} = 0 \tag{37}$$

As shown previously, the optimal pest population exceeds the myopic pest population for most possible cases, so as shown (36) and (37), this implies that the optimal chemical effort will be less than the myopic chemical effort. Taking into account the subtraction of pests consumed by the predator in (36) further increases the parameter ranges for which the optimal chemical effort is less than the myopic chemical effort. This result coincides with previous work (Harper, 1991; Harper and Zilberman 1989). Since the predator is driven to extinction for all non-outlier cases, myopic chemical control in the presence of the predator population will not be considered here.

The last component to consider is the level of mitigation for the optimal grower. Steady state mitigation can be re-written as a function of chemical effort and the pest population:

$$M_O^{SS} = E_O^{SS} - (1/\phi)(\alpha\mu N_O^{SS} - \beta) \tag{38}$$

The sign of $\alpha\mu N_O^{SS} - \beta$ will determine the relative level of mitigation. For the base parameter values, $E_O^{SS} = 0.4661$ and $M_O^{SS} = 0.7115$; the grower fully mitigates the negative effect of the chemical (i.e.- purchases a pesticide that is non-toxic to the predator at a higher price than the base chemical) and releases additional predators on the field. Relative to the base parameters, increasing $\alpha, \mu,$ and/or N_O^{SS} or decreasing β by a large enough magnitude would result in only partial mitigation. From the results in Table 2, increasing r, K, w, v, γ, α, and/or μ or decreasing p will results in an increase in N_O^{SS}. Varying all parameters creates a 9-dimensional parameter space, so again, parameters are considered in pairs and only varied in the direction that might lead to partial mitigation. Table 1 contains the relevant maximum or minimum values. Five parameter pairs are considered: γ and α, K and p, v and μ, r and β, w and p.

For three of the five parameter pairs (γ and α, v and μ, and r and β), mitigation exceeds chemical effort over the entire parameter space (Figure 5). For the remaining two pairs (K and p and w and p), there are small parameter ranges for which the grower does not fully mitigate. For K and p, there is a triangular region with a piece missing that represents the area for which the grower does not fully mitigate (Figure 4, panel a). The highest price for which partial mitigation occurs is \$0.70 (or \$770 in potential revenue per acre), and the lowest carrying capacity for which partial mitigation occurs is 5,740 pests per acre. At the lowest prices, and highest carrying capacities, however, the grower switches back to full mitigation and augmentation. This is likely due to the nonlinear way in which carrying capacity enters into the optimal pest equation.

For w and p, there is a triangular region in the parameter space for which partial mitigation occurs (Figure 1, panel b). The maximum price for which partial mitigation occurs is \$0.60 (\$660 in revenue per acre), and the minimum chemical effort price for which this occurs is \$255 per unit.

These results are somewhat surprising because they imply that for many situations, growers should be choosing selective pesticides that are nontoxic to beneficial insects, and they should be augmenting and releasing additional beneficial insects. In practice, this does not often happen. This could be due to a lack of information about beneficial insects. It could also be due to spatial externalities that might impede a grower's decision to adopt biological control when his or her neighbors are still applying the toxic pesticides (Grogan and Goodhue, 2012b).

4.5 Possible Variations

Several assumptions underlie this model. First, the predator modeled here is a specialist predator that only consumes the pest population. This is in contrast to a generalist predator that consumes a variety of insect species, some of which could be non-pest species. For a given overall predation rate, a generalist predator will have a smaller effect on the target pest species than a specialist predator because the generalist will consume other insect species. A specialist predator was chosen here because it increases the efficacy of the biological control and the chance that the predator will be conserved in the myopic case. Given that the myopic grower still does not conserve the specialist predator in most circumstances, one can conclude that the same qualitative result will hold true for a generalist predator. A generalist predator, however, will likely lead to smaller difference in the optimal and myopic pest populations because the optimal grower will not need as large of a pest population to support the generalist predator since supplemental food exists in the form of other insect species. The effect of a generalist predator on chemical effort is theoretically ambiguous. The smaller pest population could lead to lower effort in steady state, but the reduced efficacy of the predator could lead to less reliance on the predator, less augmentation, and more chemical effort.

Second, the damage function assumes that damages are a linear function of the pest population. There are several possible variations to this damage function. First, a threshold could exist below which the pest does not cause damage. This could be a case consumers or processors tolerate some maximum level of damage. If the steady state pest population in the non-threshold case falls below this threshold, a corner solution might exist for the case with a threshold. The coinciding reduction in pest control could possibly allow the predator to persist in the myopic steady state. Quadratic or exponential damage functions are two other likely possibilities. These are unlikely to change the qualitative results.

Lastly, there are a variety of predator-prey models that could be used. The model used here has been used in previously literature, but other models might be more relevant for certain predator-prey systems.

5. Conclusions

These results show that under most circumstances a grower who does not know that the predator exists will utilize more chemical control than is optimal and will drive the predator population to local extinction. This is in stark contrast to the optimal steady state where the grower mitigates all negative effects of the pesticide on the predator population and actually releases additional predators under most circumstances. The welfare difference between the optimal and myopic solutions will depend on the starting pest populations, and the calculation, complicated by two interacting state variables, is beyond the scope of this paper. However, the myopic solution is one possible solution to the optimal pest management scenario's problem. Since the myopic solution is not chosen, we know that the grower must have a higher net present value for the optimal solution.

In addition to private benefits, achieving the optimal solution has two potential classes of external benefits. The first class involves all of the non-agricultural externalities caused by pesticides including environmental and health effects. Since the myopic solution involves higher levels of pesticides for all likely cases, the myopic grower is contributing more heavily to these externalities than a grower who makes use of the predator and reduces pesticide use. The second class involves agricultural externalities caused by pesticides. Heavy pesticide use can lead to resistance and resistance will affect all growers in a region, not just the grower relying heavily on the pesticide. Pests do not become resistant to predators because the two species co-evolve. Additionally, the local extinction of the predator on the fields of myopic growers reduces the region's total predator population and may impede the use of the predator by growers who are knowledgeable about it.

These results suggest a need to inform growers about beneficial insects. Workshops to educate growers about how to identify, attract, and utilize beneficial insects would increase grower knowledge and likely increase use of beneficial insects. Additionally, grower cooperatives and associations could be ways to disseminate information, and such cooperatives are often made up of growers who are in close proximity to each other. All growers would benefit from additional use of beneficial insects.

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Table 1. Base Parameter Values

Parameter	Definition	Base Value	Units	Min	Max
p	Output price	5.100	\$/unit output	0.500	10.000
$\overline{y}$	Potential output	1000.000	unit output/acre		
K	Carrying capacity	5000.000	pests/acre	1000	10000.000
w	Chemical effort unit price	200.000	\$/unit effort	40	350.000
v	Mitigation unit price	200.000	\$/unit mitigation	40	350.000
r	Interest rate	0.050	interest	0.010	0.150
γ	Pest's intrinsic growth rate	0.400	pests	0.030	0.600
α	Predator's intrinsic growth rate	0.007	predators	0.001	0.011
μ	Predation rate	0.020	pests/predator	0.001	0.040[*]
β	Predator's intrinsic death rate	0.200	predators	0.010	0.450
q	Toxicity to pest	0.800	proportion killed	0.100	0.990
ϕ	Toxicity to predator	0.800	proportion killed	0.100	0.990

[*] This is the maximum rate found in the literature. To determine at which predation rate the predator will remain in the myopic steady state, the rate was increased to 0.300.

Table 2. The Effect of Increasing Parameter Values on the Steady State Levels of Pests, Chemical Effort, Predators, and Mitigation

Parameter		N		E			P		M
		Optimal	Myopic	Optimal	Myopic PSS>0	 PSS=0	Optimal	Myopic (PSS >0)	Optimal
p	price	<0	<0	>0	<0	>0	=0	>0	>0
$\overline{y}$	output	<0	<0	>0	<0	>0	=0	>0	>0
K	carrying capacity	>0	>0	<0	>0	=0	=0	<0	<0
w	chemical effort price	>0	>0	<0**	>0	<0	<0	<0	<0
v	mitigation price	>0	=0	<0	=0	=0	>0	=0	<0
r	interest rate	>0	>0	<0	>0	<0	>0	<0	<0
γ	N growth rate	>0	>0	>0*	>0	>0*	=0	>0*	>0*
α	P growth rate	>0	=0	<0	>0	=0	=0	<0	<0
μ	predation rate	>0	=0	<0	>0	=0	<0	>0*	<0
β	P death rate	=0	=0	=0	<0	=0	=0	>0	>0
q	toxicity to pest	<0*	<0	<0*	<0	<0*	>0	>0*	>0*
ϕ	toxicity to predator	>0*	=0	>0*	>0*	=0	<0	<0	<0*

* Sign depends on parameter values, sign shown is for base parameter values

** Sign depends on parameter values, sign shown is for base parameter values, value is negative, but approximately 0 (-5.8E-6)

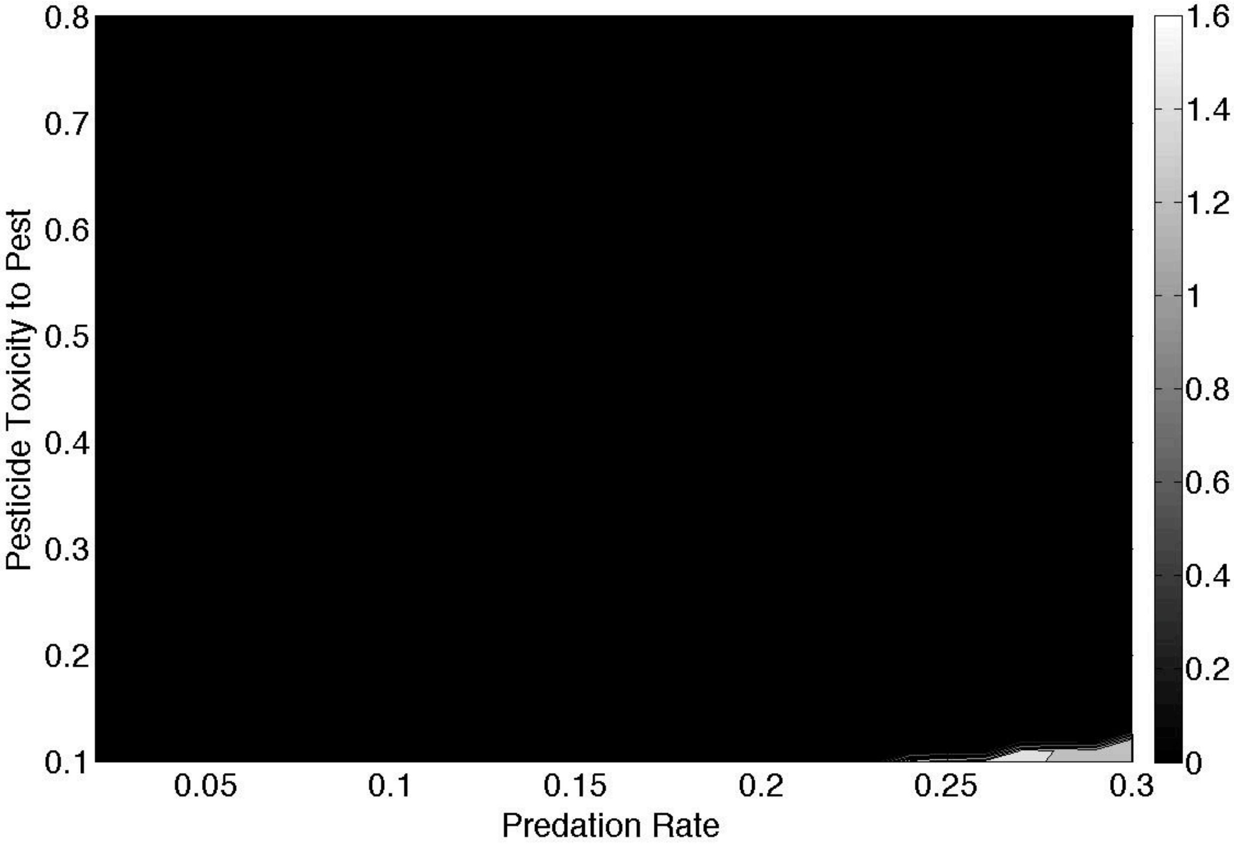

Figure 1. Contour Plot of Myopic Steady State Predator Population as a Function of the Predation Rate, μ, and the Pesticide's Toxicity to the Pest, q. All Other Parameters Held at Base Values

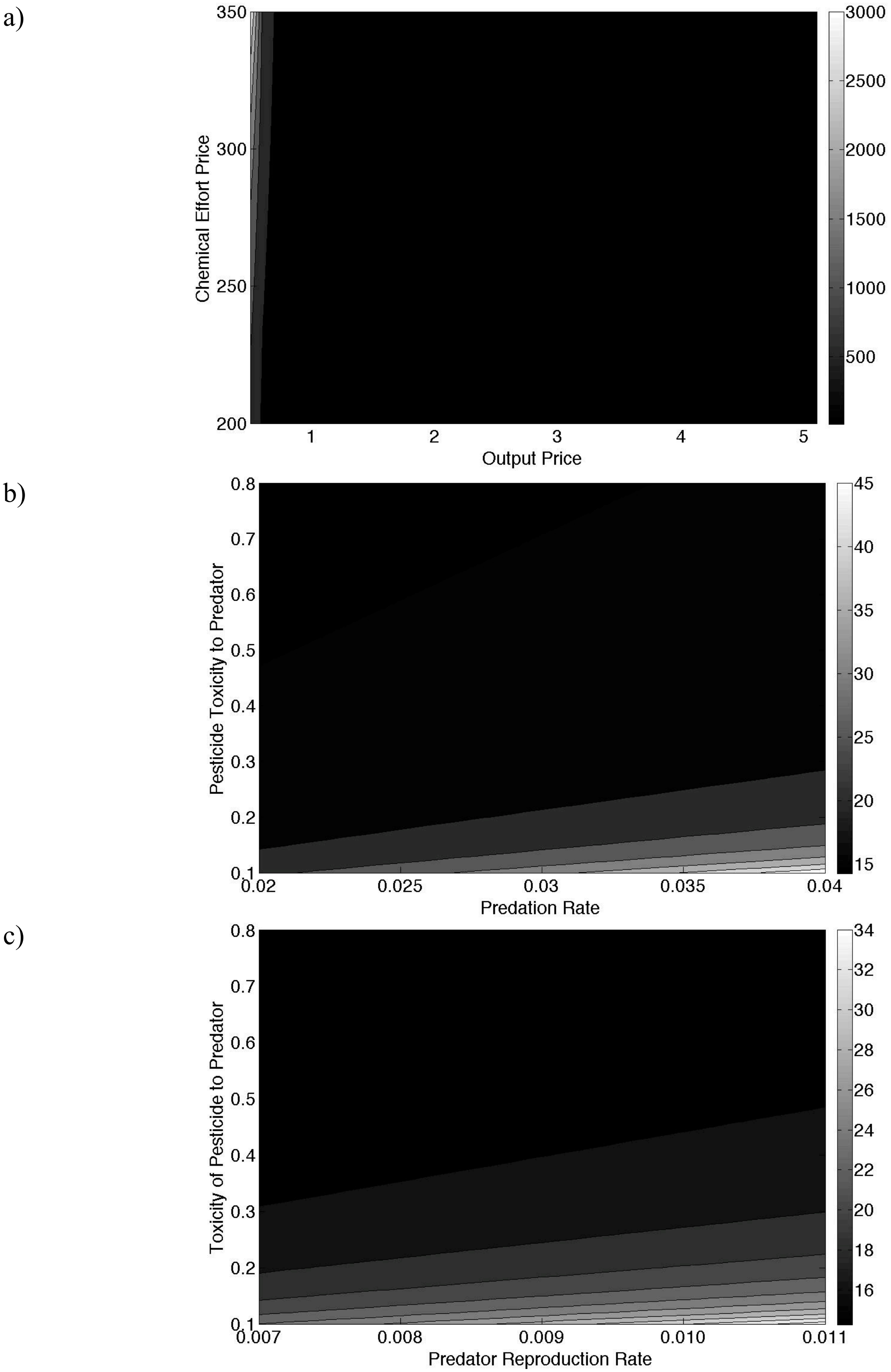

Figure 3. Contour Plot of the Difference in Steady State Pest Populations ($N_O^{SS} - N_M^{SS}$) as a Function of (a) Chemical Effort Price and Output Price and (b) Pesticide Toxicity to the Predator and Predation Rate. All Other Parameters Held at Base Values.

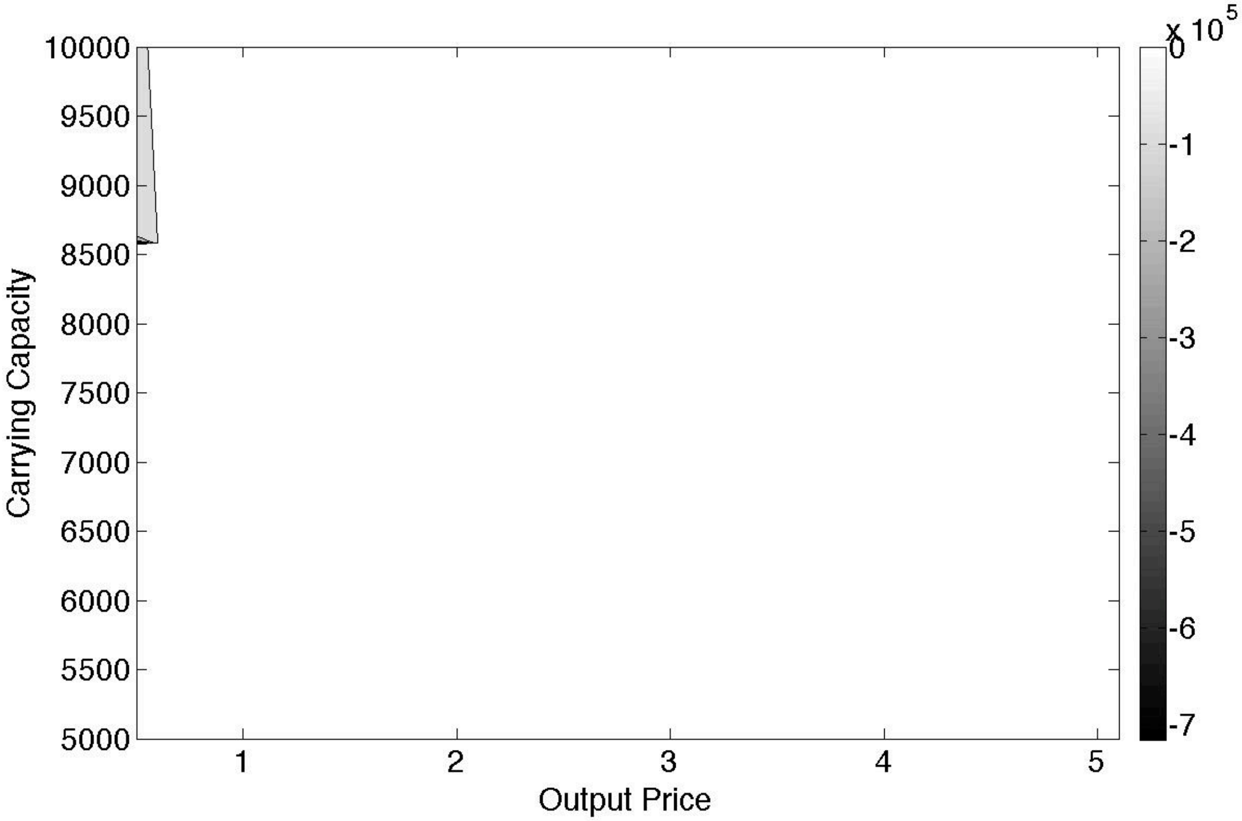

Figure 4. Contour Plot of the Difference in Steady State Pest Populations ($N_O^{SS} - N_M^{SS}$) as a Function of Carrying Capacity and Output Price. All Other Parameters Held at Base Values

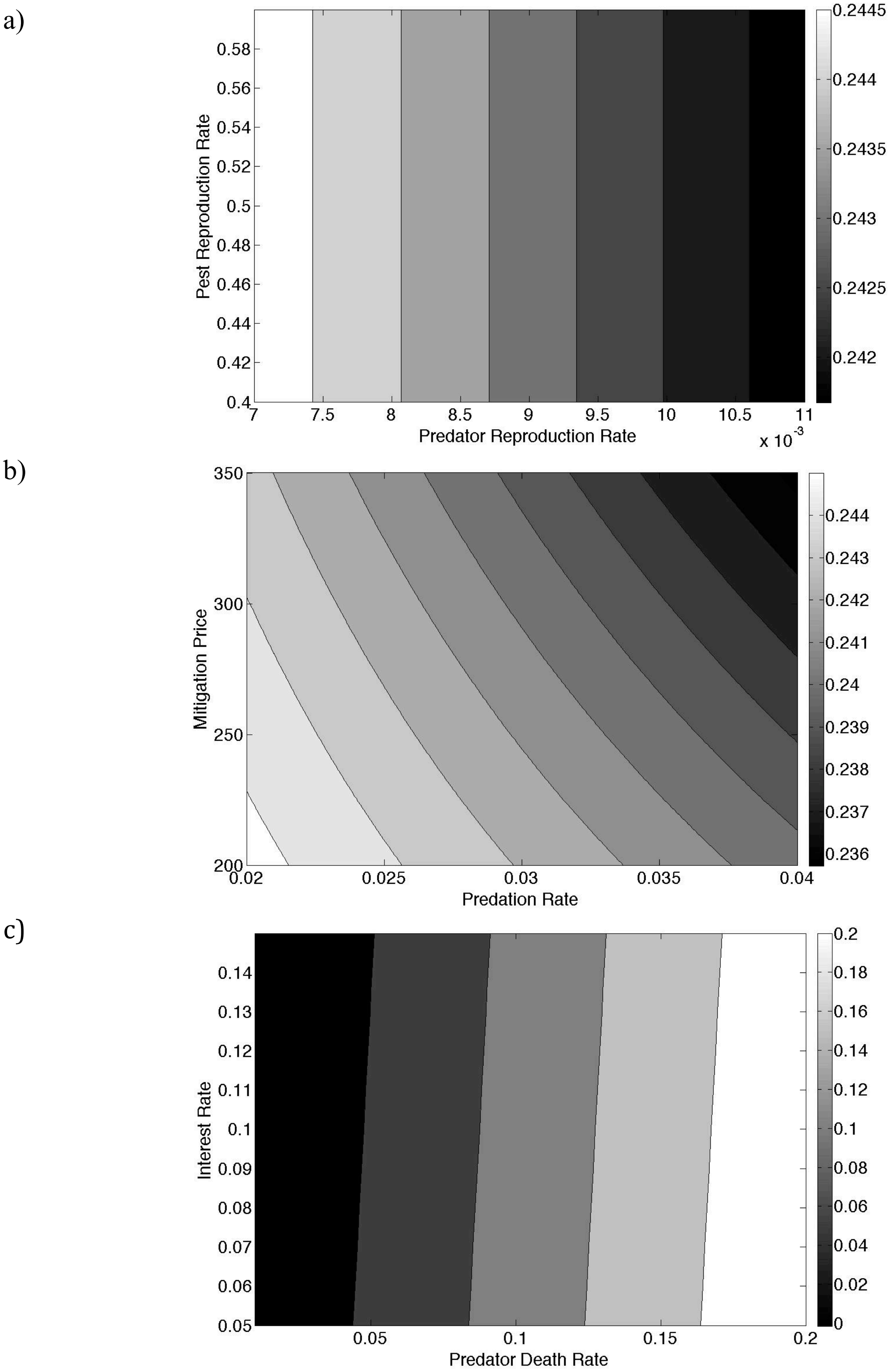

Figure 5. Contour Plot of the Difference in Mitigation and Chemical Effort ($M_O^{SS} - E_M^{SS}$) as a Function of a) Pest and Predator Reproduction Rates, b) Mitigation Price and Predation Rate, and c) Interest Rate and Predator Death Rate. All Other Parameters Held at Base Values.

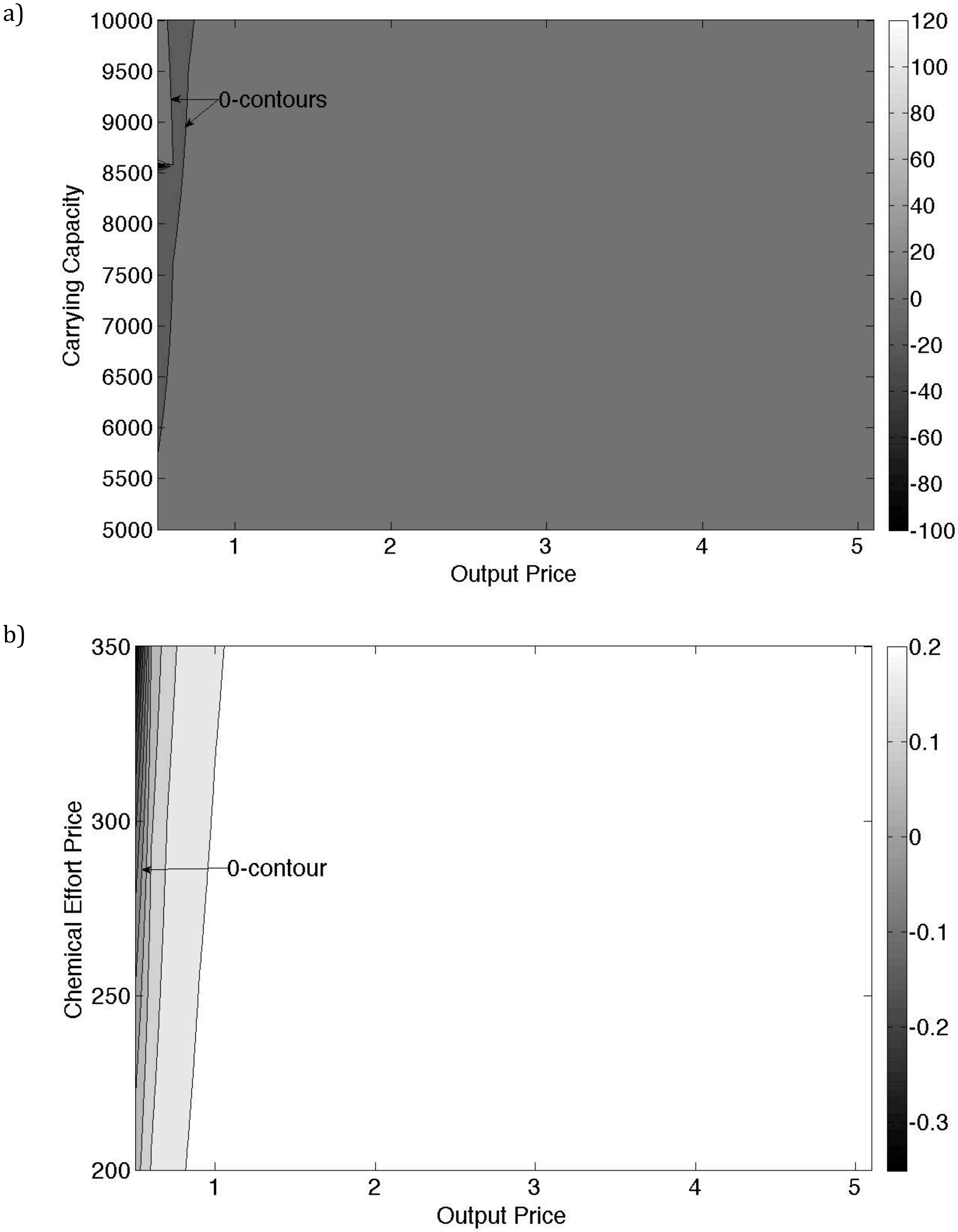

Figure 6. Contour Plot of the Difference in Mitigation and Chemical Effort ($M_O^{SS} - E_M^{SS}$) as a Function of a) Carrying Capacity and Price and b) Chemical Effort Price and Output Price. All Other Parameters Held at Base Values.