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OPTIMAL PEST MANAGEMENT IN THE PRESENCE OF NATURAL PEST CONTROL SERVICES

By

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ABSTRACT

OPTIMAL PEST MANAGEMENT
IN THE PRESENCE OF NATURAL PEST CONTROL SERVICES

By

Wei Zhang

By integrating natural pest control services into managerial decision-making, there are new opportunities for improving agricultural pest management in an economically appealing and socially desirable manner. This research develops dynamic and spatial bioeconomic models to investigate optimal economic management of an insect pest in the presence of natural enemies. Of central economic importance are the opportunity cost of natural enemy mortality due to broad-spectrum insecticides and the opportunity cost of setting aside land as non-crop habitats for the enhancement of natural enemy populations. The models are applied to a recent invasive pest of U.S. soybean, the soybean aphid, whose management is of both economic and environmental importance to the North Central region of the United States.

The thesis is divided into three essays. Essay 1 develops a dynamic bioeconomic model for the insecticide-based management of soybean aphid that explicitly takes into account both the predation effect of natural enemies on pest density and the nontarget mortality effect of aphid insecticides on the level of natural predation supplied. The study develops a natural enemy-adjusted economic threshold that represents the pest population density at which pesticide control becomes optimal in spite of the opportunity cost of injury to natural enemies of the target pest.

Essay 2 applies the bioeconomic model developed in Essay 1 for a simulation experiment on the optimal control of soybean aphid. The study examines the difference in

optimal control choices and associated economic gains with and without consideration of natural enemies. For instance, the presence of one ladybeetle would justify a change of optimal control choice from spray to no-spray when the pest density is 20 per plant. The results highlight the importance of assessing both pest and natural enemy populations in making insecticide application decisions and accounting for the opportunity cost of insecticide collateral damage to natural enemies.

The study also estimates the private economic value to farmers of the natural control services of ladybeetles in suppressing soybean aphid damage. The estimate constitutes a lower bound for the total economic value of this ecosystem service, because it omits such benefits as the avoidance of health and environmental risks from insecticide spraying.

Farmers desiring to rely on natural pest control in lieu of insecticide-based control can try to manage the habitat for natural enemies. Essay 3 develops a spatial optimization model to explore economically optimal habitat configurations for the natural enemies of crop pests. The model is applied to soybean aphid management in representative conventional and organic farming systems. Results indicate that non-crop habitat management can potentially be a promising pest management option for organic cropping systems. However, it tends to reduce farm net returns for conventional farms. Both area and shape of non-crop habitats affect economic performance, with the greatest value coming from small, scattered areas of habitat.

To my parents, my husband, and my sister for their love and support, and to those who still believe in making a difference…

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Introduction

Daily (1997) defines ecosystem services as the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. Agricultural ecosystems are actively managed by humans to optimize provisioning ecosystem services for food, fiber, and fuel (MA, 2005). To do so, they depend upon a wide variety of supporting and regulating services such as soil fertility, natural control of crop pests and pollination as inputs to production (de Groot *et al.*, 2002; MA, 2005; NRC, 2005), which directly translate to the profitability of farming as well as the social and environmental externalities to and from agriculture.

The control of pests by their natural enemies represents an important regulating ecosystem service that maintains the stability of agricultural ecosystems and has the potential to mitigate pest control costs (Naylor and Ehrlich, 1997; Pimental et al., 1997). As the limitations and negative externalities of chemical insecticides have become more obvious, the value of natural pest control services has increasingly been recognized (Naylor and Ehrlich, 1997). In addition to the well-documented human health and environmental risks (Wilson and Tisdell, 2001), insecticide application in agriculture can damage the functioning of many ecosystem services. For instance, honeybees, which are vital for the pollination of crops, are affected by most of the insecticides used, causing agricultural losses due to reduction in insect pollination of crops (Pimentel et al., 1992).

The flow of the natural pest control services critically depends on how agricultural ecosystems are managed and the diversity, composition, and functioning of the remaining ecosystems (Tilman, 1999). The functioning and viability of natural enemies can be damaged by chemically based pest management, which remains the dominant form of agricultural pest control. Use of broad-spectrum pesticides tends to severely damage populations of natural enemies, potentially exacerbating existing pest problems or even triggering the emergence of new pests (Calkins, 1983; Naylor and Ehrlich, 1997; Krishna et al., 2003). Habitat destruction and intensification of agricultural systems are destructive of natural pest control services (Naylor and Ehrlich, 1997). Natural pest control in general is positively correlated to landscape complexity, which is chiefly characterized by the proportion, size, and spatial arrangement of non-crop habitats in the landscape (Bianchi et al., 2006; Steffan-Dewenter et al., 2002).

These relationships and interactions can have potentially important economic implications for farm profitability and the management of this ecosystem service. The three essays of this dissertation focus on two integral management components: i) to conserve natural enemies so that they can effectively reduce pest populations, and ii) to enhance natural enemy populations so that more pest control services are available. The first component involves optimizing insecticide use to capitalize upon the natural pest control services—an integration of two alternative pest management mechanisms. Unfortunately, little attention has been given to the interaction or compatibility of the different technologies used in pest management (Thomas, 1999). Current chemical control practices typically don't take into account the presence of natural enemies. Untimely application of broad-spectrum insecticides can decimate natural enemy populations. The non-target mortality effects of chemical insecticides on populations of natural enemies imply inefficiencies in insecticide use if unaccounted for in the treatment decision—an "opportunity cost" to producers in terms of foregone natural control services that would have been provided by existing natural enemies. As a result, farmers may invest in unwarranted insecticide application, potentially leading to excessive release of chemical pollutions. To achieve socially optimal insecticide application with natural enemies efficiently used, key ecological factors and interactions such as the predation effect of natural enemies on pests, the non-target mortality effect of insecticides on natural enemies, and the enhancing role of non-crop habitats on natural pest control services should be incorporated into decision making.

Bioeconomic modeling of the behavior of ecological communities (pests, natural enemies, and crop plants) has the advantages of quantitatively describing biological processes and interactions and predicting their response to management decisions (King et al., 1993). Essay 1 develops a bioeconomic framework for optimal pest management that explicitly takes into account the population dynamics of natural enemies. The study develops a natural enemy-adjusted economic threshold that represents the pest population density threshold at which pesticide control becomes optimal in spite of the opportunity cost of injury to natural enemies of the target pest, whereas the conventional economic threshold is generally based on pest abundance and does not address natural enemy mortality or the impact of natural enemies on pest survival.

Essay 2 applies the bioeconomic model developed in essay 1 for a simulation experiment on optimal control of soybean aphid, a new invasive pest of soybeans in the North Central region of the United States, taking into account the contribution of major natural enemies such as ladybeetles. In particular, the analysis addresses how the optimal number and timing of insecticide applications would be different if the presence of natural enemies is accounted for in the decision making. The study also performs preliminary assessment of the economic value of the natural control services of ladybeetles in suppressing soybean aphid damage to private producers.

In the long run, effective agroecosystem management will demand more of managers than simply to reduce the non-target effect of pesticides on natural enemies. Habitat management that improves landscape complexity can potentially benefit natural enemies and in most cases result in enhanced biological control of pests (Thies and Tscharntke, 1999; Wilby and Thomas, 2002; Cardinale et al., 2003; Ostman et al., 2003; Thies et al., 2003). The second component of the management of natural pest control services thus moves beyond insecticide use thresholds to develop sustainable agricultural land use guidelines for explicit management of habitat for the natural enemies of agricultural pests. Essay 3 develops a spatial optimization model to explore economically optimal spatial habitat configuration for natural enemies of crop pests. The central question is to what extent and under what production systems that habitat management offers private producers the economic incentives for adoption.

Each of the three essays stands alone as individual paper but as a group, they are designed jointly to contribute to the economic literature on optimal pest management by incorporating the important ecological function of natural pest control into decision making.

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Essay 1:
Bioeconomic Modeling for Natural Enemy-Adjusted Economic Threshold: An Application to Soybean Aphid

1.1 Introduction

The control of pests by their natural enemies represents an important ecosystem service that maintains the stability of agricultural ecosystems and has the potential to mitigate pest control costs (Naylor and Ehrlich, 1997; Losey and Vaughan, 2006). In addition to the well-documented human health and environmental risks of applying broad-spectrum insecticides (Naylor and Ehrlich, 1997; Thomas, 1999; Heimpel *et al.*, 2004), another unwanted consequence is the decimation of ambient populations of natural enemies. Loss of natural enemies can exacerbate existing pest problems or even trigger the emergence of new pests (Calkins, 1983; Naylor and Ehrlich, 1997; Krishna *et al.*, 2003). Such unintended effects reduce the cost-effectiveness of insecticides if unaccounted for in the treatment decision. These create an "opportunity cost" to producers in terms of foregone natural control services that would have been provided by existing natural enemies[1]. Bioeconomic modeling of the behavior of ecological communities has the advantages of quantitatively describing biological processes and interactions and predicting their response to management decisions (King *et al.*, 1993). As such, it is an important tool for addressing such inefficiencies by offering decision rules that integrate natural control services into decision making.

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[1] Insecticide resistance of pests constitutes a source of "opportunity cost" experienced directly by producers. Resistance typically takes multiple seasons to develop and poses less of an immediate problem for intra-seasonal decision-making as compared to the destruction of natural enemies, and thus is not addressed by this study.

This study develops an intra-seasonal, dynamic bioeconomic optimization model to develop a natural enemy-adjusted economic threshold (NEET). The NEET is defined as the pest population density threshold at which pesticide control becomes optimal in spite of the opportunity cost of injury to natural enemies of the target pest. Using field data from Michigan collected under a multi-state soybean aphid USDA Risk Assessment and Mitigation Program (RAMP) project on "Soybean Aphid in the North Central U.S.: Implementing IPM at the Landscape Scale", the model is applied to the case of soybean aphid (*Aphis glycines*, Matsumura) (SBA). While selective insecticides may reduce the risk on natural enemies, broad-spectrum insecticides have been shown to provide greater protection from SBA (O'Neal, 2007) and are likely to remain important options for pest managers. The central question, therefore, is to choose the optimal level of broad-spectrum insecticide use to conserve natural enemies of SBA to the extent that the economic benefit to the farmer outweighs the additional cost. While the conservation of natural enemy insects is likely to confer a wide range of social and environmental benefits, our model is focused on farmers' private economic incentives for minimizing natural enemy mortality via optimizing the number and timing of insecticide applications, given a pre-determined dose and toxicity level and holding prices constant.

Following this introduction section, we provide background information on the SBA problem and the role of natural enemies in SBA regulation (section 1.2). We review existing pest management models in section 1.3, followed by a presentation of our intra-seasonal, dynamic bioeconomic optimization model in section 1.4. In section 1.5, we report on parameter estimations and discuss model validation. We then present two numerical analysis examples in section 1.6 to illustrate how the model works. Finally, we highlight contributions of the model, identify limitations and suggest future research needs (section 1.7).

1.2 Soybean aphid and its natural enemies

Soybean aphid is an invasive species that was first discovered in the North Central region of the United States in 2000. Within four years, it had spread to 21 states and south-central Canada (Landis *et al.*, 2004). Not only is SBA capable of causing extensive damage to soybean yield with documented yield loss of up to 40% (DiFonzo and Hines, 2002), SBA outbreaks are also correlated with dramatic increases in virus incidence in vegetable crops (Alleman *et al.*, 2002; Stevenson and Grau, 2003; Thompson and German, 2003; Fang *et al.*, 1985; RAMP, 2006). Since its invasion, SBA has prompted farmers to perform extensive spray of soybean acreage, making it one of the key drivers of insecticide use in the region (Smith and Pike, 2002). For example, 42% of soybean acreage in Michigan and 30% in Minnesota were sprayed during the 2005 season, compared with less than 1% before SBA arrived in 1999 in North Central region states for which data are available (NASS, 2007).

Existing natural enemy communities play a key role in suppressing SBA populations (Fox *et al.*, 2004; Aponte and Calvin, 2004; Rutledge *et al.*, 2004; Landis *et al.*, 2004; Costamagna and Landis, 2006; Berg, 1997). Natural enemies of SBA include 22 predator species (Rutledge *et al.*, 2004), 6 parasitoid species (Kaiser *et al.*, 2007), and several species of fungi that cause disease in aphids (Nielsen and Hajek, 2005). In particular, generalist predators (mainly ladybeetles, *Coccinellidae*) provide strong, season-long suppression, protecting soybean biomass and yield from SBA damage (Costamagna *et al.*, 2007a). However, most insect natural enemies are susceptible to the major insecticides used to treat SBA[2]. Evidence from Iowa indicates that insecticides applied in early season can actually result in greater SBA population later (O'Neal, 2007), undermining the cost-effectiveness of insecticide investment. Although general recommendations stress the need for assessing field situation with respect to natural enemies before spraying (e.g., Smith and Pike, 2002; NSRL, 2002; NCPMC, 2005), the current extension treatment threshold recommendation relies solely on aphid density observation, whereas no applicable decision guide has been offered to producers to conserve and capitalize on the pest regulation services supplied by ambient natural enemies.

1.3 Models of pest management

The existing models of pest management threshold decision rules have been developed on two fronts: the economic threshold (ET) model by entomologists and the marginal analysis model by economists (Mumford and Norton, 1984). Our critique of the literature necessarily focuses on the economic approach, but also discusses the evolving of the ET concept in the entomological literature and how the entomologically-based ET model is linked to (and different from) the economic approach.

Introduced as a crucial component of Integrated Pest Management (IPM) by Stern *et al.* (1959) and having since become recognized as an operational decision rule (Mumford and Norton, 1984), ET in the IPM literature refers to the pest population density at which control measures should be initiated to prevent an increasing pest

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[2] Christine DiFonzo, Department of Entomology, Michigan State University, personal communications, October 4, 2005 and March 2, 2006.

population from reaching the economic injury level (Pedigo *et al.*, 1986). With economic injury level (EIL) defined as the lowest population density that will cause economic damage and given by the equation $EIL=C/VIDK$ (where C is the cost of chemical control (\$/ac), V the value of a crop (\$/ac), I the injury inflicted by the pest, D the damage response by the crop to that injury, and K the proportionate reduction in pest attack conferred by the control action), ET can be derived from EIL by tracking backwards in time according to the population dynamics of the pest given some lag time needed for farmers to take action (Pedigo *et al.*, 1986).

Integrating the economic concepts of optimization and marginality, Headley (1972) redefined the ET as the optimal (net-return-maximizing) pest population density where the marginal value product of damage control equals the marginal cost of control. Hall and Norgaard (1973) improved Headley's framework by developing a more general model which considers the optimal timing and quantity of a single pesticide application. Even though they used time variables in their models, the models are essentially static because present control decisions do not affect future opportunities (Bor, 1995; Kamien and Schwartz, 1981). Consideration for multiple treatments later makes it necessary to design an approach for achieving optimality over time, triggering the incorporation of dynamic aspects of pest management into ET development (e.g., Talpaz and Borosh, 1974, Zacharias and Grube, 1986, Harper *et al.*, 1994, and Bor, 1995). The suppression services of natural enemies, as well as the unintended effect of broad-spectrum insecticides on the population of natural enemies, however, have not been included.

In a single treatment (i.e., static) framework, under certain circumstances (i.e., parameters C, V, I, D, and K are independent of pest population, and K is fixed for a treatment) the entomological concept of ET can potentially achieve optimality in an economic sense because the EIL is essentially determined by the economically optimal condition of marginal value produced equal to marginal factor cost. The entomological model of ET, however, is not capable of providing optimal treatment solutions when multiple treatments are required during the season.

In the entomological literature, improvements have been made to the current ET approach that is generally based on pest abundance and does not address natural enemy mortality or the impact of natural enemies on pest survival (Musser *et al.*, 2006) to incorporate the dynamic impact of natural enemies on ET (e.g., Brown, 1997, Musser *et al.*, 2006, Tang *et al.*, 2005). These modeling efforts attempt to address the inefficiency raised in situations where if pest population growth rates are substantially reduced by natural enemies, there may be enough population regulation to prevent pests from reaching the EIL, in which case treatment triggered by ET density would not guarantee yield benefit equal to the cost of control (Ragsdale *et al.*, 2007). Field observation in Minnesota shows that this outcome indeed happened in several SBA-infested field trials in 2005. Musser *et al.* (2006) propose a framework for the development of dynamic ET that moves up or down with changes in biological mortality caused by natural enemies in the period between ET determination and EIL realization, offering potential efficiency gains from reducing insecticide use. Despite the improvements, these models work with the same static EIL that is not determined based on the economic method of optimization. Thus, a dynamic bioeconomic model that models the net-return-maximizing behavior of economic agents and explicitly factors in the presence of natural enemies is needed.

1.4 Bioeconomic model of soybean aphid management

Our bioeconomic optimization model assumes that a soybean producer maximizes the returns over variable costs of pest control, subject to three biological constraints: i) population dynamics of SBA as affected by both chemical control and natural enemy suppression, ii) population dynamics of natural enemies that is coupled with prey density and subject to the toxicity of SBA insecticides, and iii) a yield response function that describes the relationship between pest density and yield potential. A stage-based dynamic framework similar to that of Harper *et al.* (1994) is adopted. Specifically, the biological components evolve over five discrete time periods corresponding to five growth stages of soybean plant within a growing season (Figure 1.1). The model incorporates factors such as the contribution of natural enemies to pest regulation, the positive impact of prey consumption on natural enemy population, and the natural enemy mortality caused by SBA insecticides, whose economic implications to optimal control have not been considered in the existing literature. The outcome of the dynamic optimization model prescribes natural enemy-adjusted optimal number and timing of insecticide application.

Olson and Badibanga (2005) developed a bioeconomic model to evaluate and compare the net returns of four potential thresholds (3, 100, 250, and 500 aphids per plant) to treat SBA and found that the 3 aphids/plant threshold a dominant strategy regardless of initial infestation date and aphid growth rate. Without accounting for natural enemies of SBA, the threshold for spraying was 99% below the prevailing North Central states extension recommendation of 250 aphids per plant (Ragsdale *et al.*, 2007).

The current model differs from Olson and Badibanga (2005)'s model in three major aspects. First, our model is intended for implementing dynamic optimization analysis, which prescribes an optimal control path for given initial status of populations of the pest and natural enemies over a finite planning horizon. In other words, after one assessment of the infested field, we predict the number and timing of treatments for the entire season, whereas the decision rule developed by Olson and Badibanga (2005) requires pest population to be monitored constantly and treatment is triggered whenever pest population reaches certain threshold. Second, limited by insufficient data, Olson and Badibanga (2005) adopt a partially developed SBA population growth model. Specifically, the growth of the aphid population follows an exponential function with fixed population growth rate and is forced to decline once the population enters a pre-determined maximum range. For the population dynamics of SBA, we adopt a daily-based SBA growth model developed by Costamagna *et al.* (2007b) that incorporates a linearly decreasing growth rate into an exponential growth model to account for the impact of host plant phenology, which has been shown as an important factor affecting aphid population growth (Rossing *et al.*, 1994; Williams *et al.*, 1999). The model has been demonstrated to accurately predict SBA population dynamics in soybeans in Michigan fields, including the population decline towards the end of the season (Costamagna *et al.*, 2007b). Third, since non-linearity is particularly common in yield damage functions (Swinton *et al.*, 1994), we adopt the Cousens (1985) rectangular hyperbolic functional form for the yield response function and select among alternative models the one that fits our data best. Most importantly, we include natural control services explicitly in decision making so as to improve the efficiency of insecticide use by private producers with potential socially desirable outcome.

The system of soybean growth stages divides plant development into vegetative (V) and reproductive (R) stages (Pedersen, 2004). Our model focuses on the five earlier reproductive stages, R1 through R5 (indexed by discrete *t* and *t*=1, 2, 3, 4, 5), during which period soybeans are most susceptible to SBA damage (Jameson-Jones, 2005). The following table describes the various stages.

Vegetative Stages	Reproductive Stages
	R1 (beginning flowering)
VE (emergence)	R2 (full flowering)
VC (unrolled unifoliolate leaves)	R3 (beginning pod)
V1 (first trifoliolate)	R4 (full pod)
V2 (second trifoliolate)	R5 (beginning seed)
V3 (third trifoliolate)	R6 (full seed)
V(n) (nth trifoliolate)	R7 (beginning maturity)
V6 (flowering will soon start)	R8 (full maturity)

Source: Pedersen, 2004

Farmers tend not to practice variable rate pesticide application due both to applicator time constraints and label rates being required for manufacturers to guarantee efficacy. Therefore, we define the control decision in each stage as a binary choice, denoted by x_t (x_t=1 for spray at fixed label-recommended rates, and x_t=0 for no spray at stage *t*). We assume that no more than one spray may occur in each stage and that the predicted yield upon stage R5 is carried through to harvest so that SBA control is only meaningful during stages R1 to R4. The growth of SBA population over the five reproductive stages of the soybean plant is given by:

$$S_{t+1} = (S_t - k_{S,t} \cdot x_t \cdot S_t) + ng_t \cdot (S_t - k_{S,t} \cdot x_t \cdot S_t) - pr_t \cdot (NE_t - k_{NE,t} \cdot x_t \cdot NE_t) \quad (1)$$

(*t*=1, 2, 3, 4)

where S_{t+1} denotes SBA density per plant at stage *t+1*, NE_t denotes density of natural enemies per plant at stage *t*, $k_{S,t}$ and $k_{NE,t}$ represent mortality rates of SBA and natural enemies from insecticide application, respectively, ng_t denotes net growth rate of SBA population in the absence of "outside" regulation, and pr_t is the aggregate predation rate per *NE* unit per time period (stage).

While an abundant number of existing natural enemy communities jointly contribute to suppressing SBA population in soybeans (Fox and Landis, 2002), the role of generalist predators (mainly *Coccinellidae*, or lady beetles) is particularly important (Costamagna *et al.*, 2007a) due to their high abundance in both number and overall suppression effectiveness (Costamagna, 2006). We therefore focus on the ladybeetle family in our quantification of the natural enemy presence by aggregating populations of major ladybeetle species. The adoption of an aggregate population level is underlined by the following considerations. First, the major regulating species vary both temporally and spatially in terms of the suppression services they provide. For instance, in Michigan, *Harmonia axyridis* (multi-colored Asian ladybeetle) and *Coccinella septempunctata* (seven-spotted ladybeetle) provide sequential pest suppression mid season through harvest, with seven-spotted ladybeetle dominating the mid season and multi-colored Asian ladybeetle dominating the late season (McKeown, 2003). Data collected at the Kellogg Biological Station (KBS) Long-term Ecological Research site at Hickory Corners in Kalamazoo County, Michigan, show that the high populations of seven-spotted ladybeetle may have aided in delaying SBA colonization of the KBS site (McKeown, 2003). The spread of SBA later in the season was subsequently further hindered by the high prevalence of multi-colored Asian ladybeetle (McKeown, 2003). It is therefore difficult to quantitatively differentiate their individual contributions. Second, detailed data on the biology and ecology of major predator species such as multi-colored Asian ladybeetle are lacking, limiting our capability to develop reliable population models for individual species. Ideally, a set of weighting coefficients should be developed to account for the relative contribution of each included species. In the current study, however, such information is not available, and we treat each species as equal in their contribution to the aggregate population level.

We adopt a dynamic Lotka-Volterra predator-prey model (Lotka, 1925; Volterra, 1926) to describe changes in the population density of natural enemies coupled with prey consumption over discrete time periods. Denoted by NE_{t+1}, the population density of natural enemies at stage $t+1$ is given by:

$$\begin{aligned} NE_{t+1} &= (NE_t - k_{NE,t} \cdot x_t \cdot NE_t) + d_t \cdot (NE_t - k_{NE,t} \cdot x_t \cdot NE_t) \\ &\quad + b_t \cdot (S_t - k_{S,t} \cdot x_t \cdot S_t) \cdot (NE_t - k_{NE,t} \cdot x_t \cdot NE_t) \end{aligned} \tag{2}$$

(t=1, 2, 3)[3]

where d_t (<0) is the natural net decline rate that NE would suffer in the absence of prey and b_t (>0) is interpreted as the reproduction rate of NE per prey encountered (Sharov, 1996, 1997, 1999).

Farmers often make sequential predictions on achievable yield over the course of the growing season based on perception of initial yield potential, pest infestation and other factors such as weather. We offer a conceptual model of yield-pest interaction that is consistent with the process for updating yield potential described above. We express

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[3] The natural enemy model is estimated for stages R1 to R3 to predict population up to stage R4 ($NE_{t+1=4}$), which in turn affects SBA population in stage R5—the last stage in which SBA can cause damage to harvest yield in our model. Therefore, we do not need t=4 for the natural enemy model.

the expected yield potential at stage $t+1$, denoted by $E_{t+1}[y]$, as a function of expected yield potential at stage t ($E_t[y]$) and pest population density at t (S_t):

$$E_{t+1}[y] = f(E_t[y], S_t), \qquad (t=1, 2, 3, 4, 5) \tag{3}$$

and $E_1[y] = \bar{y}_h, E_6[y] = y_h$

where $\bar{y}_h$ is maximum (pest-free) potential yield or average historical yield upon which the season's first prediction is based, and the actual yield at harvest, y_h, is assumed to be equal to yield potential evaluated at the final reward stage $T+1=6$. In a non-linear yield-pest interaction model such as the Cousens (1985) rectangular hyperbolic model, the conceptual model can be implemented by replacing the parameter that represents maximum yield with the fitted value of yield potential obtained in the previous period ($E_t[y]$) to render the following reformulated Cousens rectangular hyperbolic model:

$$E_{t+1}[y] = E_t[y] \cdot (1 - \frac{\eta_t \cdot S_t}{1 + \eta_t \cdot S_t / \theta_t}) \tag{4}$$

where η_t denotes the proportion of yield lost per unit of pest population and θ_t denotes the maximum proportional yield loss to pest damage ($0 \le \theta_t \le 1$).

We assume that a producer maximizes his/her expected return over variable costs of pest management (derived by subtracting total SBA control cost from soybean revenue realized at harvest) over a sequence of control decisions within the growing season, subject to biological constraints describing pest population, natural enemy population, and crop yield potential. Denoted by J, the objective function can be written as:

$$J = \underset{\{x_t\}_{t=1}^{T=5}}{Max} \; [p \cdot y_h - \sum_{t=1}^{T=5} c(x_t)] \tag{5}$$

subject to equations (1), (2), and (3) with I_1, NE_1, and y_1 are given. $\{x_t\}_{t=1}^{T=5}$ represents a sequence of control actions over the five time periods, p denotes output price, and $c(x_t)$ denotes control cost, including the cost of pest scouting to provide the basis for control decisions. No discount factor is included for this single-season optimization problem due to its relatively short duration.

Using the method of dynamic programming (Bellman, 1957), we illustrate some of the analytical solutions to the dynamic optimization problem. We adopt a general form for the yield response function because expressions of analytical solution when non-linearity presents are extremely lengthy and thus tend to hide the intuition we would like to highlight. Since the return over variable costs of control being maximized does not realize until the final reward period (T+1=6) and the control variable is binary, we have dichotomous, as opposed to continuous, optimal value functions that have to be tied to expected harvest yield, $E_6[y]$ or y_h. We solve the Bellman's equation recursively from the terminal period (T=5), during which time no control is actually necessary (i.e., $x_5^* = 0$), so the optimal value function that describes the maximum expected reward for taking action $x_5^* = 0$ is

$$V_5^* = p \cdot E_6[y] = p \cdot f(E_5[y], S_5) \tag{6}$$

Bellman's equation for t=4 is:

$$V_4 = \underset{x_4=1 \ or \ 0}{Max} \ [-c(x_4) + V_5^*] \tag{7}$$

Assuming constant control cost $c(x_t)=\bar{c}$ for each period[4], we iterate on Bellman's equation to get the first order condition (FOC) for maximization:

$$\frac{\partial V_4}{\partial x_4}=-\bar{c}+p\frac{\partial E_6[y]}{\partial S_5}\frac{\partial S_5}{\partial x_4}=0$$

which gives the following condition:

$$-\bar{c}+p\frac{\partial E_6[y]}{\partial S_5}pr\cdot k_{NE,4}NE_4=p\frac{\partial E_6[y]}{\partial S_5}k_{S,4}S_4(1+ng_4) \tag{8}$$

The two terms on the left-hand side (LHS) of (8) indicate the full marginal factor cost (MFC) of x_4 (the sum of control cost and the value of natural SBA suppression lost due to control action at t=4), whereas the term on the right-hand side (RHS) represents the marginal value product (MVP) of x_4. The optimal solution for x_4 is thus determined by the following conditions:

$$x_4^*=\begin{cases}1 \text{ if } -p\frac{\partial E_6[y]}{\partial S_5}k_{S,4}S_4(1+ng_4)\geq\bar{c}-p\frac{\partial E_6[y]}{\partial S_5}pr\cdot k_{NE,4}NE_4 \text{ or } MVP_{x4}\geq MFC_{x4}\\ 0 \text{ if } -p\frac{\partial E_6[y]}{\partial S_5}k_{S,4}S_4(1+ng_4)<\bar{c}-p\frac{\partial E_6[y]}{\partial S_5}pr\cdot k_{NE,4}NE_4 \text{ or } MVP_{x4}<MFC_{x4}\end{cases} \tag{9}$$

Substituting x_4^* back into the objective function (7) gives two possible optimal value functions for V_4^*:

$$V_4^*=\begin{cases}-\bar{c}+p\cdot y_h & \text{if } x_4^*=1\\ p\cdot y_h & \text{if } x_4^*=0\end{cases} \tag{10}$$

Consequently, we have two Bellman's equations for t=3. In the case when $x_4^*=1$,

$$V_3=\underset{x_3=1\ or\ 0}{Max}\ [-c(x_3)-\bar{c}+V_4^*] \tag{11}$$

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[4] The assumption is only made for the ease of mathematical exposition in the analytical analysis.

and the FOC for maximization is:

$$\frac{\partial V_3}{\partial x_3}=-2\bar{c}+p\frac{\partial E_6[y]}{\partial S_5}\frac{\partial S_5}{\partial NE_4}\frac{\partial NE_4}{\partial x_3}+p\frac{\partial E_6[y]}{\partial E_5[y]}\frac{\partial E_5[y]}{\partial S_4}\frac{\partial S_4}{\partial x_3}+p\frac{\partial E_6[y]}{\partial S_5}\frac{\partial S_5}{\partial S_4}\frac{\partial S_4}{\partial x_3}=0 \qquad (12)$$

where marginal conditions $\frac{\partial S_4}{\partial x_3},\frac{\partial S_5}{\partial S_4},\frac{\partial S_5}{\partial NE_4}$, and $\frac{\partial NE_4}{\partial x_3}$ can be derived from equations (1) and (2). Analogous to the conditions in (9), it can be shown that $x_3^{*}=1$ if the MVP of control as indicated by the last two terms on the RHS of (12) is greater or equal to the MFC as indicated by the first two terms on the RHS of (12), and $x_3^{*}=0$ otherwise.

The analysis illustrates how the inclusion of natural enemies affects the determination of the optimal control decision rule by raising the MFC to account for the value of lost natural pest control services that consequently justifies a lower level of pest control (or a shift from control to no-control for the binary choice case).

1.5 Model estimation

Population of soybean aphid

To estimate the predation-free net growth rate of SBA population ng_t, we adopt a meta-modeling approach by using simulated SBA growth pseudo data generated by a daily-based SBA growth model developed by Costamagna *et al.* (2007b). The model describes population growth under field conditions in the absence of natural suppression, based on Williams *et al.* (1999)'s discrete exponential population growth model. Specifically, SBA density on day d+1, denoted by a_{d+1}, is described as:

$$a_{d+1}=a_d\cdot e^{r_d} \qquad (13)$$

where

$$r_d = r_{\max}(1 - C \cdot d) \qquad (14)$$

r_d is the intrinsic growth rate of SBA that decreases in time (d), and C is the reciprocal of the time to peak population. Starting at r_{max} (the maximum intrinsic rate of increase) when $d = 0$ (where the population is at its peak), r_d decreases linearly until $r_d = 0$ when $d = 1/C$ (Costamagna *et al.*, 2007b). Costamagna *et al.* (2007b) parameterize the model using data collected from predator exclusion cage experiments conducted in Michigan soybean fields between 2003 and 2005 and show that the model is robust against variability within and between experiments. The original model calibrates a maximum intrinsic growth rate (r_{max}) of 0.40 for initial infestation occurring around June 23, 2005 (Table 1.1). Since we are interested in the SBA population during soybean reproductive stages R1 through R5, we adjust the parameter to be 0.28, denoted by $r_{max\_adjusted}$, to account for the time lapse between June 23 and the estimated date when plant enters stage R1 at KBS (around July 5, 2005) according to equation (14).

We first predict daily SBA population for the period of R1 to R5 using the Costamagna *et al.* (2007b) model. Free of predation, the SBA population increases rapidly and peaks in stage R5 before it starts to crash (Figure 1.2). The simulated pseudo data are then combined with plant stage data to compute mean population density $\hat{S}_t$ per stage. We use mean stage duration data from the literature (Fehr and Caviness, 1977) instead of estimating from our own data, which were collected using a fixed-interval sampling approach. The net growth rates in the absence of natural suppression are calculated from:

$$ng_t = (\hat{S}_{t+1} / \hat{S}_t) - 1 \qquad (15)$$

The net population growth rate is the highest during R1 at 5.29 and drop to the lowest at 1.13 in R4 (Table 1.1). The calibration is insensitive to initial density, but is sensitive to length of plant growth stages.

Population of natural enemies

To estimate the stage-specific net decline rate (d_t) and the reproduction rate (b_t) for the natural enemy population model, we use two years' of visual count data collected at KBS (2003 and 2005) and perform Ordinary Least Squares (OLS) regression analysis with robust standard errors obtained from the Huber/White estimator (Gould *et al.*, 2006) on the following equation:

$$E[\Delta_{t+1}] = d_t \cdot NE_t + b_t \cdot (S_t \cdot NE_t) + \sum_{\omega=1} \xi_{\omega,t} \cdot Dummy_{\omega} \qquad (16)$$

where E is expectation operator, $\Delta_{t+1} = NE_{t+1} - NE_t$, and $Dummy_{\omega}$ denotes a vector of dummy variables for both year and plots.

The ladybeetle species included in the quantification of natural enemy presence are *Harmonia axyridis* adult and larva, *Coccinella septempunctata* adult and larva, *Coleomegilla maculata* adult, *Cycloneda munda* adult, *Cycloneda munda* larva, and *Hippodamia convergens* adult, the last three of which are in the sample of 2005 but not 2003. Using the total count of each species during the entire sampling period lasting almost two months, we calculate species composition for each year (Figure 1.3). Among the species included, *Harmonia axyridis* was slightly smaller in share than *Coccinella septempunctata* in 2003 but became the single predominant species in 2005.

Because SBA was first detected in the United States so recently, few years of insect data are available and sample sizes are small, making it difficult to estimate stage-specific population growth parameters. As Table 1.2 shows, the reproduction rate is found significant at the 90% confidence level in stage R3 only, whereas the net decline rate is significant at the 95% and 99% confidence levels in R2 and R3, respectively. Estimates of the two parameters d_t and b_t conform to the theoretical expectation of negative decline rate and positive reproduction rate. Specifically, in the absence of SBA prey, the population density of natural enemies will decline from R2 to R3 and from R3 to R4 by 0.90 and 2.13 for each additional natural enemy in stage R2 and R3, respectively. For each SBA encountered by each additional natural enemy, the population density of natural enemies will grow from R3 to R4 by the amount of 0.002. The weak reproduction relationship between SBA and natural enemies is not uncommon because the population of generalist predators such as ladybeetles tends not to be perfectly coupled with one particular prey population (Brown, 1997).

Yield response function

Data used to estimate the yield response function were collected from two field trials (the RAMP project trial and the Michigan State University insecticide timing trial) conducted at three Michigan sites in 2005 (the Bean and Beet farm in Saginaw County of eastern Michigan, the KBS site, and a site located in Sandusky in Sanilac County that only hosted the timing trial)[5]. We fit the field trial data to the restricted form of the reformulated Cousens rectangular hyperbolic model as expressed in equation (4) using Nonlinear Least Squares estimation. The restrictions are imposed on parameter θ_t ($\theta_t = 1$

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[5] Data were provided by Christine DiFonzo, Department of Entomology, Michigan State University.

or maximum allowable yield loss = 100%) in each stage to ensure non-negative minimum yield potential as pest population approaches to infinity.

Table 1.3 reports estimation results from the restricted Cousens model for each stage. SBA damage significantly affects soybean yield potential in stages R2, R3, and R4. The proportion of yield lost per unit of pest population (η_t) in stage R2 is estimated to be negative, suggesting a "compensation" yield response relationship between pest injury and crop yield potential in R2 (Pedigo *et al.*, 1986). Yield potential responds to pest damage the most in stage R3, with an estimated 0.03% of yield potential lost per SBA per plant.

Other parameters

Little is known about predation rates of SBA by ladybeetle species. Here we propose an approximate range for the value of this important parameter. We suggest that scenario analysis be conducted to account for the uncertainty in the value of the parameter when applying the model to empirical studies. The biological literature suggests that mean daily aphid consumption by multi-colored Asian ladybeetle adults typically ranges from 15 to 65 aphids per day (Hu *et al.*, 1989, Hukusima and Kamei, 1970, Lou, 1987, Lucas *et al.*, 1997), whereas the consumption rate averaged across larval instars is 23 aphids per day (He *et al.*, 1994) (see review conducted by Kock, 2003). As the bottom figure in Figure 1.3 (year=2005) shows, 69% of the included ladybeetles are adult, while larvae account for 31%. Assuming each included ladybeetle species is equally effective consuming aphids as the multi-colored Asian ladybeetle, we obtain weighted average number of aphids eaten per ladybeetle per day:

Lower bound of the range: $15*0.69+23*0.31=17$ *aphids/day/NE*

Upper bound of the range: $65*0.69+23*0.31=52$ *aphids/day/NE*

which gives a mean of 35 aphids/day per ladybeetle. The per stage predation rate pr_t is then computed by multiplying daily predation rate by the number of days in a given stage.

We assume that insecticide will kill 99% of both SBA ($k_{S,t}$) and natural enemies ($k_{NE,t}$) at each application during the season. This value is considered reasonable given the high efficiency of current foliar products treating SBA[6]. The mortality rate for natural enemies is difficult to monitor, but current products such as Lambda-cyhalothrin (Warrior with Zeon Technology®) are highly lethal to natural enemies (O'Neal, 2007).

For price and cost parameters, we use a long-term soybean trend price of $7/bu and a treatment cost of $12/ac for the RAMP Best Management Practice treatment using Warrior at 3.2 oz/ac with field scouting provided by Song *et al.* (2006). A break-down of the cost includes $7/ac insecticide cost, $2/ac for scouting, and approximately $3/ac for spraying (Song *et al.*, 2006).

Validation

The SBA population growth model developed by Costamagna *et al.* (2007b) has been validated with experimental data. To see how well the biological model describes the ladybeetle-SBA predator-prey system, we plot model predictions of untreated SBA population densities during R1 through R5 against field data collected at KBS, Michigan, which record average initial population densities of S_I=50 aphids/plant and NE_I=1.5/plant in 2003, and S_I=70 aphids/plant and NE_I=2.5/plant in 2005 (Figure 1.4). Model predicted

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[6] Christine DiFonzo, Department of Entomology, Michigan State University, personal communications, October 4, 2005 and March 2, 2006.

SBA densities coincide fairly well with field observations from R1 to R4 for both 2003 and 2005 data. Model predicted SBA density in stage R5, however, deviates from field observation made in 2005 (data not available for stage R5 in 2003). Field population reduction around R5 is likely due to worsening plant condition (Costamagna *et al.*, 2007b) and emigration of winged aphids[7]. While the natural enemy model is estimated from field data so that the parameterization may be able to pick up some migration effect, our SBA model is developed based on simulation model parameterized from experimental data, which limits the model's ability to explicitly capture the aphid migration. Fortunately, we do not expect the deviation in predicted R5-SBA density to significantly affect the treatment decision rules the model prescribes because according to our estimation soybean yield is not found to be responsive to SBA density in stage R5 (Table 1.3).

1.6 Illustrative examples

Numerical solutions to the dynamic optimization problem (equation (5)) with respect to the NEET can be achieved through an optimizing simulation approach analogous to the algorithm of "DDPSOLVE" computer program developed by Miranda and Fackler (2002). The approach solves the "complete" solution space for given initial values of S_1, NE_1, and $E_1[y]$. Since there is a finite time horizon, and since we know that it is optimal to perform no control in the last period R5, we can specify 16 distinct feasible control paths, each representing a unique sequence of five control choices made over the periods R1-R5. We predict producer's return over variable costs of control for each control path and choose the one that yields the highest return as the optimal control path (Figure 1.5).

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[7] Christine DiFonzo, Department of Entomology, Michigan State University, personal communications, June 1, 2006.

We use two examples of initial SBA population density in R1 along with various levels of initial natural enemy density to illustrate how the model works when daily predation rate is 35 aphids/*NE* and maximum (pest-free) yield potential is 60 bu/ac. In example 1, we consider a relatively low initial pest level (S_I=40 aphids/plant), whereas in example 2 the initial pest level is relatively high (S_I=140 aphids/plant). Table 1.4 reports how population densities of SBA and natural enemies advance from R1 to R5, harvested yields, and what difference in the optimal control paths chosen when initial natural enemy density varies from 0 to 4 *NE*/plants in R1 (a range that is consistent with Michigan field data). As the optimal control paths prescribe, the frequency of spray decreases as the initial presence of natural enemies increases for given initial infestation level. The NEET is highly sensitive to natural enemy numbers, due to the high SBA predation value of ladybeetles. For instance, the pest density for spraying once in stage R1 is S_I=40 aphids/plant if $NE_I \leq 1$/plant. But if NE_I is greater than 1 per plant, there is no need to spray for the same initial pest density. The NEET for spraying twice at stage R1 and R2 is S_I=140 aphids/plant if natural enemies are not present. However, if $NE_I \geq 1$/plant at the same aphid density, the NEET calls for spraying only once in R1.

The illustrative examples demonstrate that at S_I=140 aphids/plant, the presence of only one natural enemy in R1 results in an increase of $1/ac in return to farmers, given the predation rate and initial yield potential parameters chosen. When combined with social and environmental benefits of spray frequency reduction, the value of adopting NEET insecticide management approach goes beyond private economic gains.

In validating performance of the NEET bioeconomic model, one limitation is that the simulation model finds that spraying twice in both R1 and R2 is the optimal control path for the initial pest density of 140 aphids/plant with no natural enemies present, whereas farmers and field entomologists wait longer between sprays. One reason may be that low-level natural control is present in the field, which reduces the need for insecticide control. But two limitations of the current NEET model may also have contributed to the result. First, the model does not capture the residual effect of insecticides, meaning that surviving insect population as modeled can bounce back immediately, potentially requiring another spray in the following stage to contain the infestation. Second, the model does not include the emigration of winged aphids, an important but also rather difficult aspect of the aphid-ladybeetle system to model given the current monitoring capacity.

1.7 Conclusion

The control of pests by their natural enemies represents an important ecosystem service that has the potential to mitigate pest control costs both to private producers and to society. These services, however, are often ignored in pest management threshold decision rules. Profitability and efficiency of pest management can be improved by incorporating natural pest control services into pest management decision making.

Focusing on private economic incentives, this study develops an intra-seasonal, dynamic bioeconomic model that explicitly takes into account the effect of natural pest control services on pest management and predicts pest control threshold that includes natural enemies. The model is applied to the case of soybean aphid management in Michigan. As illustrated by the numerical examples, such natural enemy-adjusted threshold is likely to lead to fewer recommendations for insecticide use than naïve models that ignore natural enemies, resulting in less insecticide use, while maintaining profitability for farmers. While the entomological threshold model does not have the right framework to provide economically optimal control recommendation, the existing economic models of pest management have lacked populations of natural enemies whose indirect yield benefit has implications for optimal control levels.

The current model can benefit from improvement in three dimensions. First, because the species composition of natural enemy communities tends to vary from field to field, weighting factors should be developed to account for the different suppression levels associated with different natural enemy species. Second, estimates for certain biological parameters such as predation rate, net decline rate of natural enemies, reproduction rate of natural enemies per prey encountered, and mortality rates of both pests and natural enemies by insecticides need refining and validation. Obtaining better parameter estimates will require new experimental designs that allow observation of biological effects by plant growth stage. In addition, the model can be strengthened by including the residual effect of insecticides and the migration behavior of insects, with the capacity of such expansion closely depending on improved data and ecological understanding of the system. Third, given that random effects such as weather play an important role in driving the underlying biological processes (e.g., insect population dynamics and crop growth), introducing stochastic processes for Monte Carlo simulation would enhance the current deterministic model.

By describing biological processes and interactions and predicting their responses to management decisions, bioeconomic modeling can improve human management of agroecosystems (King *et al.*, 1993). The multi-stage dynamic optimization model presented here demonstrates how pest suppression by natural enemies can be incorporated into a natural enemy-adjusted economic threshold for insecticide use that can maintain or even increase profitability and reduce farmers' dependence on insecticide. The model can be used to conduct a wide variety of analyses including i) identifying dynamically optimal spray strategies and estimating the implied economic value of natural control services, and ii) developing alternative mechanisms such as habitat management to enhance natural pest control services and eventually to significantly reduce the use of chemical insecticides. Furthermore, with the incorporation of cross-season carry-over factors, such as overwintering of pests and natural enemies, the current model can contribute to building multi-year models for studying long-term pest management problems.

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Table 1.1: Parameters for the SBA population model

	Value of parameters
r_{max} (Initial infestation: June 23, 2005)[a]	0.40 ± 0.03
C[b]	0.02 ± 0.001
$r_{max\_adjusted}$ (Soybean plants reach R1: July 5, 2005)	0.28
ng_1	5.29
ng_2	5.15
ng_3	2.35
ng_4	1.13

[a,b] Parameters (mean ± SE) estimated by Costamagna *et al.* (2007b).

Table 1.2: Parameters for the natural enemy population model

	Plant growth stage		
	R1	R2	R3
Net decline rate of *NE* (d_t)	-0.59	-0.90***	-2.13**
	(0.38)	(0.28)	(0.86)
Reproduction rate of *NE* per prey encountered (b_t)	0.002	-0.0001	0.002*
	(0.003)	(0.0005)	(0.001)
Number of Observations	28	28	30
R^2	0.31	0.55	0.51

Robust standard errors in parentheses

* Significant at 90%; ** significant at 95%; *** significant at 99%.

Data: Kellogg Biological Station, Hickory Corners, Michigan, 2003 and 2005; provided by Alejandro Costamagna, Department of Entomology, Michigan State University at the time of the data collection.

Table 1.3: Non-linear least squares estimation results from the reformulated restricted Cousens rectangular hyperbolic model

	R1	R2	R3	R4	R5
$E_t[y]$	37.22***				
	(1.95)				
η_t	0.0002	-0.001**	0.0003*	0.0001*	0.0002
	(0.001)	(0.001)	(0.0002)	(0.00004)	(0.001)
θ_t	1	1	1	1	1
Obs	43	43	43	43	43
Adj. R^2	0.92	0.93	0.93	0.94	0.94

Standard errors in parentheses.

* Significant at 90%; ** significant at 95%; *** significant at 99%.

Data: multiple sites in Michigan, 2005; provided by Christine DiFonzo, Department of Entomology, Michigan State University

Table 1.4: NEET illustration: population densities of SBA and natural enemies, harvest yields, and optimal spray decisions chosen for two initial values of S_1 (40 and 140 aphids/plant) given four values of NE_1 (0-4 *NE*/plant) (Daily predation rate=35 aphids/*NE*, initial maximum yield potential $E_1[y]$=60 bu/ac)

NE density at R1 (*NE*/plant)	Pest density (aphids/plant)					$y_{harvest}$ (bu/ac)	Return over variable costs of control ($/ac)	Optimal control path
	R1	R2	R3	R4	R5			
0	40	2.5	15.5	51.9	110.6	59.4	398	Spray in R1
1	40	1.5	5.5	18.2	38.8	59.8	401	Spray in R1
2	40	41.6	0	0	0	60	415	No Spray
3	40	0	0	0	0	60	415	No Spray
4	40	0	0	0	0	60	415	No Spray
0	140	8.8	0.5	1.8	3.9	60	390	Spray in R1 & R2
1	140	7.8	44.2	147.8	315.3	58.4	391	Spray in R1
2	140	6.7	34.2	114.1	243.5	58.7	394	Spray in R1
3	140	5.7	24.3	80.4	171.6	59.1	396	Spray in R1
4	140	4.6	14.3	46.7	99.7	59.5	399	Spray in R1

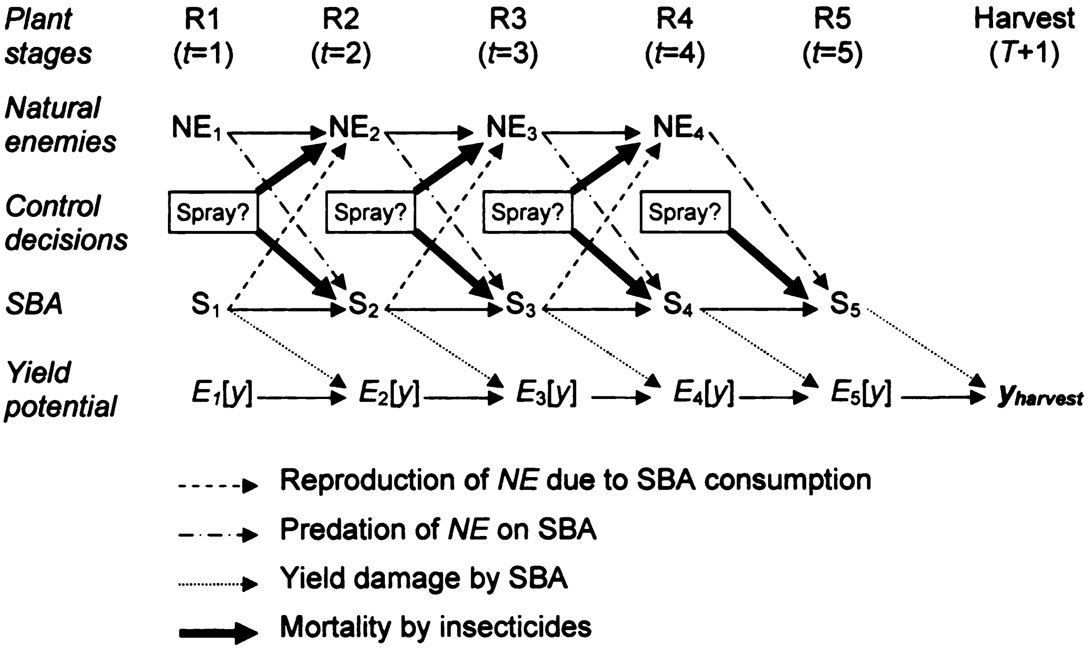

Figure 1.1: Illustration of the advancement of biological dynamics within season

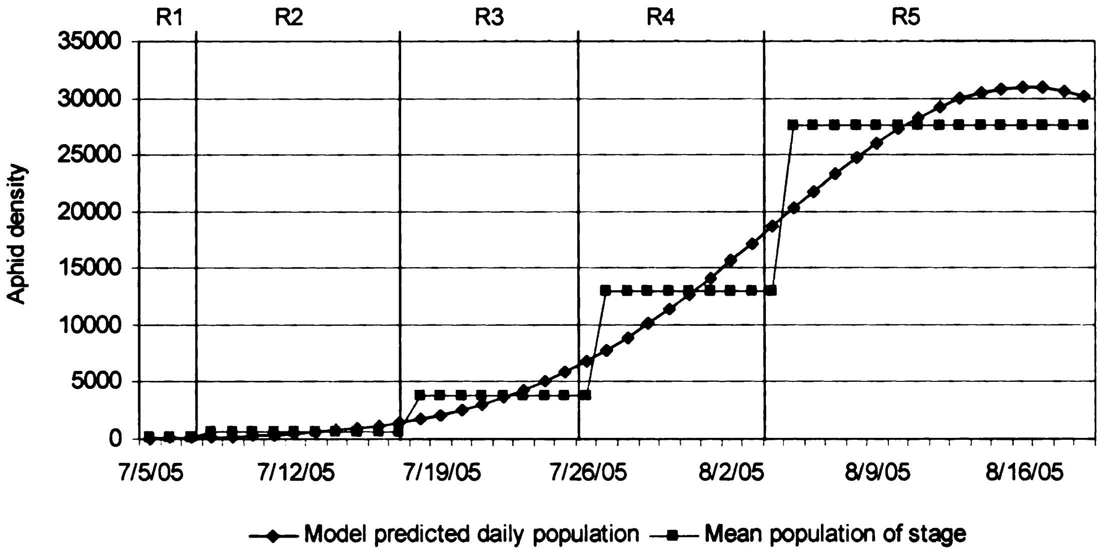

Figure 1.2: Simulated predation-free daily SBA density (aphids/plant) from Costamagna *et al.* (2007b) model

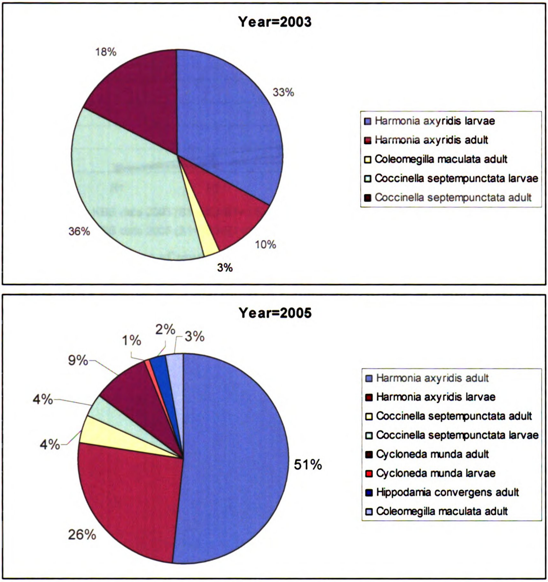

Figure 1.3: Composition of ladybeetle species included to quantify natural enemy presence (Data were provided by Alejandro Costamagna, Department of Entomology, Michigan State University, at the time the data were collected)

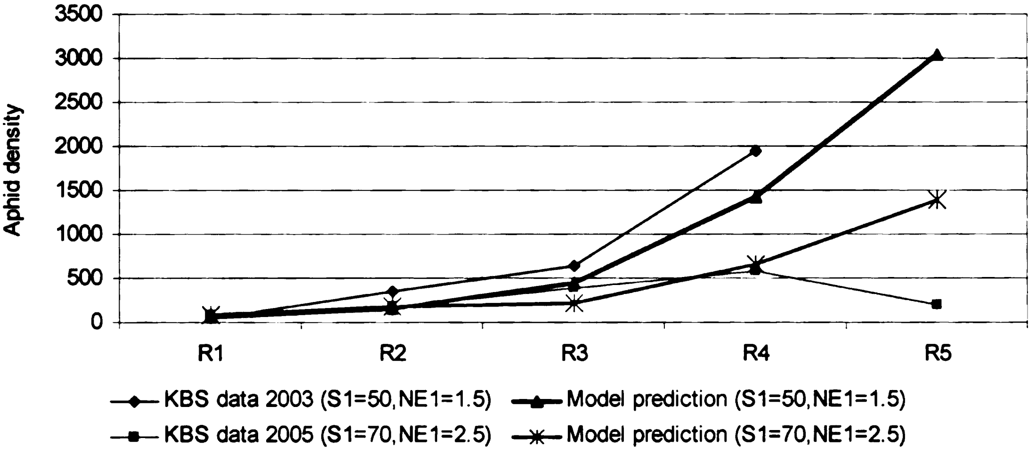

Figure 1.4: Comparison of model prediction of untreated SBA densities during R1 to R5 with field data for 2003 and 2005, KBS, Michigan. (Field data were provided by Alejandro Costamagna, Department of Entomology, Michigan State University, at the time the data were collected.)

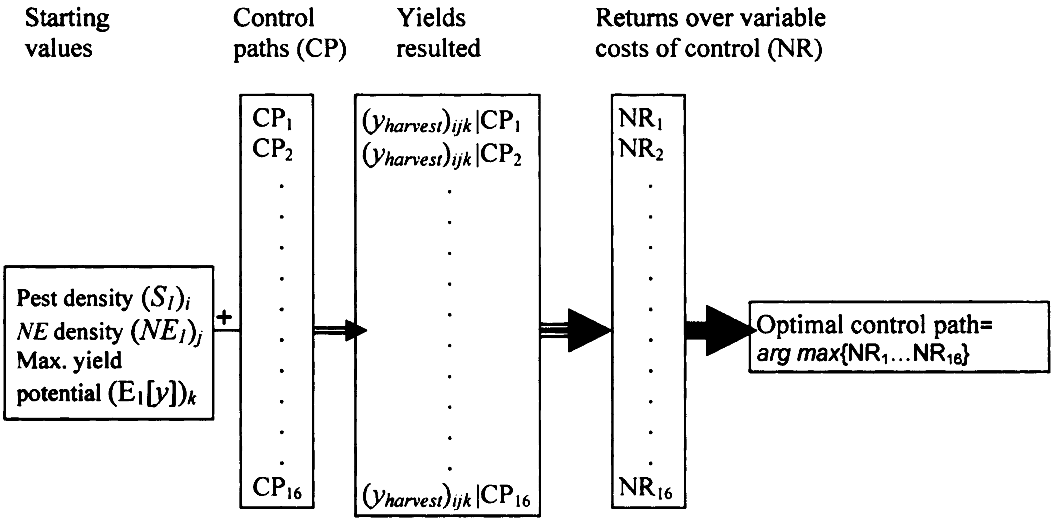

Figure 1.5: Illustration of how optimal control path is reached for a given combination of initial values of pest density $(S_l)_i$, natural enemy density $(NE_l)_j$, and maximum yield potential $(E_l[y])_k$

Essay 2:
Optimal Control of Soybean Aphid in the Presence of Natural Enemies

2.1 Introduction

Natural enemies provide an important ecosystem service of pest population suppression that maintains the stability of agricultural systems and potentially mitigates producers' pest control costs (Naylor and Ehrlich, 1997; Losey and Vaughan, 2006). While the various approaches to biological control, including importation (or classical biological control), augmentation and conservation, all directly and purposefully use the natural control services (Barbosa and Braxton, 1993), integrating available natural control services into the decision-making of chemical control offers an important approach to improving the economic efficiency of insecticide use with potentially socially desirable outcomes. Focusing on the management of soybean aphid (*Aphis glycines*, Matsumura) (SBA), a new pest of soybeans in the North Central region of the United States, this study assesses how predation by natural enemies of SBA (mainly ladybeetles, *Coccinellidae*) contributes to optimal insecticide strategies. In the process, it also provides a lower bound estimate of the value of natural pest control services.

Current chemical pest control practices typically do not take into account the presence of natural enemies. Untimely application of broad-spectrum insecticides can decimate natural enemy populations, potentially exacerbating existing pest problems or even triggering the emergence of new pests (Calkins, 1983; Naylor and Ehrlich, 1997; Krishna *et al.*, 2003). Such unintended effects imply inefficiencies in insecticide use if unaccounted for in the treatment decision—an "opportunity cost" to producers in terms of foregone natural control services that would have been provided by existing natural enemies.

Economic threshold (ET) refers to the optimal (net-return-maximizing) pest population density where the marginal value product of damage control equals the marginal cost of control (Headley, 1972). The current ET concept is generally based on pest abundance and does not address natural enemy mortality or the impact of natural enemies on pest survival (Musser *et al.*, 2006). Zhang (Essay 1) develops an intra-seasonal, dynamic bioeconomic optimization model that explicitly includes the predation effect of natural enemies on the target pest and demonstrates that the incorporation of natural pest control services into pest management threshold decision rules can potentially lead to reduction in insecticide use. This study applies the bioeconomic optimization model developed in Zhang (Essay 1) to i) identify optimal insecticide strategies for the control of SBA, taking into account the presence of natural enemies, and ii) provide preliminary assessment of the economic value of the SBA biological control services to private producers. The results suggest optimal SBA density as observed upon the initial decision point for pest control over the course of pest management, at which the prescribed control strategy is optimal despite the opportunity cost of natural enemy mortality due to insecticides. The estimated values are conservative, because they take into account only farmers' private profitability benefits from optimizing the number and timing of broad-spectrum insecticide applications in the presence of natural enemies. A full accounting of the natural pest control services would also include potential social and environmental benefits (such as averted human health risks and environmental pollution due to pesticides), which are likely to justify further reduced levels of insecticide use and higher economic value of natural pest control services.

There have been two general types of valuation studies that assess the benefits of natural control services: i) *ex post* impact assessment of classical biological control projects that look at the economic benefit of artificial introduction or massive release of natural enemies (Hill and Greathead, 2000), and ii) calculation of the aggregate annual monetary value of averted crop losses as a result of pest population suppression by extant natural enemies (e.g., Losey and Vaughan, 2006; Pimentel *et al.*, 1997). This study focuses on the natural pest control services supplied by existing natural enemies. To calculate the aggregate annual monetary value of natural pest control services, existing studies typically start by estimating the total cost of pest damage resulted from all pest control mechanisms and then attribute a fraction of the total pest control benefit to natural enemies. For instance, Pimentel *et al.* (1997) estimated that natural enemies provide approximately $100 billion worth of pest control worldwide per year (about 60% of $156 billion total averted pest control cost a year), whereas Losey and Vaughan (2006) estimated the value of natural control to be $4.5 billion annually for the US. While these aggregate values provide snapshots on the possible magnitude of the benefit from natural enemies of crop pests humans enjoy, they ignore local context (e.g., pest species, pest pressure, existing natural enemy level, the value of protected yield, cost, effectiveness, and availability of alternative pest control mechanisms), and thus are rather uninformative for the producer-level management of this ecosystem service.

Natural pest control services as regulating ecosystem services (MA, 2005) can be valued indirectly via their contribution as inputs to the biological production of marketed products. Thus, their partial economic value can be inferred from the price of marketed products (Swinton and Zhang, 2005). In this study, model results will compare producer returns over variable costs of insecticide management with and without accounting for the presence of natural enemies. The results will be used to make a preliminary estimate of the incremental return over variable costs of control resulting from an additional natural enemy in the system given a set of economic and biological conditions.

Following this introduction section, we provide background information on the SBA problem and the role of natural enemies in its regulation in section 2.2. We then briefly introduce the bioeconomic optimization model adopted in section 2.3. In section 2.4, we present numerical results from the dynamic optimization analysis for single season SBA management and the estimated economic value of natural enemies that attack SBA. Section 2.5 reports findings from a sensitivity analysis of key parameters. Finally, we highlight main findings, identify applications for the effects of natural enemy populations on optimal SBA control, and suggest future research directions (section 2.6).

2.2 Soybean aphid and its natural enemies

Soybean aphid is an invasive species that was first discovered in the North Central region of the United States in 2000. Within four years, it had spread to 21 states and south-central Canada (Landis *et al.*, 2004). Not only is SBA capable of causing extensive damage to soybean yield with documented yield loss of up to 40% (DiFonzo and Hines, 2002), SBA outbreaks are also correlated with dramatic increases in virus incidence in vegetable crops (Alleman *et al.*, 2002; Stevenson and Grau, 2003; Thompson and German, 2003; Fang *et al.*, 1985; RAMP, 2006). Since its invasion, SBA has prompted extensive spray of soybean acreage, which had previously required negligible insecticide use in the region (Smith and Pike, 2002). For example, 42% of soybean acreage in Michigan and 30% in Minnesota were sprayed during the 2005 season, compared with less than 1% before SBA arrived in 1999 in North Central region states for which data are available (NASS, 2007).

Existing natural enemy communities play a key role in suppressing SBA populations (Fox *et al.*, 2004; Aponte and Calvin, 2004; Rutledge *et al.*, 2004; Landis *et al.*, 2004; Costamagna and Landis, 2006; Berg, 1997). Natural enemies of SBA include 22 predator species (Rutledge *et al.*, 2004), 6 parasitoid species (Kaiser *et al.*, 2007), and several species of fungi that cause disease in aphids (Nielsen and Hajek, 2005). In particular, generalist predators (mainly ladybeetles, *Coccinellidae*) provide strong, season-long suppression, protecting soybean biomass and yield from SBA damage (Costamagna *et al.*, 2007). However, most insect natural enemies are susceptible to the major insecticides used to treat SBA[1]. Evidence from Iowa indicates that insecticides applied in early season can actually result in greater SBA population later (O'Neal, 2007), undermining the cost-effectiveness of insecticide investment. Although general recommendations stress the need for assessing the field situation with respect to natural enemies before spraying (e.g., Smith and Pike, 2002; NSRL, 2002; NCPMC, 2005), the current extension treatment threshold recommendation relies solely on aphid density observation. However, it was developed from field data where natural enemies were probably present, so their effect is likely to be implicit in the threshold recommendation.

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[1] Christine DiFonzo, Department of Entomology, Michigan State University, personal communications, October 4, 2005 and March 2, 2006.

Up to now, producers have not been offered decision rule that explicitly accounts for the pest regulation services supplied by ambient natural enemies.

2.3 Bioeconomic optimization model

Using field trail data from Michigan collected during 2003 and 2005 under a multi-state soybean aphid USDA Risk Assessment and Mitigation Program (RAMP) project on "Soybean Aphid in the North Central U.S.: Implementing IPM at the Landscape Scale", Zhang (Essay 1) develops an intra-seasonal, dynamic bioeconomic optimization model for SBA management over five time periods that correspond to the five reproductive stages of soybean plant growth, R1 through R5, during which soybeans are most susceptible to SBA damage (Jameson-Jones, 2005). The model assumes that a producer chooses the optimal control action (spray or no spray) at each decision point (*t*) to maximize end-of-season return over variable costs of control, subject to biological constraints describing the dynamics of pest population (S_t), natural enemy population (NE_t), and expected crop yield potential ($E_t[y]$). Denoted by *J*, the objective function over the finite time horizon covering stages R1 to R5 can be written as:

$$J = \underset{\{x_t\}_{t=1}^{T=5}}{Max}\ [p \cdot y_h - \sum_{t=1}^{T=5} c(x_t)] \tag{1}$$

subject to

$$\text{i) } E_{t+1}[y] = E_t[y] \cdot (1 - \frac{\eta_t \cdot S_t}{1 + \eta_t \cdot S_t / \theta_t}) \tag{2}$$

and $E_1[y] = \bar{y}_h, E_6[y] = y_h$, t=1, 2, 3, 4, 5

$$\text{ii) } S_{t+1} = (1 + ng_t) \cdot (S_t - k_{S,t} \cdot x_t \cdot S_t) - pr_t \cdot (NE_t - k_{NE,t} \cdot x_t \cdot NE_t),\ t=1, 2, 3, 4 \tag{3}$$

iii) $NE_{t+1} = (1+d_t)\cdot(NE_t - k_{NE,t}\cdot x_t \cdot NE_t) + b_t \cdot (S_t - k_{S,t}\cdot x_t \cdot S_t)\cdot(NE_t - k_{NE,t}\cdot x_t \cdot NE_t)$

t=1, 2, 3[2] (4)

iv) S_1, NE_1, and $E_1[y]$ are given

where

p = output price

x_t = binary choice for control. x_t=1 for spray at fixed label-recommended rates at stage t, and x_t=0 for no spray

$c(x_t)$ = control cost at stage t, including the cost of pest scouting to provide the basis for control decisions

S_t = population density of SBA per plant at stage t

NE_t = population density of natural enemies per plant at stage t

$k_{S,t}$ = mortality rate of SBA from insecticide application

$k_{NE,t}$ = mortality rate of natural enemies from insecticide application

d_t = natural net decline rate natural enemies would suffer in the absence of prey

b_t = the reproduction rate of natural enemies per prey encountered

ng_t = net growth rate of SBA population in the absence of "outside" regulation

pr_t = predation rate per natural enemy unit per stage

$E_t[y]$ = expected yield potential at stage t

η_t = proportion of yield lost per unit of pest population

θ_t = maximum proportional yield loss to pest damage ($0 \leq \theta_t \leq 1$)

$\bar{y}_h$ = pest-free yield potential or average historical yield upon which the season's first prediction is based

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[2] The model predicts population of natural enemies up to stage R4, which in turn affects SBA population in stage R5, the last stage when SBA can cause yield damage.

y_h = actual yield at harvest (assumed to be equal to yield potential evaluated at stage $T+1=6$)

Table 2.1 reports the values of parameters from Zhang (Essay 1)'s model. A few key points deserve note. First, the model assumes that no more than one spray may occur in each stage and that the predicted yield upon stage R5 is carried through to harvest so that SBA control is only meaningful during stages R1 to R4. Second, the quantification of the natural enemy presence is focused on major generalist predator species of the ladybeetle family, due to their high abundance in both number and overall suppression effectiveness (Costamagna, 2006). Populations of major ladybeetle species are aggregated, including *Harmonia axyridis* (multi-colored Asian ladybeetle) adult and larva, *Coccinella septempunctata* adult and larva, *Coleomegilla maculata* adult, *Cycloneda munda* adult, *Cycloneda munda* larva, and *Hippodamia convergens* adult. Third, based on findings from the biological literature and field observation of species composition, the model proposes an approximate range for the weighted average predation rate of SBA by ladybeetles: 17 to 52 aphids eaten per ladybeetle per day, which gives a mean consumption rate of 35 aphids/day per ladybeetle. The per stage predation rate pr_t is then computed by multiplying daily predation rate by the number of days in a given stage (Table 2.1). Fourth, for price and cost parameters, we use a long-term soybean trend price of \$6.9/bu and a treatment cost of \$12.2/ac for the RAMP Best Management Practice treatment using pesticide Lambda-cyhalothrin (Warrior with Zeon Technology®) at 3.2 oz/ac (Song *et al.*, 2006). A break-down of the cost includes \$7/ac insecticide cost, \$2/ac for scouting, and approximately \$3.2/ac for spraying (Song *et al.*, 2006). Finally, it is assumed that insecticide will kill 99% of both SBA and natural enemies at each application during the season.

Estimated values of parameters in Zhang (Essay 1) that are statistically significant are used directly in the numerical optimization analysis of this study with the exception of η_2, the proportion of yield lost per unit of pest population in stage R2, which is estimated to be negative, suggesting a "compensation" yield response relationship between pest injury and crop yield potential in R2 (Pedigo *et al.*, 1986). While this estimation is theoretically possible (Pedigo *et al.*, 1986; Tammes, 1961; Fenemore, 1982), field observations in Michigan do not show evidence of such compensation[3]. Thus, we assume that yield potential in stage R2 is not responsive to pest injury (i.e., η_2=0) in the numerical exercise. For parameters that are found insignificant in their respective models, we use zeros instead of the estimated values in the numerical optimization analysis.

2.4 Numerical analysis

The Optimizing simulation approach

We adopt an optimizing simulation approach to solving the dynamic optimization problem numerically, within a solution space that is relevant to field observations made in Michigan soybean fields (see MatLab code in Appendix A). The approach is essentially an integration of two components: i) a simulation routine to predict the economic outcome of each scenario, and ii) a selection routine to choose the control strategy (i.e., control path) that yields the best economic outcome. The algorithm of the approach is analogous to that of "DDPSOLVE", a dynamic programming computer

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[3] Christine DiFonzo, Department of Entomology, Michigan State University, personal communication, July 6, 2007.

program developed by Miranda and Fackler (2002) but with two major improvements: i) it allows the biological transition equations to contain stage-specific parameters, and ii) it significantly reduces computational expenses and thus enables us to use smaller and more accurate value intervals and wider ranges of possible initial values for the biological state variables. Specifically, the optimization is carried out as following:

- Define space matrices for initial values of state variables S_t and NE_t: i) 31 possible values for S_1 (0:5:150) (meaning a range of 0 to 150 aphids on average per plant with an interval of 5 in R1), and ii) 9 possible values for NE_1 (0:0.5:4). These ranges are chosen to reflect field observations of population densities of SBA and natural enemies in stage R1 in field trials in Michigan[4].
- Consider 11 scenarios for maximum (pest-free) yield potential ($E_1[y]$) that are consistent with common Michigan yield levels (40:2:60) (MSU Field Crops AOE Team, 2002) and 3 scenarios for daily ladybeetle predation rate (pr_t) (minimum, mean, and maximum of 17, 35, and 52 aphids per ladybeetle per day, respectively) to account for uncertainties in these parameter values.
- Specify 16 distinct possible control paths, each representing a unique sequence of five control choices made over the periods R1-R5 with the optimal control action in the last period R5 always being "no control" (i.e., x_5 =0 known).

For each of the 33 maximum yield potential-predation rate scenarios (3*11=33 scenarios), we compare the predicted returns over variable costs of control from the 16 control paths for each of the 279 combinations of initial values of population densities of SBA and natural enemies (31*9=279). The total number of simulations to run therefore amounts to

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[4] Michigan field data for 2003 and 2005 provided by Christine DiFonzo and Alejandro Costamagna, Department of Entomology, Michigan State University.

147,312 (33*279*16=147,312). In each simulation, the control path that yields the highest value of return over variable costs is designated the optimal control path.

By defining relevant ranges for the initial values of population densities of SBA and natural enemies and scenarios for maximum yield potential and predation rate, we delimit a relevant sub-space within the full optimization solution space, effectively reducing the computational expense. Certainly, the smaller the intervals are, the more accurate are the predictions. The analysis covers sufficiently wide ranges of relevant initial values of biological state variables with reasonably small intervals.

Numerical results

For this deterministic, discrete and finite time horizon problem, the dynamic optimization model predicts the sequence of control actions that would be optimal for the entire season given initial values of the population densities of SBA and its natural enemies. Because the model is deterministic, its results follow from field scouting information once in the initial period of stage R1.

To illustrate key results from the optimization analysis, we plot predicted optimal control paths against values of population densities of SBA (S_I) and natural enemies (NE_I) in stage R1 for given daily predation rates and initial yield potentials in Figures 2.1-2.3. Figures 2.1a, 2.2a, and 2.3a correspond to results associated with a lower initial yield potential of 40 bu/ac, whereas Figures 2.1b, 2.2b, and 2.3b correspond to results for a higher initial yield potential of 60 bu/ac. The figures are not normal phase planes in the sense that the x-axis represents all possible values of S_I, y-axis represents all possible values of NE_I, and each x-y coordinate in the optimal control space corresponds to an optimal control path (not just a control action at a decision point) determined jointly by S_1 and NE_1. For instance, at a daily predation rate of 35 aphids/NE and an initial yield potential (E[y_1]) of 60 bu/ac, the optimal control path is to control in both R1 and R2 and do nothing from R3 to R5 when S_1=125 aphids/plant and NE_1=0/plant (Figure 2.1b).

We organize our presentation of the key results in the following five aspects:

1) Optimal control paths

A total of three distinct optimal control paths emerge given the parameters used: (i) no control in all stages ("No spray"), (ii) control in stage R1 only ("Spray R1"), and iii) control in both R1 and R2 ("Spray R1+R2"). Note that since we have incorporated the population dynamics of natural enemies, any control action prescribed by the model remains optimal in spite of the opportunity cost of injury to natural enemies. While it is obvious that no insecticide spray is necessary during the last stage (R5), stages R3 and R4 are found to be too late to take any control action in any circumstances with respect to the values of S_1 and NE_1. "No spray" and "Spray R1" strategies prevail in all circumstances, whereas "Spray R1+R2" has to be justified by relatively heavy infestation, low natural enemy population (or low predation rate), and high initial yield potential. Figures 2.1-2.3 show that, in the absence of natural suppression (i.e., NE_1=0), "Spray R1+R2" is never optimal when E[y_1] is as low as 40 bu/ac but becomes desirable in more heavily infested situations ($S_1 \geq 125$) at a higher initial yield potential such as 60 bu/ac.

Our results show that for a pest that is capable of rapid reproduction like SBA, early treatment actions are preferred over late actions, which is consistent with the current extension recommendation for managing SBA (NCPMC, 2005). The simulation model finds that spraying twice in both R1 and R2 is the optimal control path for initial pest density exceeding 120 aphids/plant with no natural enemies present, whereas farmers and field entomologists wait longer between sprays. As Zhang (Essay 1) points out, the actual presence of natural enemies in the field, which reduces the need for insecticide control, along with two limitations of the model (i.e., omitting the residual effect of insecticides and the emigration of winged aphids) may have potentially contributed to the result.

2) The effect of natural enemies on optimal control threshold

In the absence of natural enemies as shown in the bottom rows of Figures 2.1-2.3, chemical control is cost-effective for initial pest density as low as 5 aphids/plant. This zero-natural enemy scenario exemplifies the assumption by many soybean farmers who ignore natural control services. Empirical observation shows that producers often do not hesitate to spray the fields, because of the relatively low cost of spray. The 3 aphids/plant action threshold suggested by Olson and Badibanga (2005) (the pest density at which action should be initiated to ensure spray is carried out by the 7th day from the observation of the density) is largely consistent with our result of treating SBA at 5 aphids/plant threshold *only if* the population of natural enemies is zero[5]. As Figure 2.1 shows, with just one natural enemy per plant, the optimal threshold is sharply increased to 30 aphids/plant—10 times of the level suggested by Olson and Badibanga (2005).

Spraying a second time in R2 after the first treatment (i.e., optimal control path "Spray R1+R2") would not be needed except when high pest pressure accompanies little

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[5] Among the four potential SBA treatment thresholds (3, 100, 250, and 500 aphids per plant) included in Olson and Badibanga (2005)'s analysis, 3 aphids/plant is the lowest threshold considered. It is expected that their model may suggest even smaller threshold if such scenario is included.

presence of natural enemies. For instance, at daily predation rate of 35 aphids/*NE* and initial yield potential of 60 bu/ac, the fields need to be sprayed twice in both R1 and R2 stages when initial infestation level is 125 aphids/plant and when there are no natural enemies (Figure 2.1b). The same SBA population density only needs one spray in R1 if natural enemy is just 1/plant (Figure 2.1b). Although this finding is specific to the current model parameters, it demonstrates that wise insecticide strategy can conserve natural enemies, allowing them continue suppressing pest populations and avoiding excessive use of insecticides.

3) Effect of variation in predation rate

Predation rate plays an important role in determining the optimal control decisions. The effect is best illustrated by the shrinkage of the region for optimal control path "Spray R1" (or equivalently, the expansion of the region for "No spray") in Figures 2.1-2.3 as the daily predation rate changes from 17 aphids/*NE* to the mean and maximum levels of 35 and 53 aphids/*NE*/day, respectively. A higher daily predation rate increases the threshold for insecticide use, implying that i) the same natural enemy density can now sustain a higher control threshold, or ii) fewer natural enemies are needed to sustain a given threshold density. For instance, Figure 2.2a suggests an optimal control threshold of 15 aphids/plant at NE_I=1/plant when daily predation rate is 17 aphids/*NE*, whereas the threshold becomes 30 and 45 aphids/plant for daily predation rate of 35 and 52 aphids/*NE*, respectively, holding the same initial yield potential of 40 bu/ac (Figures 2.1a and 2.3a). Predation rate is not a variable under farmer control. However, populations of species that are particularly effective suppressing SBA may be targeted to improve predation rate through habitat management that provides compatible conditions favoring certain species.

4) Effect of variation in initial yield potential (or equivalently, historical yield level)

The effect of initial yield potential on the choice of optimal control path is not obvious for moderately infested fields, i.e., S_I<125 aphids/plant. Provided that on average over 125 aphids per plant are scouted in stage R1, the same population densities of SBA and natural enemies may require more insecticides being used (i.e., optimal control path changes from "Spray R1" to "Spray R1+R2") for fields with high initial yield potentials. "Spray R1+R2" would never be needed when the initial yield potential is at the low end of 40 bu/ac, regardless of the daily predation rate (Figures 2.1 to 2.3). The result conforms to the general expectation that more productive fields justify more insecticide use than the less productive ones at given output price and control cost.

5) Values of returns to producers over variable costs of control

We plot the values of return over variable costs of control against initial SBA densities for two levels of initial natural enemy density in Figure 2.4. The initial yield potential is set at 40 bu/ac and the daily predation rate is 35 aphids/*NE*. The first curve (from the left) is associated with NE_I=0/plant, whereas the second one is associated with NE_I=1/plant.

For NE_I=0, the return to producers from optimal SBA management over variable costs of control is a monotonically decreasing function of initial pest density (Figure 2.4). Starting at the maximum level of $276/ac when pest density equals zero (S_I=0), the values of return steadily decline to $254/ac at the maximum SBA density level of

150/plant (corresponding to optimal control paths depicted in Figure 2.1a). For NE_I=1, the predicted values of return show a plateau at the \$276/ac level for S_I between 0 and 25 aphids/plant, drop to \$264/ac at S_I=30/plant, and maintain the declining trend throughout the rest range of S_I. At a daily predation rate of 35 aphids/*NE* and initial yield potential of 40 bu/ac, as a field becomes more infested, the capability of a given level of natural enemies to maintain the maximum achievable return of \$276/ac declines, although higher NE_I naturally leads to larger return for given initial SBA density as compared to lower NE_I. At a higher daily predation rate such as 52 aphids/*NE*, however, an initial density of 4 natural enemies per plant is able to maintain the maximum achievable return (\$276/ac), even in the most SBA infested fields (not shown in the figure).

6) Economic value of natural pest control services

These numerical results can be used to make a preliminary estimate of the value of the natural pest control ecosystem service. The value is calculated from the increase in return to producers over variable costs of control as a result of an increased initial population of natural enemies so the estimate constitutes a lower bound for the total economic value of this ecosystem service because it omits such benefits as the avoidance of health and environmental risks from insecticide spraying.

The value is context-dependent, because the marginal value of an additional unit of natural enemy population not only depends on the predation rate, initial yield potential and pest population, but also the existing natural enemy population and prices. To illustrate, we plot in Figure 2.5 values of an initial natural enemy density of 1 per plant as compared to the baseline of zero natural enemies per plant for various initial pest densities for an initial yield potential-daily predation rate scenario defined in Figure 2.4. At a daily predation rate of 35 aphids/*NE* and initial yield potential of 40 bu/ac, the presence of one natural enemy per plant in R1 (as compared to none) implies a sequence of minimum values associated with given initial pest populations: for instance, \$12.50/ac at S_I= 5/plant (corresponding to optimal control path changing from "Spray R1" to "No spray" in Figure 2.1a), and \$13.90/ac at S_I= 25/plant (corresponding to optimal control path changing form "Spray R1" to "No spray" in Figure 2.1a), from where the value declines as S_I increases. That the value at S_I= 25/plant is higher than that at S_I= 5/plant is because higher SBA density is capable of causing more yield loss.

Figure 2.5 also indicates that there is always a positive gain in return to producers (at the minimum \$1.70/ac when S_I=150 aphids/plant and initial yield potential is 40 bu/ac) due to the presence of one natural enemy per plant as compared to the NE_I=0 baseline, so long as the field is infested with SBA (i.e., S_I>0). The minimum gain is lower, at \$0.03/ac when S_I=150 aphids/plant, if the initial yield potential is increased from 40 bu/ac to 60 bu/ac (not shown in the figure), implying a relative advantage of using natural enemies to control pests on less productive land. When existing natural enemies are already at a relatively high density, such as 3/plant, one more natural enemy does not convey any economic value unless the field is infested with more than 75 aphids/plant in R1.

Aggregating these results for the value of natural enemies for the broad region is difficult. The reason is that we cannot observe the correct area where insecticide treatment could have been averted because natural enemies adequately suppressed SBA numbers. The problem is that in the real world we do not observe the counterfactual cases of (a) acres that never reached threshold because of natural enemies, and (b) acres that were treated but did not need it because natural enemies would have contained SBA damage.

2.5 Sensitivity analysis

To assess the effect of uncertainty associated with the economic and biological parameters used in the dynamic optimization analysis, we perform a sensitivity analysis on selected, key parameters by changing parameters one at a time holding the rest constant and comparing the results with the baseline which is based on parameters reported in Table 2.1. For a case in which daily predation rate is 35 aphids/*NE* and initial yield potential is 40 bu/ac, a total of 18 scenarios are examined (Table 2.2). Parameters estimated from field data are increased and/or decreased by one standard deviation, whereas parameters that are assumed or derived from other studies are increased and/or decreased by 5%, respectively, except for the two economic parameters, output price and control cost, whose values are varied by 20% and 50%, respectively[6]. Table 2.2 summarizes the major results from the sensitivity analysis. Specifically, we look at two aspects of changes from baseline resulted from varying parameters: choice of optimal control path and values of return over variable costs of control.

1) Choice of optimal control path

Varying the values of most of the parameters does not alter the selection of optimal control paths in most scenarios with the exception of reducing the mortality rate of SBA

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[6] We also ran scenarios for 5% of change in the values of output price and control cost and found no impact on the model results when varying control cost and only 5% of gain (or loss) when price is increased (or decreased) by 5%.

to insecticide ($k_{S,t}$) by 5% and varying control cost by 50% (Table 2.2). Lower insecticide efficacy rate means that SBA population is more likely to rapidly rebound after spraying so that delaying spray when there is reasonable amount of natural enemies present can become attractive. As a result, at a daily predation rate of 35 aphids/*NE* and initial yield potential of 40 bu/ac, a 5% decrease in $k_{S,t}$ leads to the selection of optimal control path "Spray R2" over "Spray R1" when low-medium SBA population (30-70 aphids/plant) is combined with relatively abundant natural enemies (1-2 *NE*/plant). On the one hand, too low of a SBA population (below 30 aphids/plant) does not justify any spray unless no natural enemies are present. On the other hand, given low-medium SBA population, "Spray R1+R2" would be preferred over "Spray R1" if natural enemy population is relatively low (no greater than 2 *NE*/plant) or no spray would be needed otherwise (i.e., higher than 2 *NE*/plant). When SBA population is relatively high (between 70 and 110 aphids/plant), however, 5% reduction in $k_{S,t}$ results in the choice of "Spray R1+R2" over "Spray R1", unless the natural enemy population is high enough to warrant "No spray". For SBA population above 110 aphids/plant, spray twice in both R1 and R2 would be needed, regardless of natural enemy population. The analysis also shows that a 5% increase in the survival rate of natural enemies is not large enough to induce any change to the choice of optimal control path, given the daily predation rate and initial yield potential considered in this case.

Given the low initial yield potential (40 bu/ac) considered in the current analysis, 20% change in soybean price does not have a significant impact on the choice of optimal control path (Table 2.2). Varying control cost by 50% does result in limited changes from the baseline. Specifically, increasing control cost by 50% only slightly scales down the incentive for spraying in R1 as opposed to "No spray" at medium SBA population, reconfirming the relative cost-effectiveness of current practice of insecticide application, especially when natural enemies are less than abundant in the field. This finding is reinforced by the scenario of reducing control cost by 50%, which calls for more frequent sprays (i.e., "Spray R1+R2" over "Spray R1") for relatively high SBA population when there is limited presence of natural enemies.

2) Values of return over variable costs of control

While varying the output price by 20% does not affect the choice of optimal control path, output price variation has the greatest impact on producer's return over variable costs of control, followed by scenarios reducing the mortality rate of SBA to insecticide by 5%. Specifically, varying output price by 20% leads to roughly proportional change in the value of return. Reducing the mortality rate of SBA to insecticide by 5% results in losses in return ranging from 2 to 5%, with impacts rising with SBA density. Reducing the mortality rate of natural enemies to insecticide by 5% slightly improves the returns over variable costs by up to 2.5%. Varying control cost by 50% has disproportionately small financial effects in terms of change in return over variable costs of control (ranging from 0 to 4%). This result demonstrates again the high payoff to insecticide application even for land with initial yield potential as low as 40 bu/ac.

In the two price sensitivity scenarios, the impact on model results grows as initial pest population rises, while the initial natural enemy level tends to muffle the effects. In the two insect mortality rate scenarios, impact also grows as initial pest population rises but relatively low (or high) natural enemy populations accompanying a relatively low (or high) SBA population are responsible for greater effects. The remaining sensitivity analysis scenarios have negligible impacts on returns above central costs.

2.6 Conclusion

The control of pests by their natural enemies represents an important ecosystem service that has the potential to mitigate pest control costs both to private producers and to society. This important ecosystem service, as well as the unintended effect of broad-spectrum insecticides on the populations of natural enemies, however, have not been included in the existing economic models of optimal pest management (e.g., Talpaz and Borosh, 1974; Zacharias and Grube, 1986; Harper *et al.*, 1994; Bor, 1995), nor has any applicable decision guide been offered to crop farmers to conserve and capitalize on the pest regulation services supplied by ambient natural enemies.

The current North Central states extension recommendation of action threshold of 250 aphids per plant given a 7-day window between the observation of the pest density and actual insecticide application (Ragsdale *et al.*, 2007) has been introduced as an Integrated Pest Management alternative to prophylactic SBA control. The recommendation is based on a static approach that does not account for the dynamic effects of insecticide application on natural enemies and consequently the population of the pest, especially when multiple treatments are needed. Moreover, the recommendation does not provide specific guidance on the timing of applying this threshold nor does it offer any applicable guide on how to incorporate natural enemies into pest management decision-making. Olson and Badibanga (2005)'s model implies that even the smallest population density of SBA can justify insecticide treatment, regardless of aphid growth rate. Their conclusion is only consistent with findings from this study in the absence of natural enemies.

Using a simulation experiment developed for the soybean aphid and ladybeetle prey-predator system, this study examines the difference in optimal control actions chosen with and without the consideration of natural enemies and how that difference is translated into economic gain. The results highlight the importance of assessing both pest and natural enemy populations in making pest management decisions and accounting for the opportunity cost of insecticide collateral damage to natural enemies. However, it is important to recognize that the current model is limited by some simplifications. For instance, the absence of the insecticide residual effect and insect migration behavior from the model can potentially lead to overestimation of the urgency and frequency of sprays, which has likely contributed to the lower control threshold suggested by the model than the extension recommendation, regardless of our account of the natural enemy levels. With the further incorporation of practical issues such as stochastic environmental and weather factors, time lag needed by farmers to prepare for insecticide application after the control decision is made, and the development of applicable measures of natural enemy population density, the current simple framework can potentially be developed into a decision aid model.

Based on the results from the dynamic optimization analysis, this study provides preliminary estimates of the economic value of natural pest control ecosystem service in the management of soybean aphid. These values reflect the economic benefit from an increase in the natural enemy population as inferred from the output value of the marketed soybean product, given that control decisions already take into account natural pest control services (i.e., decisions that are optimal in spite of the opportunity cost of injury to natural enemies by broad-spectrum insecticides). While caution should be paid to the extrapolation of the estimated values due to their context dependence, they offer instrumental insights on the magnitude of the economic value of natural enemy population management to private producers. In the long run, effective agroecosystem management will demand more of managers than simply to reduce the non-target effect of pesticides on natural enemies. Habitat management that improves landscape complexity can potentially benefit natural enemies and in most cases result in enhanced biological control of pests (Thies and Tscharntke, 1999; Wilby and Thomas, 2002; Cardinale *et al.*, 2003; Ostman *et al.*, 2003; Thies *et al.*, 2003). Future research should move beyond insecticide use thresholds to develop landscape-scale guidelines for explicit management of habitat for the natural enemies of agricultural pests.

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Table 2.1: Values of parameters from Zhang (Essay 1)'s model

Parameters	**R1**	**R2**	**R3**	**R4**	**R5**
Duration of plant growth stage (day)	3	10	9	9	15
Mortality rate of SBA from insecticides ($k_{S,t}$)	0.99	0.99	0.99	0.99	0.99
Mortality rate of natural enemies from insecticides ($k_{NE,t}$)	0.99	0.99	0.99	0.99	0.99
Natural enemies					
Net decline rate of *NE* (d_t)	-0.59	-0.90***	-2.13**		
Reproduction rate of *NE* per prey encountered (b_t)	0.002	-0.0001	0.002*		
Soybean aphid					
Net growth rate of SBA population (ng_t)	5.29	5.15	2.35	1.13	
Predation rate per natural enemy per stage (pr_t)					
daily predation rate=17/*NE*	51	170	153	153	
daily predation rate=35/*NE*	105	350	315	315	
daily predation rate=52/*NE*	156	520	468	468	
Soybean yield					
Proportion of yield lost per unit of pest population (η_t)	0.0002	-0.001**	0.0003*	0.0001*	0.0002
Maximum proportional yield loss to pest damage (θ_t)	1	1	1	1	1
Economic parameters					
Output price (p)			$6.9/bu		
Control cost ($c(x_t)$)			$12.2/ac		

* significant at 90%; ** significant at 95%; *** significant at 99%.

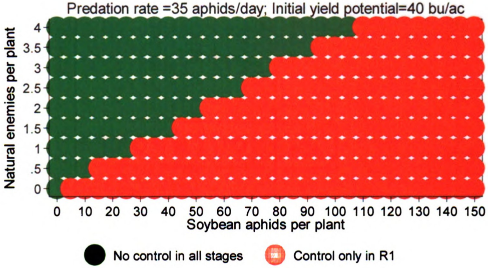
Source: Zhang (Essay 1)

Table 2.2: Summary of sensitivity analysis results organized by ranges of initial SBA densities (Initial yield potential=40 bu/ac, daily predation rate=35 aphids/*NE*)

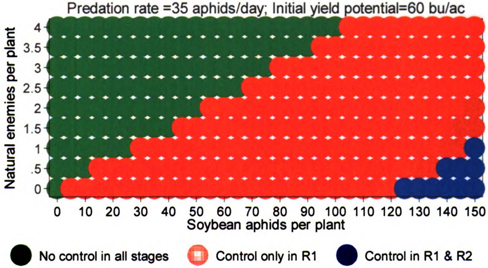
	Changes from baseline model results[a]					
Scenarios	Optimal control paths			Returns to producers over variable costs of control		
	$20 \le S_I \le 40$	$40 < S_I \le 80$	$80 < S_I \le 120$	$20 \le S_I \le 40$	$40 < S_I \le 80$	$80 < S_I \le 120$
ng_t up 5%	-	-	-	-	-	-
ng_t down 5%	-	-	-	-	-	-
$k_{S.t}$ down 5%	"Spray R1+R2" replaces "Spray R1"if S_I=40, NE_I=0; "Spray R2" replaces "Spray R1" if S_I=40, NE_I=1	"Spray R1+R2" becomes needed when NE_I is relatively low	"Spray R1+R2" replaces "Spray R1" except when if S_I=100, NE_I=4	↓ 2-4% for low NE_I	↓ 3-5% for low NE_I	↓ 3-5% for almost all levels of NE_I
$k_{NE,t}$ down 5%	-	-	-	-	↑ ≤1.5% for NE_I bet. 1-3	↑ ≤2.5% for NE_I bet.1-4
η_3 up 1 s.d.	-	-	-		↓ ≤1%	↓ ≤1%
η_3 down 1 s.d.	-	-	-		↑ ≤1%	↑ ≤1%
η_4 up 1 s.d.	-	-	-			↓ ≤1%
η_4 down 1 s.d.	-	-	-			↑ ≤1%
b_3 up 1 s.d.	-	-	-	-	-	-
b_3 down 1 s.d.	-	-	-	-	-	-
d_2 up 1 s.d.	-	-	-	-	↑ 1% for S_I=80, NE_I =3	-
d_2 down 1 s.d.	-	-	-	-	-	-
d_3 up 1 s.d.	-	-	-	-	-	-
d_3 down 1 s.d.	-	-	-	-	-	-
p up 20%	-	-	-	↑ 20-21%	↑ 20-21%	↑ 20-22%
p down 20%	-	-	-	↓ 20-21%	↓ 20-21%	↓ 20-21%
$c(x_t)$ up 50%	-	"No spray" replaces "Spray R1" for medium S_I and relatively high NE_I	-	↓ 0-2%	↓ 0-2%	↓ 0-2%
$c(x_t)$ down 50%	-	-	"Spray R1+R2" replaces "Spray R1" for relatively high S_I and low NE_I	↑ 0-2%	↑ 0-2%	↑ 0-4%

"-" represents change of 0.5% or smaller.

[a] The baseline model is based on parameters reported in Table 2.1, and initial yield potential=40 bu/ac and daily predation rate=35 aphids/*NE*.

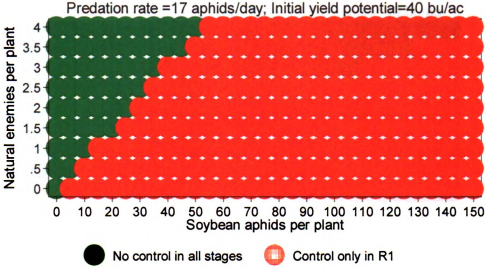


(a)

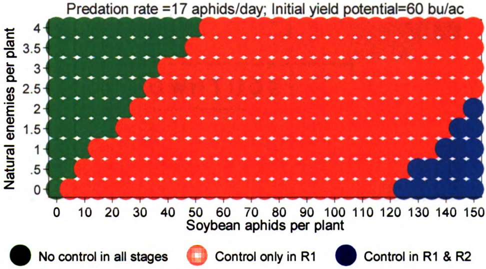


(b)

Figure 2.1: Optimal control paths for initial yield potentials of 40 bu/ac (a) and 60 bu/ac (b) at the mean daily predation rate of 35 aphids per natural enemy

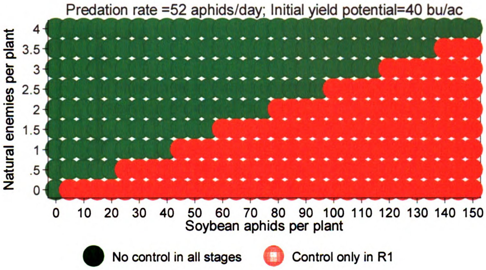


(a)

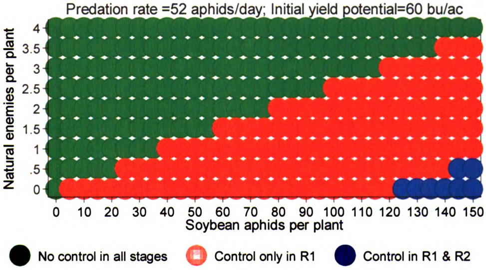


(b)

Figure 2.2: Optimal control paths for initial yield potentials of 40 bu/ac (a) and 60 bu/ac (b) at the minimum daily predation rate of 17 aphids per natural enemy



(a)



(b)

Figure 2.3: Optimal control paths for initial yield potentials of 40 bu/ac (a) and 60 bu/ac (b) at the maximum daily predation rate of 52 aphids per natural enemy

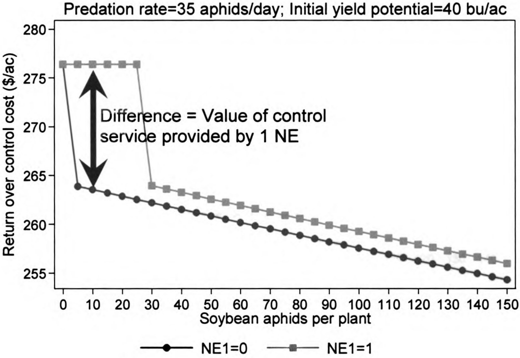


Figure 2.4: Value of producer return at initial yield potential of 40 bu/ac and daily predation rate of 35 aphids per natural enemy

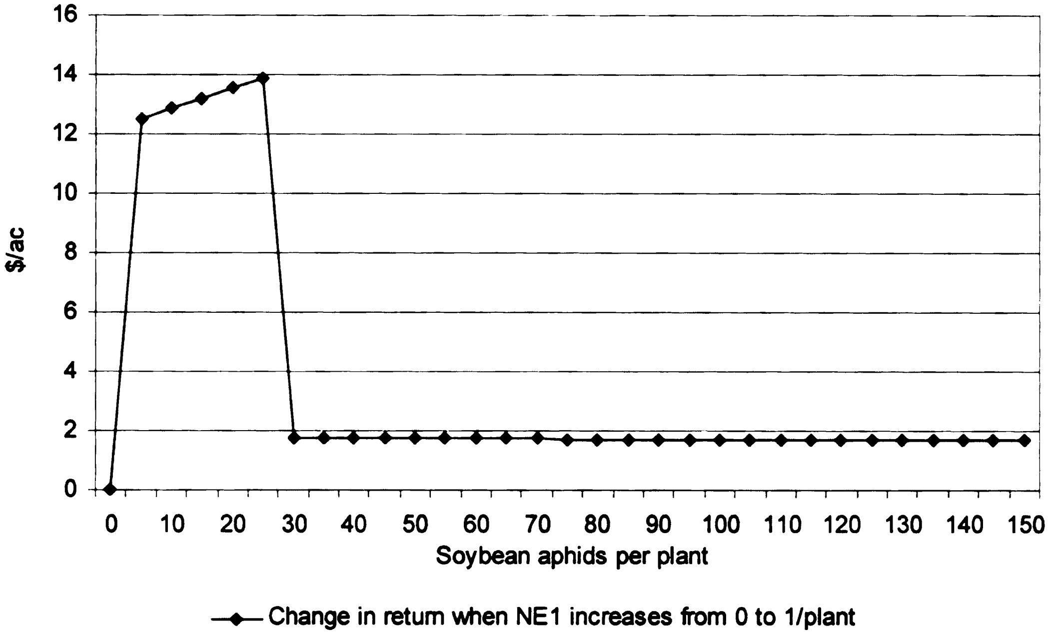


Figure 2.5: Value of one natural enemy per plant in stage R1 at daily predation rate of 35 aphids per natural enemy and initial yield potential of 40 bu/ac

Essay 3:
Spatially Optimal Habitat Management for Enhancing Natural Pest Control Services

3.1 Introduction

The control of pests by their natural enemies represents an important ecosystem service that maintains the stability of agroecosystems and has the potential to mitigate pest control costs both to private producers and to society (Naylor and Ehrlich, 1997; Losey and Vaughan, 2006). To perform this function effectively, natural enemies depend on resources such as food for adults, alternative prey or hosts, hibernation site and shelter from adverse conditions (Landis *et al.*, 2000). These factors can be supplied by crop and non-crop habitats at spatial scales compatible with the resource requirements and the dispersal capabilities of insects (Landis *et al.*, 2005). How agricultural ecosystems are managed at the site scale and the diversity, composition and functioning of the surrounding landscape can have great influence on the availability of these resources (Tilman, 1999), underlying the potential role of agricultural land use choices in enhancing natural pest control services.

Habitat management (HM), a form of conservation biological control, aims to create a suitable ecological infrastructure within the agricultural landscape to provide needed habitat resources and functions (Landis *et al.*, 2000). The potential mechanisms of HM are broadly divided into two categories: manipulation of crop systems (e.g., interplanting, cover crop, polyculture and rotation) and establishment of non-crop habitats (Landis *et al.*, 2005). As the limitations and social costs of chemical control have been increasingly recognized (Naylor and Ehrlich, 1997), there has been growing interest among ecologists in HM as a potential alternative to achieve sustainable pest management (Barbosa, 1998). Relatively undisturbed non-crop habitats (NCH) such as hedgerows and woodlots in agricultural landscapes typically support a higher degree of functional biodiversity than crop systems (Bianchi *et al.*, 2006) and usually persist at the same place for a long time so that the occurrence of their resources is more stable and predictable (Bianchi *et al.*, 2007). Empirical evidence from recent ecological research shows that pest suppression is positively correlated with the proportion of NCH in the landscape (Thies and Tscharntke, 1999; Thies *et al.*, 2003). Using a spatially explicit simulation model, Bianchi and van der Werf (2003) find the shape, area, and fragmentation of NCH elements can have important effects on the control of aphids by generalist predator *Coccinella septempunctata*. In particular, they find that pest control is achieved the best in landscapes with a substantial area of NCH and where these habitats are evenly distributed over the landscape. No prior studies, however, have investigated economically optimal spatial habitat configuration for natural enemies of crop pests. The question remains whether the "ecologically optimal" choice is the most economically desirable to private producers, especially when accounting for the increase in production cost due to farming fragmented fields.

In studying the impacts of specific HM practices in field trials, some entomologists have gone further to conduct budgetary analyses to assess the economic impact of field-level HM practices such as the establishment of vegetative strips (Barbosa, 1998). While these empirically-based studies provide useful insights on the economic feasibility of specific practices, a modeling exercise has the advantage of allowing more space to explore the economics of spatially optimal management of NCH at larger scales (such as farm and landscape) under various economic conditions and production systems. Key spatial, ecological, and economic characteristics affect how optimal HM is carried out on the farm and across the landscape. For instance, spatial distribution pattern determines how ecological services are dispersed into surrounding crop fields. In addition to output prices, economic factors such as production costs associated with habitat establishment also play a role in driving the final outcome with regard to economically optimal spatial configuration. This study develops a spatial optimization model to explore spatial manipulation of NCH in a simulated landscape so as to optimize net returns to fixed factors of production under both i) a conventional farming system (where chemical pesticides are used to treat pests), and ii) an organic farming system (where chemical pesticides are not allowed). The results provide insights on the potential economic incentive (or the lack of it) for private producers to adopt the HM practice of establishing NCH for natural enemies of crop pests.

Spatial optimization of wildlife habitats has become an important approach in population management and conservation in the past few decades (Turner *et al.,* 1995). A body of literature has developed on "reserve site selection" for maximum species conservation, given constraints on budget or on the number of sties allowed (see review in Nalle *et al.*, 2004). The approach has relatively few applications in economics, but has included forestry harvest scheduling (e.g., Hof and Bevers, 1998), land use allocation among various choices such as agriculture, industry, and recreation (e.g., Aerts *et al.,* 2005; Seppelt and Voinov, 2002), spatial exploitation of a fishery (e.g., Sanchirico and Wilen, 2000), and the more recent efforts that combine both economic objectives (e.g., production of marketed commodity) and ecological objectives (e.g., species conservation) (e.g., Hof and Joyce, 1992; Nalle *et al.*, 2004; Polasky *et al.*, 2005). For instance, Nalle *et al.* (2004) examine the joint production of wildlife and timber in a dynamic and spatial analysis to evaluate land use and land management decisions. Polasky *et al.* (2005) focus on species conservation in a working landscape by making spatially optimal land use choices that serve both biological and economic objectives. However, spatial dimension has rarely been considered in economic studies of pest management. Brown *et al.* (2002) examine a spatially dependent insect-transmitted plant disease and optimize social welfare over the width and the effectiveness of vegetative barriers. In this study, we develop a spatial optimization model to explore spatial manipulation of NCH to maximize private producers' economic outcome of crop production. Specifically, the study attempts to address three questions:

i) What is the optimal proportion and spatial configuration of NCH in the landscape?
ii) How do the outcomes differ between conventional and organic farming systems?
iii) What factors determine optimal size and configuration of NCH?

Following this introduction section, we introduce a simple conceptual model to gain insights on the economic theory guiding the spatially optimal management of NCH (section 3.2). In section 3.3, we present an illustrative empirical model based on the natural control of soybean aphid by ladybeetles. The model is comprised of an ecological module for the distribution of natural pest control services and an economic module for the optimization of net returns to fixed factors of crop production. We then report and discuss the results of the numerical analysis (section 3.4), followed by a sensitivity analysis that addresses parameter uncertainties in section 3.5. We conclude in section 3.6

by highlighting main findings, identifying limitations and applications of the model, and suggesting future research directions.

3.2 Conceptual model

This section uses a simple spatially explicit conceptual model to examine i) some general economic conditions under which spatial land use pattern optimizes the natural pest control benefits of NCH over associated variable costs, and ii) how key ecological and economic factors may affect the economic outcome. In this simple model, NCH acts as the source origin of natural enemies from which pest regulation services are dispersed into surrounding crop fields according to a spatial distribution kernel (which can be imagined as a probability density function in space), resulting in spatially linked crop yield damage protection at each point in the affected crop fields. Using a grid map of N by M dimension ($i = 1, 2, \ldots, N$, and $j = 1, 2, \ldots, M$), we define a field that is divided into $N \times M$ homogeneous cells (indexed by (i,j)) that can be either used to grow a crop or set aside as habitat to provide pest control services (Figure 3.1). Mathematically, we write the farmer's problem as one that maximizes total net return (NR) to fixed factors over a binary choice of land use in each cell (x_{ijk}):

$$\underset{x_{ijk}}{Max} \;\; NR = \sum_{i}^{N} \sum_{j}^{M} \sum_{k}^{K} \pi_{ijk} \cdot x_{ijk} \tag{1}$$

where

$$\pi_{ijk} = \begin{cases} py^0[1 - D(I)] - (1+\lambda)\; VC & \text{if } k = 1 \\ 0 & \text{if } k = 0 \end{cases} \tag{2}$$

and k indexes land use option ($k = 1$ for crop and $k = 0$ for NCH), $x_{ijk} = k$ if cell (i,j) is assigned to land use k, π_{ijk} is net return received from cell (i,j) when land use option k is applied to (i,j), p is output price of crop ($/ton), y^0 denotes maximum (pest-free) yield potential (ton/cell), I is pest density in the crop fields (pests/plant), $D(I)$ represents the damage function for the proportion of crop yield lost to pest density I, and VC denotes the variable costs of production ($/cell), which is subject to change by the proportion of λ, a coefficient measuring the average change in VC per crop cell due to change in field configuration caused by the establishment of NCH that sometimes requires adjustments in machinery fieldwork load ($\lambda=0$ if $k=1$, $\forall i,j$). By optimizing land use choice for each individual cell, x_{ijk}, a spatially linked land use pattern that satisfies optimization criteria of spatial configuration concerning area, shape, and location of NCH elements (each element referring to a cluster of spatially adjacent NCH cells) can be obtained for the landscape. Thus, the total area of NCH or the total number of cells assigned to NCH is given by $A_{NCH} = \sum_i^N \sum_j^M x_{ij,k=0} = \sum_h^H A_h$ (where h indexes NCH elements, $h=1, 2, \ldots, H$, and A_h denotes the area of element h), and the total number of land cells is the sum of NCH cells and crop cells, $A_{total} = Total\ \ area = N \cdot M = A_{crop} + A_{NCH}$ $= \sum_i^N \sum_j^M x_{ij,k=1} + A_{NCH}$. Note that although A_{NCH} is defined as the area of NCH, it contains spatial information regarding the configuration of the NCH cells (for instance, location indicated by the value of cell indices i and j).

In order to show the key relationships analytically, we consider a simple problem where a farmer chooses the size of an individual NCH element ($h=1$) such that HM is economically superior to insecticide-based pest control from the private management perspective. We use the model to solve for analytical conditions for the optimal area of

NCH. Under the pesticide control method, crops are grown in all cells (i.e., $x_{ij,k=1} = 1, \forall i, j$) and receive pesticide treatment to reduce pest density from I_0 by the proportion of ω_{chem} at the expense of c per cell, where ω_{chem} denotes the efficacy rate of insecticide and c is control cost per cell[1]. The total net return from chemical control (NR_{chem}) is then derived from aggregating net return from each individual cell π_{chem}:

$$NR_{chem} = NM \cdot \pi_{chem} = NM \cdot [py^0(1 - D_{chem}) - c - VC] \qquad (3)$$

where $D_{chem} = D[(1 - \omega_{chem})I_0] = D_0 - \Delta D_{chem}$, $D_0 = D(I_0)$, and ΔD_{chem} is the decline in the proportion of yield damage due to chemical control. Defining

$$\pi_0 = py^0(1 - D_0) - VC \qquad (4)$$

as the baseline net return per cell evaluated at untreated pest density I_0, we rewrite (3) as:

$$NR_{chem} = NM \cdot \pi_0 + NM \cdot [py^0 \Delta D_{chem} - c] \qquad (5)$$

The sign of the second term on the RHS of (5) reveals the condition for a positive gain in total net return resulted from pesticide control as compared to the no-control baseline, i.e., the value of the protected yield is greater than the cost of control ($py^0 \Delta D_{chem} - c > 0$).

Under HM, the farmer is assumed to rely on NCH for pest management. For the ease of exposition, we assume natural pest control services are evenly distributed to each point within a radius of *r*, meaning that each cell within the "impact zone" enjoys the same amount of pest reduction. The total net return under HM (NR_{NCH}) is expressed as the sum of net returns from NCH cells, crop cells within the impact zone, and crop cells outside the impact zone:

---

[1] For an organic farm, $\omega_{chem} = 0$, $c = 0$.

$$NR_{NCH} = 0 \cdot A_{NCH} + IZ \cdot [py^0(1 - D_{NCH}) - VC(1+\lambda)] + NIZ \cdot [py^0(1 - D_0) - VC(1+\lambda)] \tag{6}$$

where $D_{NCH} = D[(1 - \omega_{NCH})I_0] = D_0 + \Delta D_{NCH}$, IZ denotes the area of the "impact zone" (i.e., the number of cells within radius r), NIZ ("no-impact zone") denotes the area of the crop fields that receives no impact, and ΔD_{NCH} represents the decline in the proportion of yield damage due to NCH. Substituting equation (4) into (6) and rearranging terms, we can rewrite (6) as:

$$NR_{NCH} = NM \cdot \pi_0 - A_{NCH} \cdot \pi_0 - \lambda \cdot VC(NM - A_{NCH}) + IZ \cdot py^0 \Delta D_{NCH} \tag{7}$$

The RHS of equation (7) indicates two sources of cost due to designating A_{NCH} cells of land as habitats: i) forgone income from NCH cells ($A_{NCH}\pi_0$), and ii) change in variable costs of production on all crop cells ($\lambda \cdot VC(NM - A_{NCH})$). The last term represents a gain in the output value of the crop harvested in the impact zone. The distribution of the benefits and costs of the management approach shows a clear spatial distinction. Assuming there exists a non-trivial interior solution, the first-order condition (FOC) for the maximization of equation (7) with respect to A_{NCH} is

$$\begin{aligned} \frac{dNR_{NCH}}{dA_{NCH}} &= \lambda \cdot VC - VC \cdot \frac{\partial \lambda}{\partial A_{NCH}}(NM - A_{NCH}) - \pi_0 + py^0 \cdot IZ \cdot \frac{\partial \Delta D_{NCH}}{\partial A_{NCH}} \\ &\quad + py^0 \cdot \Delta D_{NCH} \cdot \frac{\partial IZ}{\partial A_{NCH}} = 0 \end{aligned} \tag{8}$$

Rearranging terms of equation (8), we have

$$py^0[IZ \cdot \frac{\partial \Delta D_{NCH}}{\partial A_{NCH}} + \Delta D_{NCH} \cdot \frac{\partial IZ}{\partial A_{NCH}}] = \pi_0 - \lambda \cdot VC + VC \cdot \frac{\partial \lambda}{\partial A_{NCH}}(NM - A_{NCH}) \tag{9}$$

Equation (9) renders the classic optimal condition for the choice of land use type that balances the marginal factor cost (MFC) of setting aside an additional crop cell (the RHS of the equation) with the marginal value product (MVP) of the action in terms of improved output value due to pest regulation (the LHS of the equation). The MFC includes the opportunity cost of potential net return from a crop cell ($\pi_0 - \lambda \cdot VC$) as well as a potential increase in variable costs by the amount of $\partial\lambda/\partial A_{NCH}$ that applies to all crop cells.

In addition to condition (9), the following relationship has to hold in order for a HM approach to be economically preferable over insecticide control:

$$NR_{NCH} > NR_{chem.} \tag{10}$$

Substituting equations (3) and (7) into (10), we derive

$$IZ \cdot py^0 \Delta D_{NCH} > A_{NCH} \cdot \pi_0 + \lambda \cdot VC(NM - A_{NCH}) + NM \cdot [py^0 \Delta D_{chem} - c] \tag{11}$$

The expression suggests that the size of the NCH element A_{NCH} must be chosen in a way that the benefit of yield saving collected in the impact zone is greater than the sum of three terms: i) the opportunity cost of setting aside an area of A_{NCH} for NCH purpose, ii) the increased production cost due to field fragmentation caused by NCH, and iii) the output value of the yield saving resulted from pesticide control less the cost of control aggregated over the entire crop field.

The spatially explicit impacts of A_{NCH} on ecological factors such as IZ and ΔD_{NCH} and economic factor variable costs change (λ) are not easy to show analytically using mathematical notations. However, generally speaking, $\partial\lambda/\partial A_{NCH} > 0$ if longer machinery field time is needed to farm the fragmented field as a result of changing A_{NCH}. While it is intuitive that A_{NCH} tends to positively affect IZ, its impact on ΔD_{NCH} is somewhat mixed. In the current problem where there is only one NCH element and change in A_{NCH} only affects the area of the element, $\partial \Delta D_{NCH} / \partial A_{NCH} < 0$ is possible if i) a negative scale dependence relationship presents between the density of pest control agents and the size of individual NCH element (Hambaeck and Englund, 2005), so that an increase in the size of NCH element may actually lead to lower pest control services, and ii) the increase in the area of impact zone due to change in A_{NCH} is disproportionately higher than the increase in pest control services available as A_{NCH} increases, so that on average each cell received less pest reduction impact. In cases where a unit of increase in A_{NCH} is associated with the establishment of an additional NCH element, it is conceivable that the new element generates its own impact zone but IZ and ΔD_{NCH} of existing elements are not affected so long as there is no overlap in impact zones and each NCH element is an independent source of ecological benefits. Finally, as more realistic distribution functions are adopted to describe the dispersal of pest control services into surrounding fields, ΔD_{NCH} is expected to change nonlinearly with distance from the source of the services.

While the current model looks at a simple static problem, it is worth noting that some economic aspects of non-temporary NCH are inherently dynamic. In a soybean-corn rotation, for instance, the opportunity cost of setting aside land to provide pest control services for soybean carries on into the production of the rotating crop corn, making NCH more expensive, especially if corn production does not benefit from the NCH.

3.3 Empirical model

First discovered in 2000, soybean aphid (*Aphis glycines*, Matsumura) is a new invasive pest of soybeans in the North Central region of the United States that is capable of causing extensive damage to soybean yield (DiFonzo and Hines, 2002). Existing natural enemy communities, especially generalist predator ladybeetles (*Coccinellidae*) play a key role in suppressing soybean aphid populations (Costamagna *et al.*, 2007a; Fox *et al.*, 2004; Rutledge *et al.*, 2004) and are believed to have contributed to the observed two-year cycle of aphid population where aphid outbreaks occur every two years[2]. The development of insights to enhance and capitalize on the pest control services supplied by ladybeetles through HM, therefore, is of interest not only to private producers but also to the general public with respect to protecting a major commodity crop without large scale spraying of chemical insecticide.

Using the soybean aphid-ladybeetle example, we develop an empirical model that combines i) an ecological module for calculating the distribution of pest control services given the distribution of NCH in the landscape and a distribution kernel that represents the spatial probability distribution of pest control services around a source origin[3], and ii) an economic module for evaluating the net return to fixed factors of crop production, given a land use pattern (see MatLab code in Appendix B). The two models are coupled with an optimization method that finds the land use patterns that are most economically desirable among the patterns considered given parameters assumed. By focusing on selected patterns, we effectively delimit a relevant sub-space within the full optimization solution space. The approach is chosen over performing a global search over all possible land use patterns to find an optimal solution to the problem, whose computational cost can be exceedingly high (Polasky *et al.*, 2005).

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[2] Douglas A. Landis, Department of Entomology, Michigan State University, personal communication, September 27, 2005.

[3] Wopke van der Werf, Department of Plant Sciences, Wageningen University, personal communications, October 2006 to December 2006. Dr. van der Werf is also a contributor to the simulation model code.

To illustrate our approach we apply the model to a simple agricultural landscape composed of 1600 ha (4,000 m×4,000 m) square cells or land parcels, arranged in a 800 × 800 grid (n=800) with each cell being 25 m^2 in size (Figures 3.2a to 3.2c). For simplicity, we assume that there is no existing natural habitat in the landscape. The hypothetical landscape is arbitrarily divided into four square, homogenous full-time soybean-corn farms each with the size of 400 ha (or about 988 acres)[4], arranged in a 2×2 checkboard (Figures 3.2a to 3.2c). We assume the economic agents are rational and thus consider only a selected set of options regarding the shape and location of NCH elements. Specifically, since pest control services are dispersed around a source origin within a certain range, private producers would choose to place the NCH elements in the center of the farm so that the farm enjoys as much the services as possible[5]. For practical consideration, we eliminate irregularly shaped NCH elements and consider three shape options: squares, strips, and archipelago. In the square distribution (Figure 3.2a), there is a square of *s* by *s* NCH cells in the centre of each farm. In the strip configuration (Figure 3.2b), a strip of width *w* (counted in cells) runs through the axis of each farm. Finally, a landscape is introduced with random allocation of cells to either NCH (with probability equal to the proportion of NCH in the landscape, denoted by *prop_NCH*) or crop (with probability 1-*prop_NCH*). Figure 3.2c gives a result for *prob_NCH* = 0.1. The use of selected configuration options effectively simplifies the optimization problem, making it possible to focus the optimization on the area of NCH (or *prob_NCH*) and choice among three shapes of NCH elements.

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[4] According to a national survey, the typical sizes of small, mid-size, and large commercial farms in the United States are 160, 605 and 2180 acres, respectively (USDA, 2000).

[5] In the current analysis, we don't consider the spillover of NCH benefits.

Ecological module for the distribution of pest control services

Relationships between a parameter or a variable and spatial scale are often called scale dependencies (Hambaeck and Englund, 2005). Empirical research has shown that animal densities may both increase and decrease with habitat patch size (Hambaeck and Englund, 2005), a scale dependence effect that may conceivably apply to the relationship between the pest control impact of insect natural enemies and the size of individual habitat patches (i.e., NCH elements). The resource concentration hypothesis (Root, 1973) predicts that specialist herbivores should achieve higher densities in large patches. Hambaeck and Englund (2005) propose a power relationship to model theoretical scaling relationships and use the model predictions to explain variability in density-area relations from published studies on herbivorous insect-dominated systems. However, quantitative measures of the relationship between insect predator density (and consequently the services they provide) and habitat size are not available. In the following numerical analysis, we assume predator density (or the services provided) does not depend on the size of NCH element (i.e., no scale dependence). We discuss implications of a positive relationship for pest management in the last section of the paper[6].

Assuming there is one unit of the density of pest control services ("impact") for each area unit of NCH, the amount of services per NCH cell is proportional to the area of a cell and the amount of services in an NCH element is proportional to the area of the element. Specifically,

*Services per NCH element = (Density of pest control services) * (Area of NCH element)*

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[6] Given the absence of scale dependence and the homogeneous farm assumptions, solving the landscape problem is essentially the same as solving four individual farm problems and then aggregating them for the entire landscape. We keep the multiple-farm landscape model rather than focusing on farm-level problem to allow for future exploration of landscape-scale coordination possibilities.

The services stored in each NCH element are dispersed into surrounding crop area according to a distribution kernel, which describes the probability distribution of landing locations of services around the source origin in a two-dimensional plane (Skelsey *et al.*, 2005). The positions x and y are distances from the source, and $K(x,y)$ is the probability density at location (x,y) (Skelsey *et al.*, 2005). We consider 3 options of distribution kernels (Figures 3.3a to 3.3c): i) vertical cylinder (Figure 3.3a) with a probability density equal to $1/\pi r^2$ within a radius r from the source, and 0 elsewhere

$$K(x,y)=\begin{cases}1/\pi r^2 \ \mathit{for} \ \sqrt{x^2+y^2}\le r\\ 0 \ \mathit{for} \ \sqrt{x^2+y^2}>r\end{cases} \tag{12}$$

ii) rotated exponential (Laplace) kernel (Figure 3.3b)

$$K(x,y)=\frac{\alpha^2}{2\pi}e^{-\alpha\sqrt{x^2+y^2}} \tag{13}$$

where α is the slope of the decline of allocated services with distance, and iii) two-dimensional normal (Gaussian) kernel (Figure 3.3c)

$$K(x,y)=\frac{1}{2\pi\theta^2}e^{-\frac{x^2+y^2}{2\theta^2}} \tag{14}$$

where θ represents the standard deviation. The mean dispersal distance in the plane is r for a cylindrical kernel, $2/\alpha$ for a Laplace kernel, and $\theta\sqrt{\pi/2}$ for a Gaussian kernel. The Laplace kernel has a stronger peak and more rapid decay as compared to the Gaussian kernel, whereas the cylindrical kernel has a flat top near the center rather than a sharp peak. The Laplace kernel has been used in the ecological literature to model the dispersal of ladybeetles (e.g., Bianchi and van der Werf, 2003; Bianchi *et al.*, 2007). The other two kernels are included in order to investigate the sensitivity of model outcomes to differently shaped kernels.

Allocated actual control impact measured in terms of the percentage of reduction in pest density per unit area of crop area is proportional to the "impact" per unit area of NCH and depends on the proportion of NCH in the landscape which corresponds to an overall pest reduction magnitude across crop fields. We estimate the relationship between the average percentage of reduction in pest density across crop fields and the proportion of NCH in the landscape using simulation results from Bianchi and van der Werf (2003) (Appendix C) for the interaction between aphids in wheat and *Coccinella septempunctata*, a major aphid predator in the ladybeetle family that has been identified as a major contributor to the natural suppression of soybean aphids (McKeown, 2003; Costamagna, 2006) (Figure 3.4)[7]. Although the scale of the landscape simulated in Bianchi and van der Werf (2003) is smaller than the one defined in our model, which may potentially lead to over-estimation of the pest control impact of NCH, their model provides the best available quantitative information on the relationship between aphid density and the proportion of NCH in the landscape as a result of *Coccinella septempunctata* predation. Other potential sources of secondary data, including the empirical studies by Thies and Tscharntke (1999) and Thies *et al.* (2003) are not suitable because they look at the parasitoid category of natural enemies, which is likely to have different pest-natural enemy interaction and require different resources from habitats as compared to predators. Figures 3.5(i)a to 3.5(i)c, 3.5(ii)a to 3.5(ii)c, and 3.5(iii)a to 3.5(iii)c render graphical

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[7] To find values at intermediate points, we use the "interp1" command in MatLab that performs linear interpolation between data points (The MathWorks Inc., 1994-2007).

illustrations of the distribution of pest control services from various shapes of NCH, given 10% of landscape area devoted to NCH.

Economic module for the evaluation of land use decisions

Practice of pest management varies with farming systems, which has important implications for the economic performance of HM on private producers. We consider two types of farming systems, a conventional system and an organic system[8]. In the baseline, we assume that the application of chemical insecticides is triggered by the occurrence of the new soybean pest in a conventional farm, whereas synthetic insecticides are not allowed in an organic farm so that the pest goes untreated[9]. Under HM, both farming systems rely on NCH to control soybean aphid. We define net returns to fixed factors (*NR*) for a soybean-corn rotation (one crop at a time) as following:

Baseline: $$NR_{base} = NR_{base\_soy} + NR_{base\_corn} \tag{15}$$

HM: $$NR_{NCH} = NR_{NCH\_soy} + NR_{NCH\_corn} \tag{16}$$

where

$$NR_{base\_soy} = [p_{soy} \cdot y_{base\_soy} - VC_{soy} - TCost_{spray}] \cdot Area_{total} \tag{17}$$

gives the baseline net return for soybean, which is derived by multiplying the total land area (represented by total number of cells), $Area_{total}$, by the net return per cell. p_{soy} is the price of soybean output ($/ton), VC_{soy} denotes variable costs of production, and $TCost_{spray}$

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[8] To ensure a healthy system, certified organic farms are often required to include one and sometimes two other crops rotated with soybean and corn (Delate, 2003). Our loosely defined organic farm, however, only includes two rotating crops, soybean and corn. This simplification makes direct comparison between conventional and organic systems easier without affecting the implications we draw from the analysis.

[9] Many organic farms use non-synthetic insecticides such as biological insecticides, but usually on higher value crops than soybean and corn.

represents the cost of soybean aphid control ($TCost_{spray}=Cost_{spray}*Number\_of\_sprays$). Both VC_{soy} and $TCost_{spray}$ are scaled to a per-cell base (\$/cell). The baseline yield (ton/cell), y_{base_soy} is described by a Cousens hyperbolic yield function (Cousens, 1985):

$$y_{base\_soy} = y_{soy\_\max}\left(1-\frac{\eta[(1-Efficacy_{spray})pest_{initial}]}{1+\eta[(1-Efficacy_{spray})pest_{initial}]/\mu}\right) \tag{18}$$

where y_{soy_max} is the maximum (pest-free) yield potential, $Efficacy_{spray}$ is the efficacy rate of soybean aphid insecticides, $pest_{initial}$ is the untreated average pest density, η denotes the proportion of yield lost per unit of pest population, and μ denotes the maximum proportional yield loss to pest damage ($0\leq \mu \leq 1$). Assuming equal efficacy rate across crop cells, y_{base_soy} is a scalar. Similarly, the baseline net return for corn is given by:

$$NR_{base\_corn} = [p_{corn} \cdot y_{base\_corn} - VC_{corn}] \cdot Area_{total} \tag{19}$$

The net return for soybean under HM is:

$$NR_{NCH\_soy} = \sum_{l=1}^{Area_{soy}} [p_{soy} \cdot y_{NCH\_soy,l} - (1+\lambda) \cdot VC_{soy}] \tag{20}$$

where λ, determined by NCH configuration, measures the average change in variable costs of production per crop cell due to change in field configuration caused by NCH, and $Area_{NCH}$ denotes the area of NCH (represented by the number of NCH cells). The summation operator is necessary because the amount of pest control services allocated to each crop cell (and consequently crop yield) is spatially variant rather than uniform across crop cells as in equation (18). Soybean yield in crop cell l (ton/cell), $y_{NCH\_soy,l}$, thus is described by the Cousens hyperbolic yield function (Cousens, 1985):

$$y_{NCH\_soy,l} = y_{soy\_\max}\left(1-\frac{\eta[(1-\omega_l)pest_{initial}]}{1+\eta[(1-\omega_l)pest_{initial}]/\mu}\right) \tag{21}$$

where ω_l represents allocated pest control services (the proportion of reduction in pest density) in crop cell l. Finally, the net return for corn under HM is given by:

$$NR_{NCH\_corn} = [p_{corn} \cdot y_{base\_corn} - (1+\lambda) \cdot VC_{corn}] \cdot (Area_{total} - Area_{NCH}) \qquad (22)$$

which indicates that variable costs of corn production, VC_{corn}, are also affected by the establishment of NCH by a factor of $1+\lambda$ because the non-temporary nature of the NCH. For each cell assigned to NCH that is not available for corn production, there is an opportunity cost of foregone income.

The above expressions (equations (15)-(22)) apply to both farming systems with $Efficacy_{spray}=0$ and $Cost_{spray}=0$ for the organic system and $Efficacy_{spray}>0$ and $Cost_{spray}>0$ for the conventional system.

To assess the land use patterns under HM, we refer to relative economic performance of HM as compared to the baseline for each farming system. We define the proportion of change in net return to fixed factors from the baseline (nr) as:

$$nr = \frac{NR_{NCH} - NR_{base}}{NR_{base}} = \frac{(NR_{NCH\_soy} + NR_{NCH\_corn}) - (NR_{base\_soy} + NR_{base\_corn})}{(NR_{base\_soy} + NR_{base\_corn})} \qquad (23)$$

Thus, the economic objective of the farmer is to choose the area and shape of NCH to maximize equation (23).

3.4 Numerical analysis

Parameters

Table 3.1 summarizes parameters used in the numerical analysis along with their sources, including literature, estimations from field data, estimations from secondary data, and assumptions. We use the simulation model developed by Costamagna *et al.* (2007b) to predict three levels of average predation-free soybean aphid population density (aphids/plant) for the period of soybean plant growth stage R1 (reproductive stage one) to R5, corresponding to three levels of initial pest density as starting values for running the simulation model (30, 47 and 73 aphids/plant at the beginning of stage R1) taken from Michigan field data, assuming stage R1 begins on July 5[10]. We assume the number of sprays needed is one for low and medium infestation levels (5000 and 8000 aphids/plant on average during R1-R5, respectively) and two for high infestation level (12000 aphids/plant). The assumption is made based on results from Zhang (Essay 2), which suggests that, in the absence of predators, soybeans be sprayed twice for mean aphid density in stage R1 equal to or greater than 120 per plant, and once otherwise. This study rounds that value to 100, which corresponds to average density of 12000 aphids/plant for the period of stage R1 to R5.

To measure how the variable costs of production change as the crop fields are re-configured to establish NCH, we focus on the change in machinery field time spent on turning. Turns are an important part of machinery field efficiency with turning time typically ranging from 12% to 15% of the total field time (Bowers, 1992). Assuming a width of 5 meters for crop strip (approximately 6 rows or 15 feet wide) and following operation modes as illustrated in Figures 3.6a to 3.6c, we first count the approximate number of turns needed with and without NCH for all shapes and values of *prop_NCH* considered (Appendix D)[11]. We assume that 15% of the machinery field time is spent on

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[10] Data were provided in 2005 and 2006 by Alejandro Costamagna and Christine DiFonzo, Department of Entomology, Michigan State University.

[11] With archipelago, land cells are randomly assigned to either crop or NCH so that actual locations of NCH cells are not predictable given *prop_NCH*. We therefore assume the NCH cells are evenly distributed across the landscape and estimate the approximate number of turns that might be needed to operate on such fields.

turning in the baseline (no NCH), based on which any change in the number of turns made to accommodate NCH can be converted to change in the percentage of machinery time spent on turning. We then combine production cost data (UIUC, 2003) to estimate the amount of change in variable costs of production (λ) due to change in machinery field time for soybean and corn separately under both conventional and organic systems with cost savings on seed in NCH accounted for. The cost composition varies with types of farming system and with crop grown: the percentage of machinery cost (including repair, fuel, and hire) is highest for organic soybean (63%), followed by organic corn (40%) (UIUC, 2003) (Appendix E). As Figures 3.7 and 3.8 show, field re-configuration can induce both positive and negative changes in the variable costs of production, depending on the shape and proportion of NCH. The overall magnitude of such changes remains small for the square and strip shapes (within the range of -4% to +4%), but can be remarkably high for the archipelago shape.

Numerical results

In the baseline, pesticide control proves to be cost-effective for conventional farms, saving 95% to 91% of the pest-free level of net return to fixed factors for the soybean-corn rotation. By contrast, organic farms suffer significant loss to the new soybean pest ranging from 38% to 50% reduction in net returns, depending on the level of pest infestation that goes without any control as well as the distribution kernels used. As expected, the organic farms have a much higher stake than the conventional farms in considering HM as a potential pest control mechanism in the face of the new soybean pest. This conclusion is not only because of the difference in the baseline pest management approaches, but also the considerable variability in the initial (pre-soybean aphid) net returns to fixed factors given the economic parameters assumed. Specifically, organic systems earn almost twice the level of net return conventional systems earn, mainly attributed to the price premium of organic products as well as a small variable costs advantage in producing organic corn. This advantage exists in spite of the existence of yield disadvantages associated with both organic soybean and corn (Table 3.1).

Our presentation of key results is focused on the medium infestation level and Laplace distribution kernel, followed by a discussion of the effects of pest pressure and differently shaped distribution kernels. Overall, 1% of NCH (*prop_NCH*=0.01) arranged in archipelago is found the optimal solution for HM approach to controlling soybean aphid among all configuration options considered. The land use pattern leads to an increase in net return by 59% from the no-control baseline under the organic system. For conventional farms, reliance on HM in lieu of insecticide-based aphid control reduces net returns in all simulations. However, NCH has the least negative effect at 1%, configured in an archipelago pattern, which results in a decrease by a mere 4% from the insecticide-based control baseline under the conventional system (Figure 3.8).

The negative slope of the curves associated with archipelago after peaking at *prop_NCH*=0.01 implies a decreasing returns to scale effect of the area of NCH in the landscape, compounded by the opportunity cost of land use change and increased production cost due to farming a fragmented field (Figure 3.9). Due to the rapid rise in the estimated change in variable costs of production for archipelago as *prop_NCH* increases, the relative advantage of archipelago over square and strip at any given *prop_NCH* declines sharply once passing the peak at *prop_NCH*=0.01. In addition, the performance of archipelago after the peak point declines at a much faster rate under the organic system than the conventional system as *prop_NCH* increases, partly because the estimated changes in variable costs of production under the organic system are about three times of those under the conventional system for the archipelago pattern. The effect of the variable costs change becomes more obvious in Figure 3.10 when such change is ignored (i.e., λ=0), in which case the archipelago is preferred over the square and strip configurations at any given positive area of NCH within the relevant range.

Between square and strip patterns, our results indicate that the strip pattern consistently shows better economic performance in both systems, although its comparative advantage is small under the conventional system (Figure 3.9). Specifically, 9% of NCH arranged in strips leads to the smallest reduction by 32% in net return under the conventional system, 0.2% smaller than the best achievable level that the square pattern can offer at *prop_NCH*=0.16. Under the organic system, over 27% of improvement in net return can be expected at *prop_NCH*=0.05 for strip, 5% higher than the best achievable level by square at *prop_NCH*=0.15.

Overall, the adoption of HM by a conventional system makes the farm worse off, which in the best scenario amounts to 4% reduction in net return as compared to the insecticide-based control baseline when NCH is established in archipelago pattern and accounts for 1% of total land area (Figure 3.9). The figure also shows that a conventional farm would be 54% worse off under the "doing nothing" scenario (i.e., *prop_NCH*=0) than applying insecticide to control the pest. In sharp contrast, the organic system gains significantly in economic performance after establishing NCH. Specifically, an organic farm would be better off than doing nothing by setting aside any positive amount of land in strips or squares as habitats or 1-3% of land in an archipelago pattern to provide pest control services. With 1% of NCH arranged in an archipelago, the increase in net return reaches the highest level of 59%, more than twice the largest improvement the strip configuration can achieve with 5% of land devoted to NCH.

While pest infestation level does not significantly influence the optimal choices with regard to the shape and area of NCH, it does play a role in determining the performance of HM relative to the baseline management. For instance, under the conventional system (and assuming a Laplace distribution kernel), the reductions in net return are 5% and 4% for low and medium infestation levels, respectively, given the optimal solution of 1% of NCH arranged in an archipelago pattern. At high infestation level, however, the same land use pattern leads to a slight increase in net return by 0.3%. This can be attributed to both the higher insecticide control cost under the high infestation scenario (when two applications of insecticides would be needed as compared to only one for low to medium pest levels) and the relatively lower return to insecticide control in the baseline as the number of pests escaped from the control tends to be higher when there is high infestation. Under the organic system, infestation levels have a more visible impact on the relative performance of HM. Specifically, the increases in net returns from the baseline are 41%, 59%, and 77% for low, medium, and high infestation levels, respectively, resulted from the same optimal configuration of NCH (i.e., 1% of NCH arranged in an archipelago).

For square and strip patterns, higher pest pressure always corresponds to greater disadvantage (under the conventional system) or advantage (under the organic system) of HM relative to the baselines. For archipelago, however, there exists a threshold level of

NCH area (*prop_NCH*=0.13), below which the gap between HM and chemical control gets smaller as infestation level increases under the conventional system, meaning that the higher the pest level is, the smaller the disadvantage of HM is as compared to the insecticide-based control baseline. Likewise, under the organic system, the higher the pest level, the better HM performs relative to the baseline for *prop_NCH* below 0.09. The result reflects the fact that archipelago contrasts with square and square patterns with respect to its superior ecological benefit and extraordinarily high production cost. When *prop_NCH* is relatively small (below the threshold levels), the farm benefits more from the ecological benefit associated with archipelago than suffering from increased production cost, including foregone yield. Higher pest levels simply exaggerate this effect.

Given the parameters assumed, our results show that model outcomes are sensitive to the differently shaped distribution kernels used to describe the dispersal of natural pest control services around the NCH for square and strip patterns but remain robust to the choice of distribution kernel for archipelago. Given equal mean dispersal distance of 100 meters, the Laplace kernel is responsible for the best relative performance of HM as compared to the baseline (i.e., the most increase in net return under the organic system or the least reduction in net return under the conventional system), followed by Gaussian and cylindrical kernels for square and strip patterns (Figure 3.11). From the economic perspective, this result can be interpreted as "efficiency" difference between various dispersal modes of natural enemies or their services[12]. Coverage appears to be more important than intensity of control. When the landscape is mapped in a way that

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[12] Note that the distribution kernel is not a choice variable. Our analysis demonstrates that the distribution kernel implemented in the simulation model can have an impact on the economic outcomes, highlighting the need for better understanding of this important ecological factor.

each unit of land (i.e., cell) is sufficiently small as approached in this study, small patches of habitat as characterized by archipelago collectively deliver the same amount of control services across landscape, regardless of the dispersal patterns of natural enemies (Figure 3.11). This possibly raises another tradeoff relationship between the increase in production cost associated with field fragmentation and the robustness of overall ecological impact of habitats to natural enemy dispersal behavior.

3.5 Sensitivity analysis

To investigate the effects of variations in a set of key spatial, ecological, and economic parameters, we perform sensitivity analyses on a specific case where infestation level is set at medium, natural pest control services are distributed according to a Laplace kernel, and the shape of NCH is strip. We look at how the relative performance of HM changes as values of these parameters are varied by 5% in both directions (except for the price of soybean, p_{soy}, which is varied by 10% in both directions).

We report in Table 3.2 the percentage changes of the relative performance of HM from model outcomes based on parameters reported in Table 3.1 as a result of varying parameter values. Overall, model results are robust to parameter variations for the conventional system, except for efficacy rate of soybean aphid insecticides and natural enemy mean dispersal distance. Specifically, when decreasing $Efficacy_{spray}$ by 5% (no increase scenario is included because the baseline value is already 0.99), the advantage of chemical control relative to HM reduces by 18.4%. Extending (or reducing) the mean dispersal distance of natural enemies by 5 meters results in the advantage of chemical control over HM decreasing (or increasing) by 3.4%. The impacts of parameter variations on model results under the organic system are generally stronger than those on the conventional system, because of the differentiated levels of yield potential and economic coefficients. In particular, model outcomes are most sensitive to variations in the mean dispersal distance and soybean price, followed by maximum soybean yield potential and the yield loss coefficient.

3.6 Conclusion and future research needs

Natural enemies provide important ecosystem services to agriculture by suppressing pest damage to crop yield and also, less visibly, by maintaining an ecological equilibrium that prevents herbivore insects from reaching pest status. Enhancing this service by providing essential resources and compatible environment to natural enemies constitutes a potential alternative to the current insecticide-based pest management approach, which, in recent decades, has increased the frequency of pesticide resistance, pest outbreak and resurgence. The result is to make chemical control more costly and unreliable, and to produce unintended negative health outcomes for nontarget organisms, including humans (Thomas, 1999).

This study explores economically optimal spatial habitat configuration for natural enemies of crop pests. The model developed here focuses on the simple function of non-crop habitats as sources of natural pest control services and evaluates the economic tradeoffs associated with land use choices between farming and setting aside land as natural enemy habitats. Not only is there an opportunity cost of forgone income from setting aside land, but the economic outcome is also highly dependent on the spatial configuration of the non-crop habitats as well as the spatial distribution of natural control services into the surrounding crop fields. Our three main findings follow:

First, non-crop habitat management is a promising pest management option for organic systems, not only because of their relatively high profitability, but also because of the constrained options in the pest management toolbox as compared to conventional systems. While any positive amount of habitat in square and strip shapes would guarantee an improvement in net return level from the no-control baseline, small area of habitat in archipelago results in the best outcome. Moreover, the higher the pest pressure is under an organic system, the greater the advantage of habitat management over the no-control management baseline, except when a relatively large area of habitat is arranged in high-cost archipelago shape.

The adoption of habitat management in a conventional soybean-corn system, however, tends to reduce farm net returns, highlighting the need for reducing the private cost of habitat management. In addition, it is important to note that the full economic value of the services from non-crop habitats is likely to be higher than that estimated from the private producer perspective in this study. Besides the social and environmental benefits from reducing the use of chemical insecticides, diversely structured agricultural landscapes tend to be positively related to other socially desirable ecological benefits such as habitats for beneficial insects and wildlife. Non-crop habitats could become attractive if policy were to reward all the ecosystem services due to their positive externalities.

Second, the shape and area of habitats are important factors in spatially optimal land use decisions. Land use patterns that devote a small amount of land to archipelago habitat patches show the best economic performance in both systems. However, the benefit of fragmentation disappears rapidly as the area of habitat increases, leaving it inferior to strip and square patterns. While Bianchi and van der Werf (2003) find that better pest control is achieved in landscapes with a substantial area of non-crop habitats and where these habitats are distributed in small patches over the landscape, our analysis highlights the tradeoff between economic and ecological performance associated with the area and patchiness of habitat. From a private producer perspective, patchiness is only desirable when the total habitat area and configuration yield pest control benefits that balance the opportunity cost of land use change and increased production cost caused by field fragmentation.

Third, the spatial distribution of natural control services to crop fields is an important factor determining the economic performance of habitat management. The simulation experiment in this study considers a simplified case in which natural pest control services are dispersed around a source origin into the crop fields within a certain range. The more complicated interactions associated with re-distribution and crowding of insect populations are ignored. Given equal mean dispersal distance assumed, we find positive association between the coverage (or spatial extent) of natural pest control services (as opposed to intensity of control) and the relative performance of habitat management for square and strip configurations. For archipelago, however, the use of different distribution kernels in the simulation model made no difference on the relative performance of habitat management. In practice, optimal habitat configuration is likely to be species specific, highlighting the need to rely on solid ecological knowledge in building models for management decision support. Economic parameters such as prices of organic products and biological parameters such as the pest mortality rate due to insecticides also have important impact on the model results.

Several issues deserve future attention. First, while not considered in the current study, species scale dependence may have important implications for spatially explicit models involving land use choices. If natural enemy density increases exponentially with area of contiguous habitat, the aggregation of patchy habitats may become desirable and coordinated action among multiple land managers may become socially desirable. Future research into habitat management may also benefit from enhanced capability to link actual natural enemy population density with the size of non-crop habitats. Such linkage would allow us to explore more species-targeted management practices as well as integrated approaches that combine natural control with chemical control.

Second, obtaining improved parameter estimates (such as the efficacy rate of insecticides and species spatial distribution scale parameters) represents an important direction to strengthen such interdisciplinary research. The relationship between the area and spatial configuration of non-crop habitats in the landscape and the density of natural enemies remains a highly relevant ecological question to be explored. Furthermore, the estimation of the pest regulation effect of non-crop habitats could greatly benefit from the use of empirical data.

Finally, given the spatial nature of the dispersal of natural enemies and their services, issues of externalities and spillovers will arise, which may influence the design of socially optimal policy incentives. While the model developed here is capable of investigating such issues at the landscape scale, it is beyond the scope of the current analysis. Future research may also look into potential opportunities for bundling habitat management policies with other policy incentives that address issues such as water pollution and soil conservation. Two factors are particularly important when thinking about socially optimal land use choices: the distribution of natural enemies in space and the scale dependence effect. The latter offers a potential gain in total control services generated from a larger contiguous non-crop habitat if species population increases disproportionately with habitat size, whereas a longer dispersal distance as described by the Laplace kernel ensures that the services reach more crop fields. For instance, strip habitats near farm borders may produce better collective outcomes than individual farms establishing their own habitats of equal area. Parkhurst *et al.* (2002) conduct an experiment to explore a voluntary incentive mechanism, the agglomeration bonus, designed to protect endangered species and biodiversity by reuniting fragmented habitat across private land. The mechanism provides incentives for non-cooperative landowners to voluntarily create a contiguous reserve across their common border (Parkhurst *et al.*, 2002). Such policy mechanisms may be useful when models like the one developed here show coordination benefits to optimal spatial configuration of non-crop habitats.

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Table 3.1: Values of parameters used in the numerical analysis and their sources or estimations

Parameters	Values	Sources
η: proportion of yield lost per unit of pest population	0.00026	Estimated from Michigan field data for 2005 provided by Christine DiFonzo
μ: maximum allowable yield loss	1	Model restriction
p_{soy} conventional	$247.9/ton[13]	UIUC (2003) Food-Grade
p_{soy} organic	$518/ton	UIUC (2003) Food-Grade
p_{corn} conventional	$85.1/ton	UIUC (2003) Regular hybrid
p_{corn} organic	$133.2/ton	UIUC (2003), Feed grade
y_{max_soy} conventional	3.08 ton/ha	UIUC (2003) Food-Grade
$y_{max\ soy}$ organic	2.45 ton/ha	UIUC (2003) Food-Grade
y_{max_corn} conventional	10.85 ton/ha	UIUC (2003) Regular hybrid
$y_{max\ corn}$ organic	9.45 ton/ha	UIUC (2003) Feed grade
VC_{soy} conventional	$260/ha	UIUC (2003) Food-Grade
VC_{soy} organic	$260/ha	UIUC (2003) Food-Grade
VC_{corn} conventional	$490/ha	UIUC (2003) Regular hybrid
VC_{corn} organic	$472.5/ha	UIUC (2003) Feed grade
$pest_{initial}$: control-free pest infestation level (avg soybean aphid density during soybean plant stages R1 through R5)	5000 (low), 8000 (medium), and 12000 (high) aphids/plant	Predicted from Costamagna *et al.* (2007b) model with starting values taken from Michigan field data
$Cost_{spray}$: cost of spray per application	$30.5/ha	Song *et al.* (2006)
Number_of_sprays	1 for low, medium infestation; 2 for high infestation	Adapted from results in essay 2
$Efficacy_{spray}$: efficacy rate of soybean aphid insecticides	0.99	Assumed
r: radius of cylindrical kernel	100 m	Assumed
α: slope of the decline of allocated services with distance for Laplace kernel	0.02 m^{-1}	Assumed
θ: standard deviation of Gaussian kernel	80 m	Assumed
Avg. percentage of reduction in pest density responding to the percentage of NCH in landscape	See Figure 3.4	Estimated from simulation results from Bianchi and van der Werf (2003)
λ: Proportion of change in variable costs due to the establishment of NCH	See Figure 3.7-3.8	Estimated using cost data from UIUC (2003) and estimate of the amount of machinery field time spent on turning (Bowers, 1992) (Appendix D)

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[13] 1 metric ton = 36.74 (37) bushels soybeans (60 pound bu) and 1 bushel/acre = 0.0673 (0.07) metric tons/hectare (Weiland and Smith, 2007). 1 hectare = 2.471 (2.5) acres

Table 3.2: Summary of sensitivity analysis results (Medium pest infestation, Laplace kernel, and strip NCH)

	Changes in outcomes (*nr* associated with optimal *prop_NCH*) from baseline*	
Parameters	Conventional	Organic
η: proportion of yield lost per unit of pest population	↑5%: ↓ 1.4%	↑5%: ↑ 3.3%
	↓5%: ↑ 1.5%	↓5%: ↓ 3.3%
p_{soy}	↑10%: ↓ 2.3%	↑10%: ↑ 6.8%
	↓10%: ↑ 2.7%	↓10%: ↓ 7.2%
y_{max_soy}	↑5%: ↓ 1.2%	↑5%: ↑ 3.5%
	↓5%: ↑ 1.3%	↓5%: ↓ 3.5%
VC_{soy}	↑5%: ↓ 1.1 %	↑5%: ↑ 1.7%
	↓5%: ↑ 1%	↓5%: ↓ 1.6%
$Cost_{spray}$: cost of spray per application	↑5%: ↑ 0.4 %	
	↓5%: ↓ 0.4%	
$Efficacy_{spray}$: efficacy rate of soybean aphid insecticides	↓5%: ↑ 18.4%	
Mean dispersal distance ($2/\alpha$)	↑5%: ↑ 3.4%	↑5%: ↑ 5.2%
	↓5%: ↓ 3.4%	↓5%: ↓ 5.1%
Avg. percentage of reduction in pest density responding to the percentage of NCH in landscape	↑5%: ↑ 0.5%	↑5%: ↑ 0.7%
	↓5%: ↓ 0.5 %	↓5%: ↓ 0.8 %

* The baseline refers to model outcomes based on parameters given in Table 3.1.

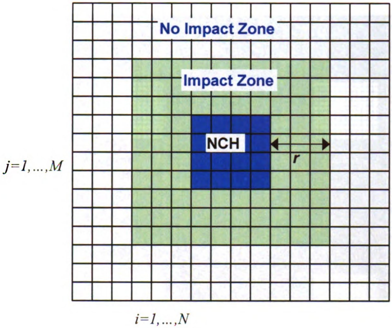

Figure 3.1: The distribution of land between non-crop habitats, impact zone, and no impact zone

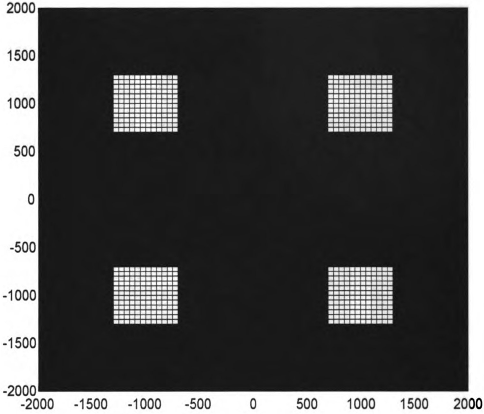

Figure 3.2a: Illustration of landscape configuration with four farms and three NCH configurations (prepared in 80×80 grid and with *pro_NCH*=0.1): Square

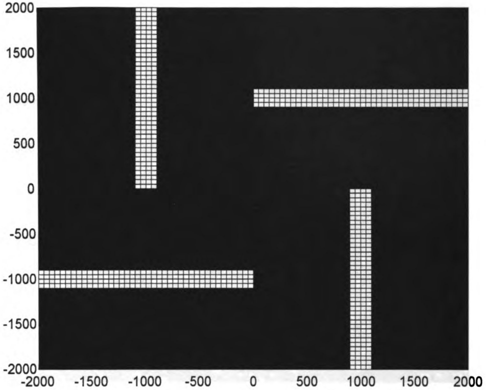

Figure 3.2b: Illustration of landscape configuration with four farms and three NCH configurations (prepared in 80×80 grid and with *pro_NCH*=0.1): Strip

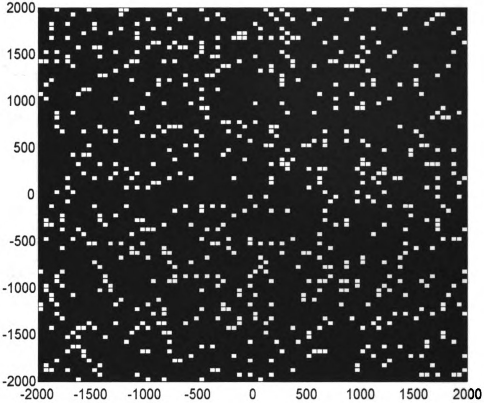

Figure 3.2c: Illustration of landscape configuration with four farms and three NCH configurations (prepared in 80×80 grid and with *pro_NCH*=0.1): Archipelago

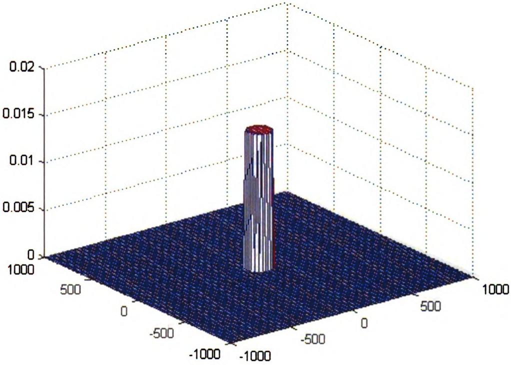

Figure 3.3a: Illustration of distribution kernels (prepared in 200×200 grid): Cylindrical kernel (radius=100 m)

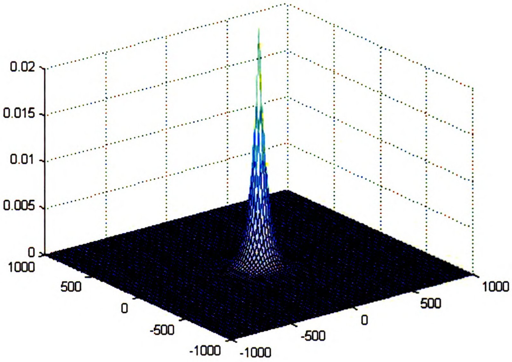

Figure 3.3b: Illustration of distribution kernels (prepared in 200×200 grid): Laplace kernel (α=0.02 m^{-1})

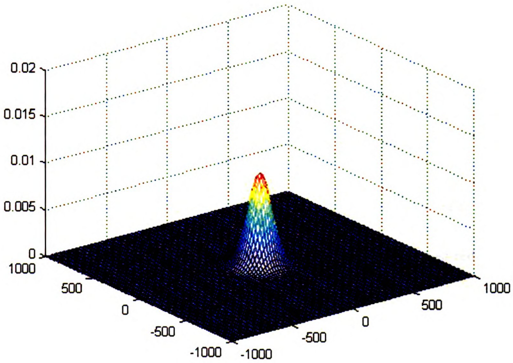

Figure 3.3c: Illustration of distribution kernels (prepared in 200×200 grid): Gaussian kernel (θ=80 m)

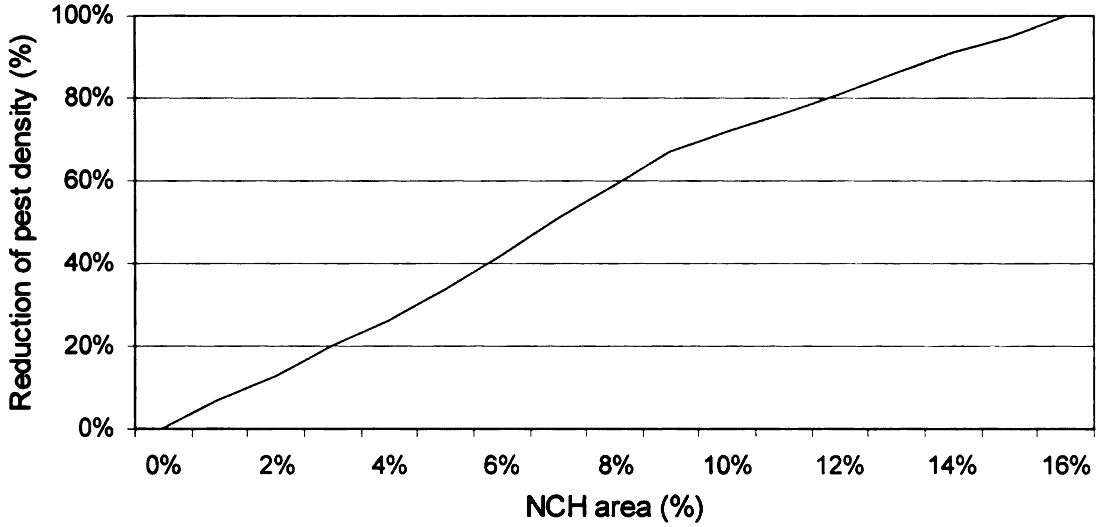

Figure 3.4: The relationship between the NCH area and the average pest reduction impact (Estimated from Bianchi and van der Werf, 2003)

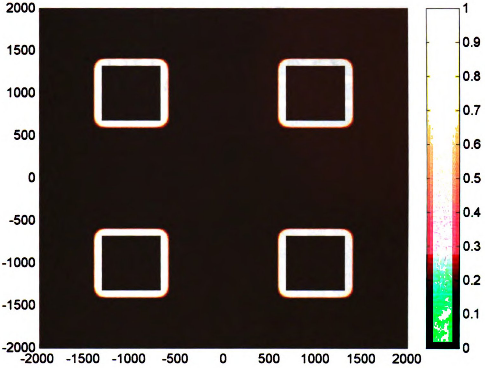

Figure 3.5(i)a: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Cylindrical kernel; Square

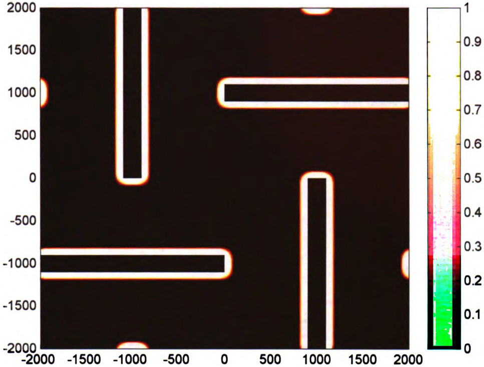

Figure 3.5(i)b: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Cylindrical kernel; Strip

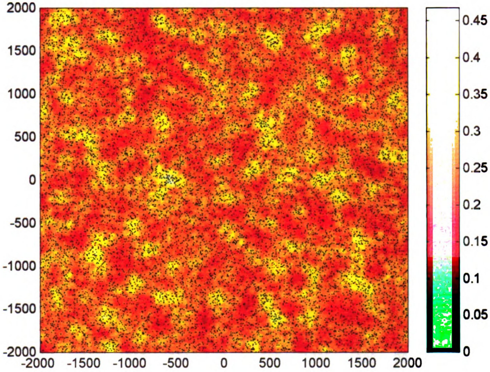

Figure 3.5(i)c: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Cylindrical kernel; Archipelago

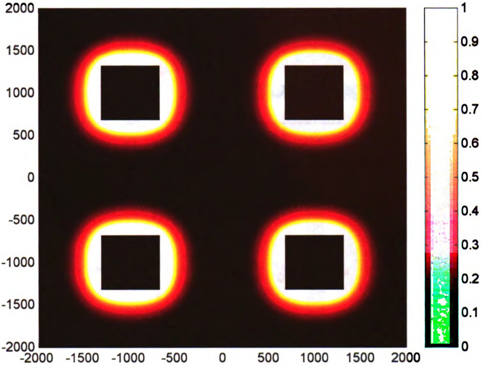

Figure 3.5(ii)a: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Laplace kernel; Square

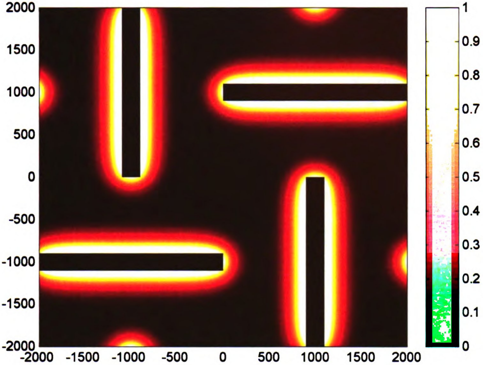

Figure 3.5(ii)b: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Laplace kernel; Strip

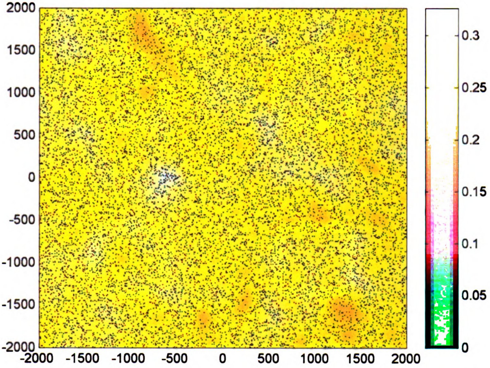

Figure 3.5(ii)c: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Laplace kernel; Archipelago

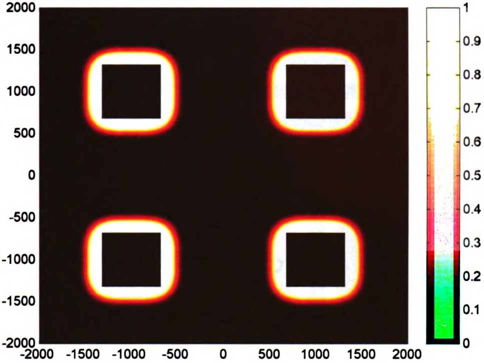

Figure 3.5(iii)a: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Gaussian kernel; Square

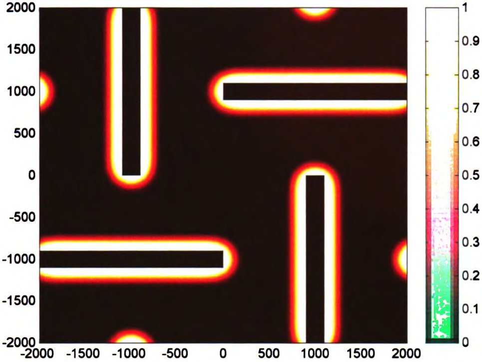

Figure 3.5(iii)b: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Gaussian kernel; Strip

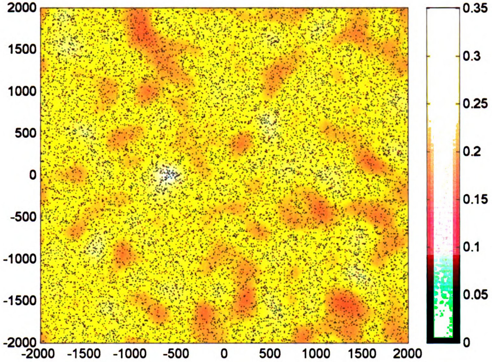

Figure 3.5(iii)c: Illustration of distributions of pest control impact (proportion of reduction), prepared with *prop_NCH*=0.1 in a 400×400 grid: Gaussian kernel; Archipelago

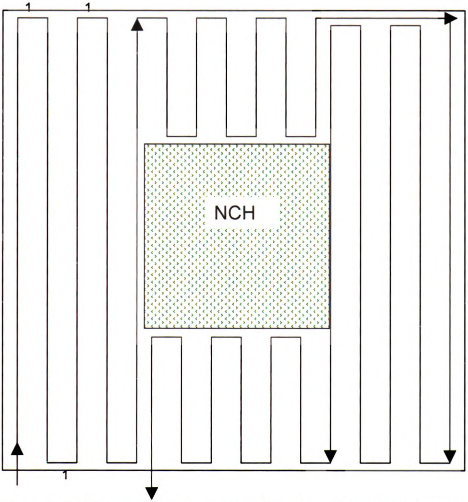

Figure 3.6a: Illustration of assumed modes of machinery field operation (the number "1" represents one turn): Square

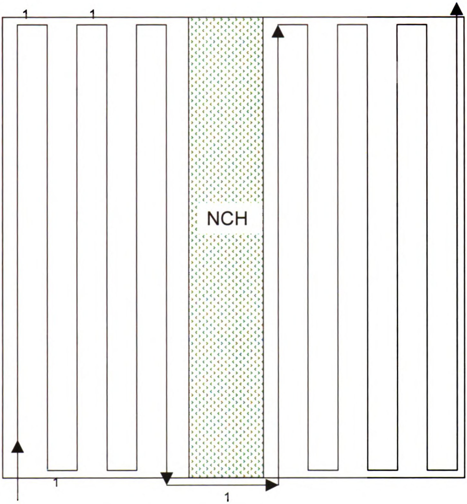

Figure 3.6b: Illustration of assumed modes of machinery field operation (the number "1" represents one turn): Strip

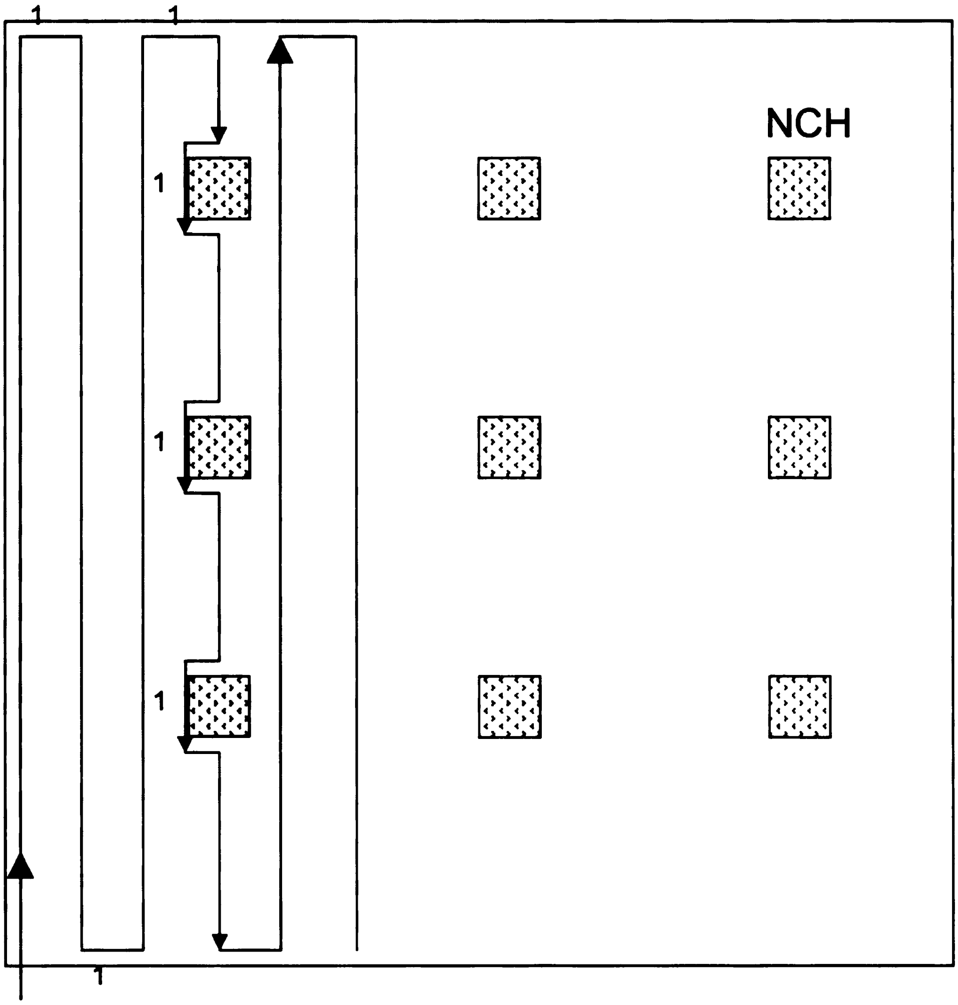

Figure 3.6c: Illustration of assumed modes of machinery field operation (the number "1" represents one turn): Archipelago

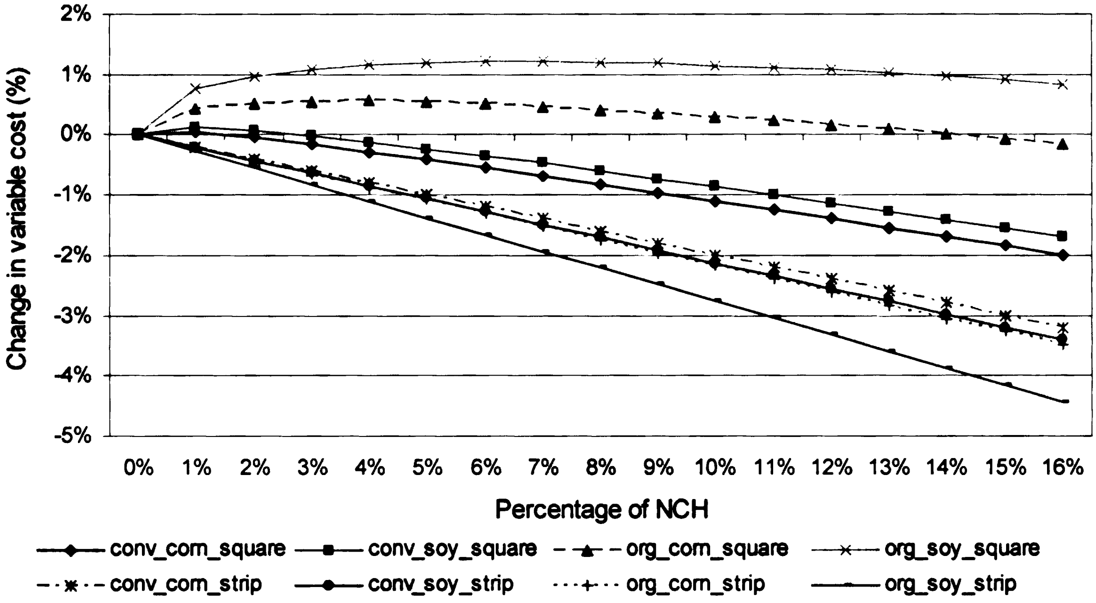

Figure 3.7: Estimated values of the percentage of change in variable costs of production for square and strip patterns

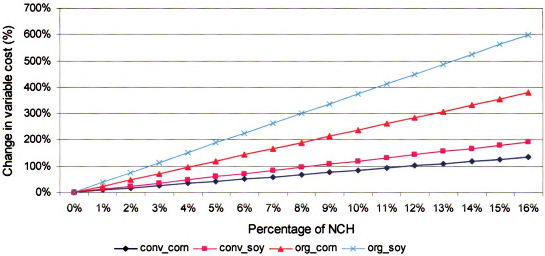

Figure 3.8: Estimated values of the percentage of change in variable costs of production for archipelago pattern

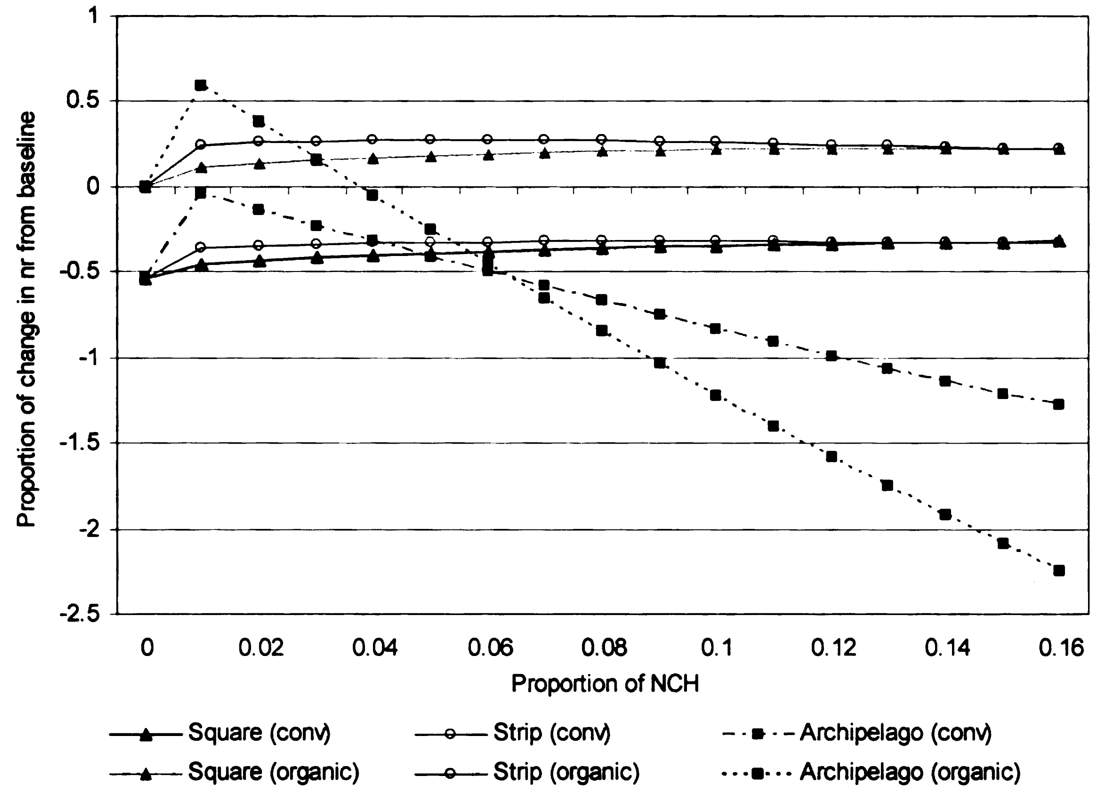

Figure 3.9: Proportion of change in net return to fixed factors (Medium pest infestation, Laplace kernel)

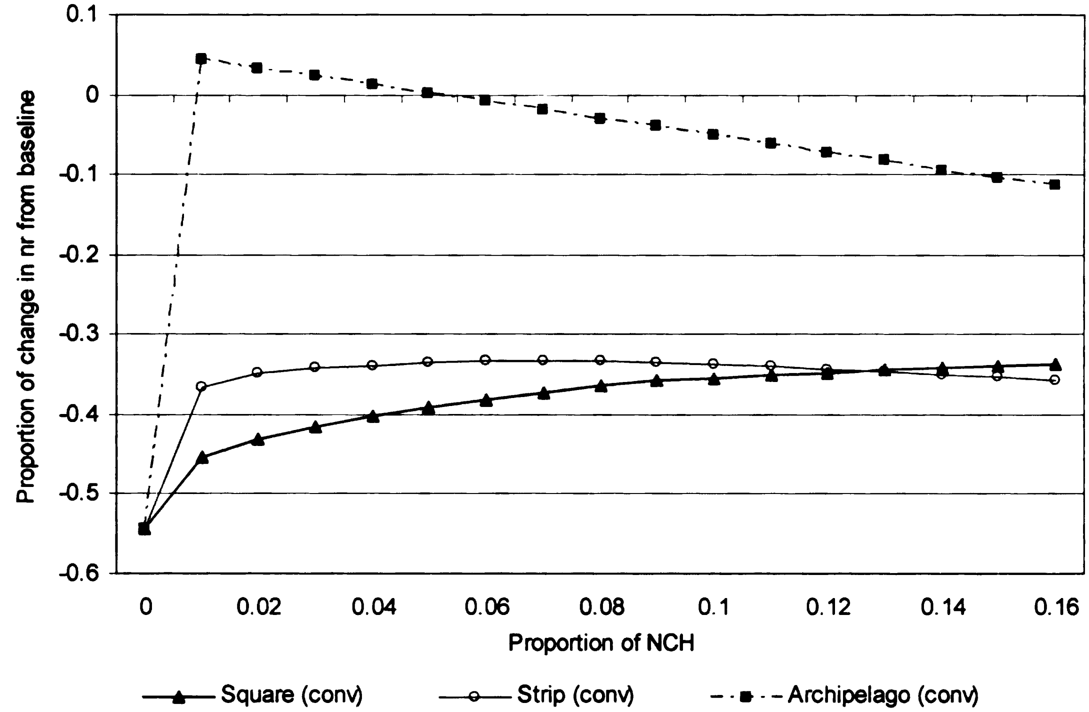

Figure 3.10: Proportion of change in net return to fixed factors for a conventional farm when change in variable costs of production is ignored (Medium pest infestation, Laplace kernel)

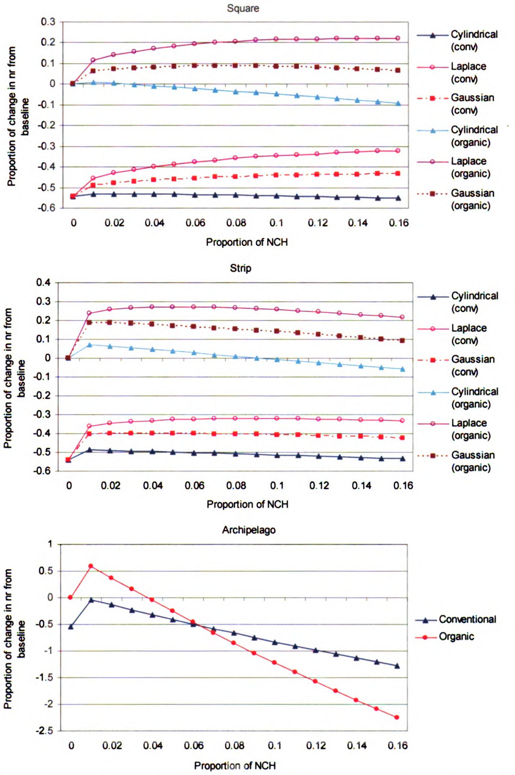

Figure 3.11: The effect of distribution kernels on the relative performance of HM at medium pest infestation

Conclusions

The three essays of this dissertation explore two approaches to managing natural pest control ecosystem services in order to achieve improved pest management in agricultural systems. Essays 1 and 2 focus on integrating natural pest control into insecticide decision-making so that natural enemies of crop pests are conserved and efficiently used to the extent that the marginal factor cost of insecticide application (including the opportunity cost of natural enemy mortality from insecticides) balances the marginal value of the yield benefit. Essay 3 moves beyond insecticide-based pest management to look at optimal spatial land use decisions for the management of habitats of natural enemies.

By conserving (or better utilizing) and enhancing the natural pest control services, there are new opportunities for improving pest management in an economically appealing and socially desirable manner. To promote such opportunities would require not only a tremendous increase in scientific understanding of ecosystems, but also major innovations to our economic and social institutions to capture this value and incorporate it into day-to-day decision-making (Daily and Ellison, 2002). The approach presented here offers a useful framework for the management of other supporting and regulating ecosystem services that serve as inputs to biological production of marketed agricultural products.

The three essays employ bioeconomic modeling and optimization analysis to explore the economic consequences of these opportunities on private producers. According to these experiments, there are clearly economic gains from incorporating natural enemies into insecticide decisions, which effectively delays and reduces the need for insecticide spraying. The economic advantage of establishing non-crop habitats in agricultural landscape, however, depends on the alternative pest management practices available. For instance, relying on non-crop habitats of natural enemies for the management of pests may not be economically viable if chemical control remains a cost-effective option, as under a conventional farming system. The relevant policy question, therefore, is how to develop policy instruments i) to promote the adoption of natural enemy-incorporated insecticide strategies that have the potential to improve economic returns to private producers, and ii) to provide private producers with needed economic incentives to adopt sustainable pest management approaches, such as habitat management, that enhance the natural pest control services. In the second case, values of ecological and environmental benefits from the establishment of non-crop habitats (e.g., enhanced ecosystem services provided by beneficial pollinator insects) may be of interest because they help justify the social incentives for supporting such practices. Results from Essay 3 show the magnitude of reduction in private net returns to fixed factors of production as a result of habitat management. Such estimates may serve as a lower bound for the financial support needed for conventional farmers to adopt habitat management voluntarily.

At the landscape scale, coordination issues are also relevant to the management of natural pest control services when spillovers exist for the distribution of natural control benefits and the costs due to nontarget natural enemy mortality from insecticides. The spillover of natural control benefits may reduce private incentives for voluntary adoption due to the free-rider problem. Because of the nontarget natural enemy mortality from insecticides, even if some farmers decide to adopt biological pest control strategies, they could be harmed by pesticide use on neighboring farms (Wilson and Tisdell, 2001). Such spillover effects would require individual farmers to coordinate action in adopting sustainable management approaches if economic losses are to be avoided (Wilson and Tisdell, 2001). Finally, scale matters for natural enemy habitats that may affect socially optimal spatial land use choices. If natural enemy density increases disproportionately with size of habitat, the aggregation of patchy habitats through coordinated action may become socially desirable.

References

Daily, G.C., and K. Ellison. 2002. *The New Economy of Nature--The Quest to Make Conservation Profitable*. Washington D.C.: Island Press/Shearwater Books.

Wilson, C., and C. Tisdell. 2001. "Why farmers continue to use pesticides despite environmental, health and sustainability costs." *Ecological Economics* 39: 449-462.

Appendix A:

MatLab code for the optimal insecticide management model (Essay 2)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Single-season optimizing simulation model: Interaction between
% soybean aphid, natural enemies, and soybean yield
% Author: Wei Zhang, 2007
%
% Soybean aphid population growth module developed by Felix Bianchi,
% Alejandro Costamagna, and Wopke van der Werf, May 2005 (Costamagna et
% al., 2007), and modified by Wei Zhang
%
% Reference:
% Costamagna, A.C., W. van der Werf, F.J.J.A. Bianchi, and D.A. Landis.
% 2007. "An exponential growth model with decreasing r captures bottom-
% up effects on the population growth of Aphis glycines Matsumura
% Hemiptera: Aphididae)." Agricultural and Forest Entomology 9:1-9.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc

% PARAMETERS
    % SIMULATION TIME STEP
    DELT=1;
    % SBA DAILY POPULATION GROWTH FITTED BY WILLIAMS MODEL: Estimated
from the generalized model
    RGRMAX = 0.3978; % corresponds to the first infestation date at KBS
in 2005, which is approximately 6/23/05
    C = 0.0240;
    % Kill rate of insecticides
    KI = 0.99;
    KN = 0.99;
    % Death rate of natural enemy
    D1 = 0;
    D2 = -0.9;
    D3 = -2.13;
    % Birth rate of natural enemy due to consumption of SBA
    B1 =0;
    B2 =0;
    B3 = 0.002;
    % Percentage of yield loss due to 1 unit of SBA
    YD1 = 0;
    YD2 = 0;
    YD3 = 0.0003;
    YD4 = 0.0001;
    YD5 = 0;
    % Percentage of maximum yield loss
    YM1 = 1; % restricted to be one
    YM2 = 1;
    YM3 = 1;
    YM4 = 1;
    YM5 = 1;
    % CONTROL COST
```

```
    COST =12.18;
    % OUTPUT PRICE
    PRICE =6.91;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SBA population density for each stage in the absence of predation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

fid = fopen('SBA_no_predation_26Jul07.txt','w');
% PLANT GROWTH STAGE
    % At KBS in 2005, R1 approximately began on July 5
    % Mean R-stage length data from literature: 3,10,9,9,15 days

    DATE0R1_KBS = datenum('7/5/2005');
    DATE1R1_KBS = datenum('7/7/2005');
    DATE0R2_KBS = datenum('7/8/2005');
    DATE1R2_KBS = datenum('7/17/2005');
    DATE0R3_KBS = datenum('7/18/2005');
    DATE1R3_KBS = datenum('7/26/2005');
    DATE0R4_KBS = datenum('7/27/2005');
    DATE1R4_KBS = datenum('8/4/2005');
    DATE0R5_KBS = datenum('8/5/2005');
    DATE1R5_KBS = datenum('8/19/2005');

    R1_KBS = DATE1R1_KBS-DATE0R1_KBS+1; % Number of days during R1
    R2_KBS = DATE1R2_KBS-DATE0R2_KBS+1;
    R3_KBS = DATE1R3_KBS-DATE0R3_KBS+1;
    R4_KBS = DATE1R4_KBS-DATE0R4_KBS+1;
    R5_KBS = DATE1R5_KBS-DATE0R5_KBS+1;

    L_KBS = R1_KBS+R2_KBS+R3_KBS+R4_KBS+R5_KBS;

% Initial conditions (SBA/plant)
    I=73.45; % KBS, mean of multiple plots, 7/5/05

    TIME=0;

    % R1 Time Loop: FINISH TIME OF SIMULATION (DAY)
    TIME_KBS =L_KBS;

        while TIME<TIME_KBS

    % SBA population model
    DATE_INFESTATION = datenum ('6/23/2005'); % This is the day when
SBA population has a maximum intrinsic growth rate (RGRMAX)
    BEFORE_R1 = DATE0R1_KBS-DATE_INFESTATION;

    RGRMAX_ADJUST = RGRMAX * (1-C * BEFORE_R1); % derive the "RGRMAX"
for the first day of R1
    RGR = RGRMAX_ADJUST * (1 - C * TIME); % Relative Growth Rate
    RA = I*(exp(RGR) - 1); % SBA population Growth Rate (SBA/day)

    % Output
    output=[TIME; I; RA; RGR];
    fprintf(fid, '%12.0f %12.6f %12.6f %12.6f\n', output);

% Integration
```

```
      % Time integration
      TIME=TIME+DELT;
      % Integration of aphid population
    I=I+RA;
    end
    I=I;

fclose(fid)
load SBA_no_predation_26Jun07.txt;

SBA_R1_NP=mean(SBA_no_predation_26Jun07((1:R1_KBS),2)); % obtain
average density of SBA population
SBA_R2_NP=mean(SBA_no_predation_26Jun07(((R1_KBS+1):(R1_KBS+R2_KBS)),2)
);
SBA_R3_NP=mean(SBA_no_predation_26Jun07(((R1_KBS+R2_KBS+1):(R1_KBS+R2_K
BS+R3_KBS)),2));
SBA_R4_NP=mean(SBA_no_predation_26Jun07(((R1_KBS+R2_KBS+R3_KBS+1):(R1_K
BS+R2_KBS+R3_KBS+R4_KBS)),2));
SBA_R5_NP=mean(SBA_no_predation_26Jun07(((R1_KBS+R2_KBS+R3_KBS+R4_KBS+1
):(R1_KBS+R2_KBS+R3_KBS+R4_KBS+R5_KBS)),2));

SBA_KBS_NP = zeros(4,1);
SBA_KBS_NP=[SBA_R1_NP SBA_R2_NP SBA_R3_NP SBA_R4_NP SBA_R5_NP];

% Calculate net growth rate of SBA density
NG1=(SBA_R2_NP/SBA_R1_NP)-1;
NG2=(SBA_R3_NP/SBA_R2_NP)-1;
NG3=(SBA_R4_NP/SBA_R3_NP)-1;
NG4=(SBA_R5_NP/SBA_R4_NP)-1;

NG=[NG1 NG2 NG3 NG4];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Simulation over ranges of daily predation rate, initial yield
% potential, all possible control paths, and initial values of SBA and
% NE densities in R1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

fid = fopen('output_Aug07.txt','w');

for j = 35  % mean predation rate (SBA/day/NE)
        PR = j;

for g = 40:2:60   % range and interval of initial yield potential
    Y1 = g;

% define control path: X=1 if control, X=0 if no control
X1=[0 1]';
X2=[0 1]';
X3=[0 1]';
X4=[0 1]';
X=gridmake(X1, X2, X3, X4);
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           Stage R1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Simulate initial values of SBA_R1 and NE_R1
for k =0:5:150 % range and interval of initial values of SBA_R1
    SBA_R1 = k;

    for h = 0:.5:4 % range and interval of initial values of NE_R1
        NE_R1 =h;


      for i=1:16   % A total of 16 possible control paths
            X1 = X(i,1);
            X2 = X(i,2);
            X3 = X(i,3);
            X4 = X(i,4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           Stage R2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
PR_R1 = PR * R1_KBS;
SBA_R2=max(0, (SBA_R1-KI*X1*SBA_R1)+ NG1*(SBA_R1-KI*X1*SBA_R1)-
PR_R1*(NE_R1-KN*X1*NE_R1));
NE_R2=max(0, (NE_R1-KN*X1*NE_R1)+ D1*(NE_R1-KN*X1*NE_R1)+B1*(SBA_R1-
KI*X1*SBA_R1)*(NE_R1-KN*X1*NE_R1));
Y2 = Y1*(1-(YD1*SBA_R1)/(1+(YD1*SBA_R1/YM1)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           Stage R3
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
PR_R2 = PR * R2_KBS;
SBA_R3=max(0, (SBA_R2-KI*X2*SBA_R2)+ NG2*(SBA_R2-KI*X2*SBA_R2)-
PR_R2*(NE_R2-KN*X2*NE_R2));
NE_R3=max(0, (NE_R2-KN*X2*NE_R2)+ D2*(NE_R2-KN*X2*NE_R2)+B2*(SBA_R2-
KI*X2*SBA_R2)*(NE_R2-KN*X2*NE_R2));
Y3 = Y2*(1-(YD2*SBA_R2)/(1+(YD2*SBA_R2/YM2)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           Stage R4
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
PR_R3 = PR * R3_KBS;
SBA_R4=max(0, (SBA_R3-KI*X3*SBA_R3)+ NG3*(SBA_R3-KI*X3*SBA_R3)-
PR_R3*(NE_R3-KN*X3*NE_R3));
NE_R4=max(0, (NE_R3-KN*X3*NE_R3)+ D3*(NE_R3-KN*X3*NE_R3)+B3*(SBA_R3-
KI*X3*SBA_R3)*(NE_R3-KN*X3*NE_R3));
Y4 = Y3*(1-(YD3*SBA_R3)/(1+(YD3*SBA_R3/YM3)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%           Stage R5
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
PR_R4 = PR * R4_KBS;
SBA_R5=max(0, (SBA_R4-KI*X4*SBA_R4)+ NG4*(SBA_R4-KI*X4*SBA_R4)-
PR_R4*(NE_R4-KN*X4*NE_R4));
%NE_R5=max(0, (NE_R4-KN*X4*NE_R4)+ D4*(NE_R4-KN*X4*NE_R4)+B4*(SBA_R4-
KI*X4*SBA_R4)*(NE_R4-KN*X4*NE_R4));
Y5 = Y4*(1-(YD4*SBA_R4)/(1+(YD4*SBA_R4/YM4)));
```

```
SBA = [SBA_R1 SBA_R2 SBA_R3 SBA_R4 SBA_R5];
NE = [NE_R1 NE_R2 NE_R3 NE_R4];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%            HARVEST
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Harvest yield
YH = Y5*(1-(YD5*SBA_R5)/(1+(YD5*SBA_R5/YM5)));
% Net return from pest management
QR = PRICE*YH-(X1+X2+X3+X4)*COST;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%            Optimization: find optimal control paths
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Output of all possible control paths
output=[PR; PR_R1; PR_R2; PR_R3; PR_R4; Y1; Y2; Y3; Y4; Y5; YH; QR; X1;
X2; X3; X4; SBA_R1; SBA_R2; SBA_R3; SBA_R4; SBA_R5; NE_R1; NE_R2; NE_R3;
NE_R4 ];

fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.0f %12.0f %12.4f %12.4f
%12.4f %12.4f %12.4f %12.4f %12.0f %12.0f %12.0f %12.0f %12.4f %12.4f
%12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f\n', output);

        end
       end
end
end
end

fid = fopen('maxqr_Aug07.txt','w');  % Calculating max net return
load output_Aug07.txt;
    for i=1:16:49089
    [MAXQR INDEX] = max(output_Aug07((i:(i+16-1)),12));

    output=[MAXQR; INDEX];
    fprintf(fid,'%12.4f %12.0f\n', output);
    end

load maxqr_Aug07.txt;
MAXQR = maxqr_Aug07(:,1);
INDEX = maxqr_Aug07(:,2);

fid = fopen('ocp_Aug07.txt','w');
load output_Aug07.txt;
        for i=1:1:3069 % (49104/16)
        A = output_Aug07([((i-1)*16+1):(i*16)],:);
        ocp = A((INDEX(i,1)),:);
        ocp1 = horzcat (ocp, INDEX(i,1));
        output=[ocp1];
        fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.0f %12.0f %12.4f
%12.4f %12.4f %12.4f %12.4f %12.4f %12.0f %12.0f %12.0f %12.0f %12.4f
%12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.0f\n',
output);

        end
```

Appendix B:
MatLab code for the habitat spatial optimization model (Essay 3)

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Spatially Optimal Non-crop Habitats (NCH) for Natural Pest Control
% Services at the Landscape Scale
% Author: Wei Zhang and Wopke van der Werf (Oct 2006-Nov 2007)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  Conventional farming systems   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear;
fid =
fopen('HM_11Nov07_conv_SeedSaving_SameMeanDispersalDis_n800.txt','w');

% Setup of a square space, representing a landscape
n = 800;      % Number of divisions along x-axis for landscape

nx = n;         % number of cell divisions along x-axis
ny = n;         % number of cell divisions along y-axis
size = 4000;    % total landscape measures "size" by "size" m
dx = size/n;    % cell width in x-direction (m)
dy = size/n;    % cell width in y-direction (m)
x = dx * [-nx/2:1:nx/2-1]; % calculation of x-coordinates in m
y = dy * [-ny/2:1:ny/2-1]; % calculation of y-coordinates in m
[X,Y] = meshgrid(x,y); % setting up the matrix of (x,y) coordinates

% Initial pest population density per plant in soybeans
pest0_l = 5000;     % low infestation
pest0_m = 8000;     % medium infestation
pest0_h = 12000;    % high infestation

n_spray = 0;        % Number of sprays in a season

pest0 = 0;

for j = 1:3
    if j==1
    pest0 = pest0_l
    n_spray = 1
    elseif j==2
    pest0 = pest0_m
    n_spray = 1
    elseif j==3
    pest0 = pest0_h
    n_spray = 2
    end

% Yield damage function (Cousens, 1985)
d1 = 0.00026; % proportion of yield loss due to 1 unit of pest density
per plant
```

```
d2 = 1;         % Proportion of maximum yield loss
% Assuming efficacy rate of insecticides is 99%
dm = (d1 * (pest0 * 0.01))./(1 + (d1 * (pest0 * 0.01) / d2 )); %
proportion of yield loss due to pest density pest0

% Assume homogeneous farms, Soybean-corn rotation
farmingsystem = 'conventional';
farmingsystem = 2;

% Conventional soybean production (pesticide control)
price_s = 6.7;     % Price of conventional Food-Grade, Clear Hilum
Soybeans (UIUC 2003)
ymax_s = 44;       % Yield of conventional Food-Grade, Clear Hilum
Soybeans (UIUC 2003) (bu/ac)
pcost_s = 104;     % Variable production cost of Food-Grade, Clear Hilum
Soybeans (UIUC 2003) ($/ac)
ccost_s = 12.18;  % Cost of pesticide control ($/ac) (Song et al. 2006)
tccost_s = n_spray * ccost_s;   %Total pesticide control cost

% Conventional corn production
price_c = 2.3;     % Price of conventional regular hybrid corn ($/bu)
(UIUC 2003)
ymax_c = 155;      % Yield of conventional regular hybrid corn (bu/ac)
(UIUC 2003)
pcost_c = 196;     % Variable production cost of regular hybrid corn
(UIUC 2003)($/ac)


landscape = zeros(n)

% Defining farms - the landscape has four farms, arranged in a 2x2
checkerboard
farm1 = [ones(ny/2) zeros(ny/2); zeros(nx/2,nx)]
farm2 = farm1(:,nx:-1:1)
farm3 = farm1(ny:-1:1,:)
farm4 = farm1(ny:-1:1,nx:-1:1)

farm = zeros (n/2)

% Maximum (pest-free) profit per cell from soybean-corn rotation (no
pest for soybean)
spi_max_cell = 2.4710439 .* (ymax_s * price_s -pcost_s)* (dx * dy
/10000); % Maximum (pest-free) profit per cell from soybean
cpi_max_cell = 2.4710439 .* (ymax_c * price_c -pcost_c)* (dx * dy
/10000); % Profit per cell from corn
rotpi_max_cell = spi_max_cell + cpi_max_cell;

rotpi_max_farm = (farm * (-1) + 1) .* rotpi_max_cell;
tpi_max_farm = sum(sum(rotpi_max_farm));    % Maximum (pest-free)
profit per farm

tpi_max_ls = 4 * tpi_max_farm;  % Maximum (pest-free) profit for
landscape
```

```
%%%%%%%%% Baseline: Conventional farm1 with soybean infested with
"pest0"; control with insecticides %%%%%%%%%%%%

y0_s = (farm * (-1) + 1) .* (ymax_s * (1 - dm));    % Actual soybean
yield given pest0 (bu/ac)
y0_c = (farm * (-1) + 1) .* ymax_c;  % Corn yield
% Proft per cell
spi0_cell = 2.4710439 .* (y0_s * price_s - pcost_s - tccost_s)* (dx *
dy /10000);
cpi0_cell = 2.4710439 .* (y0_c * price_c - pcost_c)* (dx * dy /10000);
rotpi0_cell = spi0_cell + cpi0_cell;

tpi0_farm = sum(sum(rotpi0_cell)); % Baseline profit level per farm

tpi0_ls = 4 * tpi0_farm;   % Baseline profit level for the whole
landscape


pp=[0 4 9 16];     % NCH area (percentage of total landscape area)
reduc_data = [0 26 67 100];      % pest reduction (%) corresponding to
NCH area (%). Parameters estimated from Bianchi and van der Werf (2003)
simulation results for C7 and aphid


ncadist = 1 % Define shape of NCH


xp = dx * [-(nx/2)/2:1:(nx/2)/2]          % x-coordinates for plotting
yp = dy * [-(ny/2)/2:1:(ny/2)/2]          % y-coordinates for plotting
[xplot,yplot] = meshgrid(xp,yp) % setting up the matrix of (x,y)
coordinates for plotting

% Kernel parameters (mean dispersal distance = 100 meters)
% Radius of cylindrical distribution K of impact
radius = 100 % m
% Standard deviation of Guassian distribution K of impact
sigma = 80 % m
% Range parameter of Laplace Distribution K of impact
range = 50 % m


% Distribution of pest control impact in space

% Cylindrical distribution kernel (K) for impact of natural enemies
x = dx * [-nx/2/2:1:nx/2/2-1]; % calculation of x-coordinates in m
y = dy * [-ny/2/2:1:ny/2/2-1]; % calculation of y-coordinates in m
[X,Y] = meshgrid(x,y); % setting up the matrix of (x,y) coordinates

K1 = (sqrt(X.^2 + Y.^2) < radius)
integral = sum(sum(K1))
K1 = K1/integral
fK1 = fft2(K1)

% Laplace distribution kernel (K) for impact of natural enemies
K2 = exp(-(sqrt(X.^2 + Y.^2))/range)
integral = sum(sum(K2))
K2 = K2/integral
```

```
fK2 = fft2(K2)

% Gaussian distribution kernel (K) for impact of natural enemies
K3 = exp(-(X.^2 + Y.^2)/(2 * sigma^2))
integral = sum(sum(K3))
K3 = K3/integral
fK3 = fft2(K3)


%%%% Proportion of NCH = 0 --> no pest control, no control cost %%%%%%
for ncadist=1:3
   for p = 0      % NCH area (percentage of total landscape area)
   reduc = 0      % pest reduction (%) corresponding to p
   shape = farm

   r1 = 0   % Proportion of pest reduction (i.e. measurable actual
impact)
   r2 = 0
   r3 = 0

   cp_s = 0 % Proportion of change in variable cost of production for
soybean due to establishing NCH under conventional system
   cp_c = 0 % Proportion of change in variable cost of production for
soybean due to establishing NCH under conventional system

   pest1 = pest0 * (1 - r1)
   pest2 = pest0 * (1 - r2)
   pest3 = pest0 * (1 - r3)

   dm1 = (d1 * pest1)./(1 + (d1 * pest1 / d2 ))
   dm2 = (d1 * pest2)./(1 + (d1 * pest2 / d2 ))
   dm3 = (d1 * pest3)./(1 + (d1 * pest3 / d2 ))

   y1_s1 = (shape * (-1) + 1) .* (ymax_s * (1 - dm1))       % Actual
soybean yield (bu/ac)
   y1_s2 = (shape * (-1) + 1) .* (ymax_s * (1 - dm2))
   y1_s3 = (shape * (-1) + 1) .* (ymax_s * (1 - dm3))

   spi1_cell1 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s1 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)  % Soybean profit per CELL
   spi1_cell2 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s2 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)
   spi1_cell3 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s3 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)

   cpi1_cell = (shape * (-1) + 1) .* 2.4710439 .* (y0_c * price_c -
pcost_c * (1 + cp_c)) * (dx * dy /10000) % Corn profit given NCH taken
out of production

   rotpi1_cell1 = spi1_cell1 + cpi1_cell  % Profit per soybean-corn
rotation
   rotpi1_cell2 = spi1_cell2 + cpi1_cell
   rotpi1_cell3 = spi1_cell3 + cpi1_cell

   tpi1_farm1 = sum(sum(rotpi1_cell1))   % profit per rotation per farm
   tpi1_farm2 = sum(sum(rotpi1_cell2))
   tpi1_farm3 = sum(sum(rotpi1_cell3))
```

```
   tpi1_ls1 = 4* tpi1_farm1     % profit for landscape
   tpi1_ls2 = 4* tpi1_farm2
   tpi1_ls3 = 4* tpi1_farm3

   % Change in soybean profit at the farm scale from baseline
   change_farm_s1 = ( (sum(sum(spi1_cell1))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s2 = ( (sum(sum(spi1_cell2))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s3 = ( (sum(sum(spi1_cell3))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   % Change in rotation profit at the farm scale from baseline
   change_farm1 = (tpi1_farm1 - tpi0_farm) / tpi0_farm
   change_farm2 = (tpi1_farm2 - tpi0_farm) / tpi0_farm
   change_farm3 = (tpi1_farm3 - tpi0_farm) / tpi0_farm
   % Change in rotation profit at the landscape scale from baseline
   change_ls1 = (tpi1_ls1 - tpi0_ls) / tpi0_ls
   change_ls2 = (tpi1_ls2 - tpi0_ls) / tpi0_ls
   change_ls3 = (tpi1_ls3 - tpi0_ls) / tpi0_ls

   check1 = change_ls1 - change_farm1
   check2 = change_ls2 - change_farm2
   check3 = change_ls3 - change_farm3

% Output
output=[farmingsystem; n; pest0; n_spray; p; reduc; alpha; beta; cp_s;
cp_c; ncadist; change_farm_s1; change_farm_s2; change_farm_s3;
change_farm1; change_farm2; change_farm3;change_ls1; change_ls2;
change_ls3];

fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.2f %12.2f %12.2f %12.2f
%12.4f %12.4f %12.0f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f
%12.4f %12.4f\n', output);

end
end


%%%%%%%%%% Square %%%%%%%%%%%%%%%%%%%%%%%%%%%
for ncadist = 1   % Landscapes with square NCH
      for p = 1:1:16
          if p == 1
              cp_s = 0.001
              cp_c = 0
          elseif p == 2
              cp_s = 0.001
              cp_c = -0.001
          elseif p == 3
              cp_s = 0
              cp_c = -0.002
          elseif p == 4
              cp_s = -0.001
              cp_c = -0.003
          elseif p == 5
              cp_s = -0.002
              cp_c = -0.004
```

```
          elseif p == 6
              cp_s = -0.004
              cp_c = -0.005
          elseif p == 7
              cp_s = -0.005
              cp_c = -0.007
          elseif p == 8
              cp_s = -0.006
              cp_c = -0.008
          elseif p == 9
              cp_s = -0.007
              cp_c = -0.010
          elseif p == 10
              cp_s = -0.009
              cp_c = -0.011
          elseif p == 11
              cp_s = -0.010
              cp_c = -0.013
          elseif p == 12
              cp_s = -0.011
              cp_c = -0.014
          elseif p == 13
              cp_s = -0.013
              cp_c = -0.015
          elseif p == 14
              cp_s = -0.014
              cp_c = -0.017
          elseif p == 15
              cp_s = -0.016
              cp_c = -0.018
          elseif p == 16
              cp_s = -0.017
              cp_c = -0.020
          end

   reduc=interp1(pp, reduc_data, p) % pest reduction (%) corresponding
to p
   s = round(sqrt (n^2*(p/100)/4)/2) * 2  % Define size of the NCH
squares
   square = [zeros(n/4-s/2,n/2); zeros(s,n/4-s/2) ones(s) zeros(s,n/4-
s/2); zeros(n/4-s/2,n/2)]
   size_of_square = s^2 * dx * dy
   source = square * dx * dy * alpha*(size_of_square)^beta
   shape = square

   totalsource = sum(sum(source))

   fsource = fft2(source)

   impact1 = max(0, real(fftshift(ifft2(fK1 .* fsource))))
   impact2 = real(fftshift(ifft2(fK2 .* fsource)))
   impact3 = real(fftshift(ifft2(fK3 .* fsource)))

   % Balance check: total impact must be equal before and after
distribution over the landscape
   after1 = sum(sum(impact1))
   after2 = sum(sum(impact2))
```

```
   after3 = sum(sum(impact3))
   before = sum(sum(source))
   relerr1 = (after1 - before)/before
   relerr2 = (after2 - before)/before
   relerr3 = (after3 - before)/before
   relimpact1 = impact1/totalsource
   relimpact2 = impact2/totalsource
   relimpact3 = impact3/totalsource

   ic = sum(sum(shape *(-1) + 1))
   crop_impact1 = (shape * (-1) + 1) .* impact1
   crop_impact2 = (shape * (-1) + 1) .* impact2
   crop_impact3 = (shape * (-1) + 1) .* impact3
   tcrop_impact1 = sum(sum(crop_impact1))
   tcrop_impact2 = sum(sum(crop_impact2))
   tcrop_impact3 = sum(sum(crop_impact3))

   r1 = min(1, (reduc * ic / tcrop_impact1) .* crop_impact1 )
   r2 = min(1, (reduc * ic / tcrop_impact2) .* crop_impact2 )
   r3 = min(1, (reduc * ic / tcrop_impact3) .* crop_impact3 )

   pest1 = pest0 * (1 - r1)
   pest2 = pest0 * (1 - r2)
   pest3 = pest0 * (1 - r3)

   dm1 = (d1 * pest1)./(1 + (d1 * pest1 / d2 ))
   dm2 = (d1 * pest2)./(1 + (d1 * pest2 / d2 ))
   dm3 = (d1 * pest3)./(1 + (d1 * pest3 / d2 ))

   y1_s1 = (shape * (-1) + 1) .* (ymax_s * (1 - dm1)) % Actual soybean
yield (bu/ac)
   y1_s2 = (shape * (-1) + 1) .* (ymax_s * (1 - dm2))
   y1_s3 = (shape * (-1) + 1) .* (ymax_s * (1 - dm3))

   spi1_cell1 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s1 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)  % Soybean profit per CELL
   spi1_cell2 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s2 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)
   spi1_cell3 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s3 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)

   cpi1_cell = (shape * (-1) + 1) .* 2.4710439 .* (y0_c * price_c -
pcost_c * (1 + cp_c)) * (dx * dy /10000) % Corn profit given NCH taken
out of production

   rotpi1_cell1 = spi1_cell1 + cpi1_cell  % Profit per soybean-corn
rotation
   rotpi1_cell2 = spi1_cell2 + cpi1_cell
   rotpi1_cell3 = spi1_cell3 + cpi1_cell

   tpi1_farm1 = sum(sum(rotpi1_cell1))   % profit per rotation per farm
   tpi1_farm2 = sum(sum(rotpi1_cell2))
   tpi1_farm3 = sum(sum(rotpi1_cell3))

   tpi1_ls1 = 4* tpi1_farm1     % profit for landscape
   tpi1_ls2 = 4* tpi1_farm2
   tpi1_ls3 = 4* tpi1_farm3
```

```
   % Change in soybean profit at the farm scale from baseline
   change_farm_s1 = ( (sum(sum(spi1_cell1))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s2 = ( (sum(sum(spi1_cell2))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s3 = ( (sum(sum(spi1_cell3))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   % Change in rotation profit at the farm scale from baseline
   change_farm1 = (tpi1_farm1 - tpi0_farm) / tpi0_farm
   change_farm2 = (tpi1_farm2 - tpi0_farm) / tpi0_farm
   change_farm3 = (tpi1_farm3 - tpi0_farm) / tpi0_farm
   % Change in rotation profit at the landscape scale from baseline
   change_ls1 = (tpi1_ls1 - tpi0_ls) / tpi0_ls
   change_ls2 = (tpi1_ls2 - tpi0_ls) / tpi0_ls
   change_ls3 = (tpi1_ls3 - tpi0_ls) / tpi0_ls

   check1 = change_ls1 - change_farm1
   check2 = change_ls2 - change_farm2
   check3 = change_ls3 - change_farm3

% Output
output=[farmingsystem; n; pest0; n_spray; p; reduc; alpha; beta; cp_s;
cp_c; ncadist; change_farm_s1; change_farm_s2; change_farm_s3;
change_farm1; change_farm2; change_farm3;change_ls1; change_ls2;
change_ls3];

fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.2f %12.2f %12.2f %12.2f
%12.4f %12.4f %12.0f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f
%12.4f %12.4f\n', output);

end
end


%%%%%%%%%% Strip %%%%%%%%%%%%%%%%%%%%%%%%%%%
for ncadist = 2   % Landscapes with strip NCH
    for p = 1:1:16
          if p == 1
              cp_s = -0.002
              cp_c = -0.002
          elseif p == 2
              cp_s = -0.004
              cp_c = -0.004
          elseif p == 3
              cp_s = -0.006
              cp_c = -0.006
          elseif p == 4
              cp_s = -0.009
              cp_c = -0.008
          elseif p == 5
              cp_s = -0.011
              cp_c = -0.010
          elseif p == 6
              cp_s = -0.013
              cp_c = -0.012
         elseif p == 7
```

```
              cp_s = -0.015
              cp_c = -0.014
          elseif p == 8
              cp_s = -0.017
              cp_c = -0.016
          elseif p == 9
              cp_s = -0.019
              cp_c = -0.018
          elseif p == 10
              cp_s = -0.021
              cp_c = -0.020
          elseif p == 11
              cp_s = -0.023
              cp_c = -0.022
          elseif p == 12
              cp_s = -0.026
              cp_c = -0.024
          elseif p == 13
              cp_s = -0.028
              cp_c = -0.026
          elseif p == 14
              cp_s = -0.030
              cp_c = -0.028
          elseif p == 15
              cp_s = -0.032
              cp_c = -0.030
          elseif p == 16
              cp_s = -0.034
              cp_c = -0.032
          end

   reduc=interp1(pp, reduc_data, p) % pest reduction (%) corresponding
to p
   w = max(round((n^2 * (p/100)/4)/(n/2)),1)     % Define width of the
strips
   strip = [zeros(n/4-round(w/2),n/2);ones(w,n/2);zeros(n/2-w-(n/4-
round(w/2)),n/2)]
   size_of_strip = w * n/2 * dx * dy
   source = strip * dx * dy * alpha*(size_of_strip)^beta
   shape = strip

   totalsource = sum(sum(source))

   fsource = fft2(source)

   impact1 = max(0, real(fftshift(ifft2(fK1 .* fsource))))
   impact2 = real(fftshift(ifft2(fK2 .* fsource)))
   impact3 = real(fftshift(ifft2(fK3 .* fsource)))

   % Balance check: total impact must be equal before and after
distribution over the landscape
   after1 = sum(sum(impact1))
   after2 = sum(sum(impact2))
   after3 = sum(sum(impact3))
   before = sum(sum(source))
   relerr1 = (after1 - before)/before
   relerr2 = (after2 - before)/before
```

```
   relerr3 = (after3 - before)/before

   relimpact1 = impact1/totalsource
   relimpact2 = impact2/totalsource
   relimpact3 = impact3/totalsource

   ic = sum(sum(shape *(-1) + 1))
   crop_impact1 = (shape * (-1) + 1) .* impact1
   crop_impact2 = (shape * (-1) + 1) .* impact2
   crop_impact3 = (shape * (-1) + 1) .* impact3
   tcrop_impact1 = sum(sum(crop_impact1))
   tcrop_impact2 = sum(sum(crop_impact2))
   tcrop_impact3 = sum(sum(crop_impact3))

   r1 = min(1, (reduc * ic / tcrop_impact1) .* crop_impact1 )
   r2 = min(1, (reduc * ic / tcrop_impact2) .* crop_impact2 )
   r3 = min(1, (reduc * ic / tcrop_impact3) .* crop_impact3 )

   pest1 = pest0 * (1 - r1)
   pest2 = pest0 * (1 - r2)
   pest3 = pest0 * (1 - r3)

   dm1 = (d1 * pest1)./(1 + (d1 * pest1 / d2 ))
   dm2 = (d1 * pest2)./(1 + (d1 * pest2 / d2 ))
   dm3 = (d1 * pest3)./(1 + (d1 * pest3 / d2 ))

   y1_s1 = (shape * (-1) + 1) .* (ymax_s * (1 - dm1))       % Actual
soybean yield (bu/ac)
   y1_s2 = (shape * (-1) + 1) .* (ymax_s * (1 - dm2))
   y1_s3 = (shape * (-1) + 1) .* (ymax_s * (1 - dm3))

   spi1_cell1 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s1 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)  % Soybean profit per CELL
   spi1_cell2 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s2 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)
   spi1_cell3 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s3 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)

   cpi1_cell = (shape * (-1) + 1) .* 2.4710439 .* (y0_c * price_c -
pcost_c * (1 + cp_c)) * (dx * dy /10000) % Corn profit given NCH taken
out of production

   rotpi1_cell1 = spi1_cell1 + cpi1_cell  % Profit per soybean-corn
rotation
   rotpi1_cell2 = spi1_cell2 + cpi1_cell
   rotpi1_cell3 = spi1_cell3 + cpi1_cell

   tpi1_farm1 = sum(sum(rotpi1_cell1))   % profit per rotation per farm
   tpi1_farm2 = sum(sum(rotpi1_cell2))
   tpi1_farm3 = sum(sum(rotpi1_cell3))

   tpi1_ls1 = 4* tpi1_farm1     % profit for landscape
   tpi1_ls2 = 4* tpi1_farm2
   tpi1_ls3 = 4* tpi1_farm3

   % Change in soybean profit at the farm scale from baseline
```

```
   change_farm_s1 = ( (sum(sum(spi1_cell1))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s2 = ( (sum(sum(spi1_cell2))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s3 = ( (sum(sum(spi1_cell3))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   % Change in rotation profit at the farm scale from baseline
   change_farm1 = (tpi1_farm1 - tpi0_farm) / tpi0_farm
   change_farm2 = (tpi1_farm2 - tpi0_farm) / tpi0_farm
   change_farm3 = (tpi1_farm3 - tpi0_farm) / tpi0_farm
   % Change in rotation profit at the landscape scale from baseline
   change_ls1 = (tpi1_ls1 - tpi0_ls) / tpi0_ls
   change_ls2 = (tpi1_ls2 - tpi0_ls) / tpi0_ls
   change_ls3 = (tpi1_ls3 - tpi0_ls) / tpi0_ls

   check1 = change_ls1 - change_farm1
   check2 = change_ls2 - change_farm2
   check3 = change_ls3 - change_farm3

% Output
output=[farmingsystem; n; pest0; n_spray; p; reduc; alpha; beta; cp_s;
cp_c; ncadist; change_farm_s1; change_farm_s2; change_farm_s3;
change_farm1; change_farm2; change_farm3;change_ls1; change_ls2;
change_ls3];

fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.2f %12.2f %12.2f %12.2f
%12.4f %12.4f %12.0f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f
%12.4f %12.4f\n', output);

end
end


%%%%%%%%%% Archipelago %%%%%%%%%%%%%%%%%%%%%%%%%%
for ncadist = 3   % Landscapes with archipelago NCH
     for p = 1:1:16
          if p == 1
              cp_s = 0.12
              cp_c = 0.084
          elseif p == 2
              cp_s = 0.239
              cp_c = 0.168
          elseif p == 3
              cp_s = 0.359
              cp_c = 0.252
          elseif p == 4  %
              cp_s = 0.479
              cp_c = 0.337
          elseif p == 5
              cp_s = 0.598
              cp_c = 0.421
          elseif p == 6
              cp_s = 0.718
              cp_c = 0.505
          elseif p == 7
              cp_s = 0.837
              cp_c = 0.589
```

```
            elseif p == 8
                cp_s = 0.957
                cp_c = 0.673
            elseif p == 9
                cp_s = 1.077
                cp_c = 0.757
            elseif p == 10
                cp_s = 1.196
                cp_c = 0.841
            elseif p == 11
                cp_s = 1.316
                cp_c = 0.926
            elseif p == 12
                cp_s = 1.436
                cp_c = 1.010
            elseif p == 13
                cp_s = 1.555
                cp_c = 1.094
            elseif p == 14
                cp_s = 1.675
                cp_c = 1.178
            elseif p == 15
                cp_s = 1.794
                cp_c = 1.262
            elseif p == 16
                cp_s = 1.914
                cp_c = 1.346
            end

   reduc=interp1(pp, reduc_data, p) % pest reduction (%) corresponding
to p

   for i=1:(n/2)
       for j=1:(n/2)
           archip(i,j)=(rand(1)< (p/100));
       end
   end
           archip
           source = archip * dx * dy * alpha*(dx*dy)^beta
           shape = archip

   totalsource = sum(sum(source))

   fsource = fft2(source)

   impact1 = max(0, real(fftshift(ifft2(fK1 .* fsource))))
   impact2 = real(fftshift(ifft2(fK2 .* fsource)))
   impact3 = real(fftshift(ifft2(fK3 .* fsource)))

   % Balance check: total impact must be equal before and after
distribution over the landscape
   after1 = sum(sum(impact1))
   after2 = sum(sum(impact2))
   after3 = sum(sum(impact3))
   before = sum(sum(source))
   relerr1 = (after1 - before)/before
   relerr2 = (after2 - before)/before
```

```
   relerr3 = (after3 - before)/before

   relimpact1 = impact1/totalsource
   relimpact2 = impact2/totalsource
   relimpact3 = impact3/totalsource

   ic = sum(sum(shape *(-1) + 1))
   crop_impact1 = (shape * (-1) + 1) .* impact1
   crop_impact2 = (shape * (-1) + 1) .* impact2
   crop_impact3 = (shape * (-1) + 1) .* impact3
   tcrop_impact1 = sum(sum(crop_impact1))
   tcrop_impact2 = sum(sum(crop_impact2))
   tcrop_impact3 = sum(sum(crop_impact3))

   r1 = min(1, (reduc * ic / tcrop_impact1) .* crop_impact1 )
   r2 = min(1, (reduc * ic / tcrop_impact2) .* crop_impact2 )
   r3 = min(1, (reduc * ic / tcrop_impact3) .* crop_impact3 )

   pest1 = pest0 * (1 - r1)
   pest2 = pest0 * (1 - r2)
   pest3 = pest0 * (1 - r3)

   dm1 = (d1 * pest1)./(1 + (d1 * pest1 / d2 ))
   dm2 = (d1 * pest2)./(1 + (d1 * pest2 / d2 ))
   dm3 = (d1 * pest3)./(1 + (d1 * pest3 / d2 ))

   y1_s1 = (shape * (-1) + 1) .* (ymax_s * (1 - dm1))       % Actual
soybean yield (bu/ac)
   y1_s2 = (shape * (-1) + 1) .* (ymax_s * (1 - dm2))
   y1_s3 = (shape * (-1) + 1) .* (ymax_s * (1 - dm3))

   spi1_cell1 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s1 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)  % Soybean profit per CELL
   spi1_cell2 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s2 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)
   spi1_cell3 = (shape * (-1) + 1) .* 2.4710439 .* (y1_s3 * price_s -
pcost_s * (1 + cp_s)) * (dx * dy / 10000)

   cpi1_cell = (shape * (-1) + 1) .* 2.4710439 .* (y0_c * price_c -
pcost_c * (1 + cp_c)) * (dx * dy /10000) % Corn profit given NCH taken
out of production

   rotpi1_cell1 = spi1_cell1 + cpi1_cell  % Profit per soybean-corn
rotation
   rotpi1_cell2 = spi1_cell2 + cpi1_cell
   rotpi1_cell3 = spi1_cell3 + cpi1_cell

   tpi1_farm1 = sum(sum(rotpi1_cell1))   % profit per rotation per farm
   tpi1_farm2 = sum(sum(rotpi1_cell2))
   tpi1_farm3 = sum(sum(rotpi1_cell3))

   tpi1_ls1 = 4* tpi1_farm1     % profit for landscape
   tpi1_ls2 = 4* tpi1_farm2
   tpi1_ls3 = 4* tpi1_farm3

   % Change in soybean profit at the farm scale from baseline
```

```
   change_farm_s1 = ( (sum(sum(spi1_cell1))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s2 = ( (sum(sum(spi1_cell2))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   change_farm_s3 = ( (sum(sum(spi1_cell3))) - (sum(sum(spi0_cell))) )
/ (sum(sum(spi0_cell)))
   % Change in rotation profit at the farm scale from baseline
   change_farm1 = (tpi1_farm1 - tpi0_farm) / tpi0_farm
   change_farm2 = (tpi1_farm2 - tpi0_farm) / tpi0_farm
   change_farm3 = (tpi1_farm3 - tpi0_farm) / tpi0_farm
   % Change in rotation profit at the landscape scale from baseline
   change_ls1 = (tpi1_ls1 - tpi0_ls) / tpi0_ls
   change_ls2 = (tpi1_ls2 - tpi0_ls) / tpi0_ls
   change_ls3 = (tpi1_ls3 - tpi0_ls) / tpi0_ls

   check1 = change_ls1 - change_farm1
   check2 = change_ls2 - change_farm2
   check3 = change_ls3 - change_farm3

% Output
output=[farmingsystem; n; pest0; n_spray; p; reduc; alpha; beta; cp_s;
cp_c; ncadist; change_farm_s1; change_farm_s2; change_farm_s3;
change_farm1; change_farm2; change_farm3;change_ls1; change_ls2;
change_ls3];

fprintf(fid,'%12.0f %12.0f %12.0f %12.0f %12.2f %12.2f %12.2f %12.2f
%12.4f %12.4f %12.0f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f %12.4f
%12.4f %12.4f\n', output);

end
end


end
```

Appendix C:
Estimated relationship between the pest reduction impact and the proportion of non-crop habitats in the landscape

Aphid density (aphids/m^2)[a]	Proportion of non-crop habitats in landscape	Proportion of reduction in aphid density as compared to the case when the proportion of non-crop habitats in landscape is 0.01[b]
4600	0.01	0
3400	0.04	0.26
1533	0.09	0.67
0	0.16	1

[a] Aphid density in wheat at the time of harvest (Julian date 230). Data source: Bianchi and van der Werf, 2003

[b] Calculated by author.

Appendix D:
Proportion of change in variable costs of production due to the establishment of non-crop habitats (Lambda)

Square

prop_ NCH	# of strips in NCH	# of strips outside NCH	# of turns	proportion of total field time	coef of machinery cost	Lambda (organic corn)	Lambda (conv corn)	Lambda (organic soy)	Lambda (conv soy)
0	0	400	399	0.15	1	0.00	0.00	0.00	0.00
0.01	40	360	439	0.17	1.02	0.00	0.00	0.01	0.00
0.02	57	343	456	0.17	1.02	0.01	0.00	0.01	0.00
0.03	69	331	468	0.18	1.03	0.01	0.00	0.01	0.00
0.04	80	320	479	0.18	1.03	0.01	0.00	0.01	0.00
0.05	89	311	488	0.18	1.03	0.01	0.00	0.01	0.00
0.06	98	302	497	0.19	1.04	0.01	-0.01	0.01	0.00
0.07	106	294	505	0.19	1.04	0.00	-0.01	0.01	0.00
0.08	113	287	512	0.19	1.04	0.00	-0.01	0.01	-0.01
0.09	120	280	519	0.20	1.05	0.00	-0.01	0.01	-0.01
0.1	126	274	525	0.20	1.05	0.00	-0.01	0.01	-0.01
0.11	133	267	532	0.20	1.05	0.00	-0.01	0.01	-0.01
0.12	139	261	538	0.20	1.05	0.00	-0.01	0.01	-0.01
0.13	144	256	543	0.20	1.05	0.00	-0.02	0.01	-0.01
0.14	150	250	549	0.21	1.06	0.00	-0.02	0.01	-0.01
0.15	155	245	554	0.21	1.06	0.00	-0.02	0.01	-0.02
0.16	160	240	559	0.21	1.06	0.00	-0.02	0.01	-0.02

Appendix D (cont'd):
Proportion of change in variable costs of production due to the establishment of non-crop habitats (Lambda)

Strip									
prop_ NCH	# of strips in NCH	# of strips outside NCH	# of turns	proportion of total field time	coef of machinery cost	Lambda (organic corn)	Lambda (conv corn)	Lambda (organic soy)	Lambda (conv soy)
0	0	400	399	0.15	1	0.00	0.00	0.00	0.00
0.01	4	396	395	0.15	1	0.00	0.00	0.00	0.00
0.02	8	392	391	0.15	1	0.00	0.00	-0.01	0.00
0.03	12	388	387	0.15	1	-0.01	-0.01	-0.01	-0.01
0.04	16	384	383	0.14	0.99	-0.01	-0.01	-0.01	-0.01
0.05	20	380	379	0.14	0.99	-0.01	-0.01	-0.01	-0.01
0.06	24	376	375	0.14	0.99	-0.01	-0.01	-0.02	-0.01
0.07	28	372	371	0.14	0.99	-0.02	-0.01	-0.02	-0.01
0.08	32	368	367	0.14	0.99	-0.02	-0.02	-0.02	-0.02
0.09	36	364	363	0.14	0.99	-0.02	-0.02	-0.02	-0.02
0.1	40	360	359	0.13	0.98	-0.02	-0.02	-0.03	-0.02
0.11	44	356	355	0.13	0.98	-0.02	-0.02	-0.03	-0.02
0.12	48	352	351	0.13	0.98	-0.03	-0.02	-0.03	-0.03
0.13	52	348	347	0.13	0.98	-0.03	-0.03	-0.04	-0.03
0.14	56	344	343	0.13	0.98	-0.03	-0.03	-0.04	-0.03
0.15	60	340	339	0.13	0.98	-0.03	-0.03	-0.04	-0.03
0.16	64	336	335	0.13	0.98	-0.03	-0.03	-0.04	-0.03

Appendix D (cont'd): Proportion of change in variable costs of production due to the establishment of non-crop habitats (Lambda)

Archipelago								
prop_ NCH	number of NCH cells	Number of turns	proportion of total field time	coef of machinery cost	Lambda (organic corn)	Lambda (conv corn)	Lambda (organic soy)	Lambda (conv soy)
0	0	399	0.15	1	0.00	0.00	0.00	0.00
0.01	1600	1999	0.75	1.60	0.24	0.08	0.37	0.12
0.02	3200	3599	1.35	2.20	0.47	0.17	0.75	0.24
0.03	4800	5199	1.95	2.80	0.71	0.25	1.12	0.36
0.04	6400	6799	2.56	3.41	0.95	0.34	1.50	0.48
0.05	8000	8399	3.16	4.01	1.19	0.42	1.87	0.60
0.06	9600	9999	3.76	4.61	1.42	0.50	2.24	0.72
0.07	11200	11599	4.36	5.21	1.66	0.59	2.62	0.84
0.08	12800	13199	4.96	5.81	1.90	0.67	2.99	0.96
0.09	14400	14799	5.56	6.41	2.13	0.76	3.37	1.08
0.1	16000	16399	6.17	7.02	2.37	0.84	3.74	1.20
0.11	17600	17999	6.77	7.62	2.61	0.93	4.12	1.32
0.12	19200	19599	7.37	8.22	2.85	1.01	4.49	1.44
0.13	20800	21199	7.97	8.82	3.08	1.09	4.86	1.56
0.14	22400	22799	8.57	9.42	3.32	1.18	5.24	1.67
0.15	24000	24399	9.17	10.02	3.56	1.26	5.61	1.79
0.16	25600	25999	9.77	10.62	3.79	1.35	5.99	1.91

Appendix E:
Production costs by farming system and crop

Soybean

	Machinery (repair, fuel and hire) ($/ha)	Seed ($/ha)	VC ($/ha)	Proportion of machinery cost in VC	Proportion of seed cost in VC
Organic	162.5	47.5	260	0.63	0.18
Conv	52.5	47.5	260	0.20	0.18

Corn

	Machinery (repair, fuel and hire) ($/ha)	Seed ($/ha)	VC ($/ha)	Proportion of machinery cost in VC	Proportion of seed cost in VC
Organic	187.5	75	472.5	0.40	0.16
Conv	70	87.5	490	0.14	0.18

Source: UIUC, 2003.