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Spatially optimal habitat management for enhancing natural control of an invasive agricultural pest: Soybean aphid[☆]

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ABSTRACT

By their direct effects on private profitability, invasive agricultural pests create special incentives for management that set them apart from other categories of invasive species. One attractive nonchemical management approach for agricultural pests relies upon biological control by natural enemies. By improving the habitat of natural enemies of invasive agricultural pests, biological pest control can become privately attractive. This study develops a spatial optimization model to explore economically optimal spatial configuration of natural enemy habitat in agricultural landscapes. The model is applied to the management of soybean aphid (*Aphis glycines*), a recent invasive pest species of soybean production systems in the North Central region of the United States. Results indicate that non-crop habitat management can be a promising pest management option for organic cropping systems. Under current prices, however, habitat management tends to reduce net returns for conventional farms. Both area and configuration of non-crop habitats affect economic performance, with the greatest value coming from small, scattered areas of habitat.

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1. Introduction

Viable tactics for managing invasive species (IS) once they have successfully established depend upon their biology and available management approaches. In the ways that they affect humans and the incentives for management, invasive agricultural pests stand apart from many other IS. Invasive agricultural pests affect humans via economic damage to crops and livestock. The impact on a marketed product creates a direct incentive for private action to manage the pest. Moreover, farmers are trained and equipped for pest management. Management of invasive agricultural pests poses unique challenges as compared to native pest species, as the invasion often requires tailoring existing control means or identification of new tactics. By contrast, native pest outbreaks often result from unusual breakdown of a previously balanced system, so re-establishing the system balance is often a feasible and natural choice of control strategy. This study explores the economic potential of an ecological approach to invasive agricultural pest control that relies on habitat management to enhance the population of natural enemies. Concepts are illustrated with a quantitative analysis of the case of soybean aphid (*Aphis glycines*), a major new invasive pest species of soybean in the North Central region of the United States.

Natural enemies provide important ecosystem services to agriculture by mitigating yields losses as a result of pest damage (Naylor and Ehrlich, 1997). Less visibly, they also prevent herbivore insects from reaching pest status (Losey and Vaughan, 2006). To perform this function effectively, natural enemies depend on resources such as food for adults, alternative prey or hosts, hibernation sites and shelter from adverse conditions (Landis et al., 2000). Habitat management (HM) is a form of conservation biological control that aims to create a suitable ecological infrastructure within the agricultural landscape to provide needed habitat resources and functions (Landis et al., 2000). HM designed to meet the needs of natural enemies of crop pests can attract species that offer the ecosystem service of natural biocontrol. In particular, relatively undisturbed non-crop habitats (NCH), such as hedgerows and woodlots in agricultural landscapes, typically support a higher degree of biodiversity providing natural pest control than do crop systems (Bianchi et al., 2006). Empirical evidence from recent ecological research shows that pest suppression is positively correlated with the proportion of NCH in the landscape (Thies and Tscharrntke, 1999; Thies et al., 2003). As the limitations and social and environmental costs of the traditional insecticide-based pest management approach have been increasingly recognized (Naylor and Ehrlich, 1997), there has been growing interest in HM as a potential alternative to achieve sustainable pest management (Barbosa, 1998).

Soybean aphid (SBA) invaded the soybean production systems of United States in 2000 and has since quickly spread over the North Central region. The species is capable of causing extensive damage to soybean yield, valued in total at \$0.6–2.6 billion over 2003–2017 (Song and Swinton, 2008). Since its invasion, SBA has prompted farmers to perform extensive spraying of soybean acreage, making it one of the key drivers of insecticide use in the region (Smith and Pike, 2002; Song and Swinton, 2008). The management of SBA is thus of both economic and environmental importance to the region.

As a privately manageable invasive agricultural pest, SBA offers a unique case to study IS management. Unlike native pest species, some agricultural pests IS lack natural enemies and their populations can increase and spread to damaging levels that are difficult and costly to eradicate (USDA-ERS, 2007). For the specific case of SBA, existing natural enemies play a key role in suppressing SBA populations in North America (Berg et al., 1997; Aponte and Calvin, 2004; Fox et al., 2004; Landis et al., 2004; Rutledge et al., 2004; Costamagna and Landis, 2006). In particular, generalist predators of the lady beetle family (*Coccinellidae*) provide strong, season-long suppression, protecting soybean biomass and yield from SBA damage (Costamagna et al., 2007a). They include a mix of native (e.g., the convergent lady beetle, *Hippodamia convergens*) and exotic species (e.g., the multicolored Asian lady beetle, *Harmonia axyridis*, and the seven-spotted lady beetle, *Coccinella septempunctata*).

The seven-spotted lady beetle was repeatedly introduced to North America from Europe for the biological control of aphids (Weeden et al., 2007) and depends on non-crop landscape elements, such as hedgerows, for hibernation (Bianchi and van der Werf, 2003). The multicolored Asian lady beetle made its way into the United States through a number of accidental and planned releases as a biological control agent to control aphids and other soft-bodied insects (Jones and Boggs, 2008). While they seek overwintering sites in and around buildings due to the lack of natural hibernation

(overwintering) sites (i.e., cracks and crevices within cliff faces) that are prevalent in their native habitat (Jones and Boggs, 2008), they obtain critical nutrition from plant-provided resources, especially during periods of prey scarcity (Landis et al., 2005). Both species are considered more effective predators than the native lady beetle species (Jones and Boggs, 2008; Weeden et al., 2007). Landscapes vary in their suitability for natural enemy species, and understanding how habitats can be established within agricultural landscapes to influence pest suppression is critical to successfully managing invaders in their non-native range (Gardiner et al., 2009).

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 been developed on “reserve site selection” for maximum species conservation, given constraints on budget or on the number of sites allowed [see review in Nalle et al. (2004)]. Application of the approach in economics has been relatively limited, 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 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. 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. No economic studies, however, have examined the optimal spatial configuration of natural enemy habitat in agricultural landscapes.

Using a spatially explicit simulation model, Bianchi and van der Werf (2003) find that shape, area, and fragmentation of NCH elements can have important effects on the control of aphids by seven-spotted lady beetle. In particular, they find that aphid control is achieved the best in landscapes with a substantial area of NCH and where these habitats are evenly distributed at a fine spatial grain 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 opportunity cost of giving up income from currently farmed lands to increase habitat area for natural enemies, as well as the increased production costs of farming fragmented fields.

As compared to budgetary analyses of field-level HM practices [e.g., see Barbosa (1998)], spatial bioeconomic modeling is more suitable for exploring the economics of spatially optimal management of NCH at larger scales (such as farm and landscape), taking into account various production systems and key spatial, ecological, and economic characteristics. This study develops a spatial optimization model to explore spatial manipulation of NCH in a simulated landscape. The model optimizes private producers’ 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 used). The results provide insight on agricultural land use choices with regard to using NCH to control invasive agricultural pests. Specifically, the study attempts to address three questions: (i) What is the economically optimal proportion and spatial configuration of NCH for natural enemies of invasive agricultural pest species? (ii) How do economically optimal outcomes differ between conventional and organic farming systems? and (iii) What factors most influence the economically optimal size and configuration of NCH?

Following this section, we present a spatial optimization model that 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, based on the natural population control of SBA by lady beetles. We then report results of the numerical analysis, followed by a sensitivity analysis that addresses parameter uncertainties. Finally, we highlight the contributions to research into invasive species management, identifying limitations and future research directions.

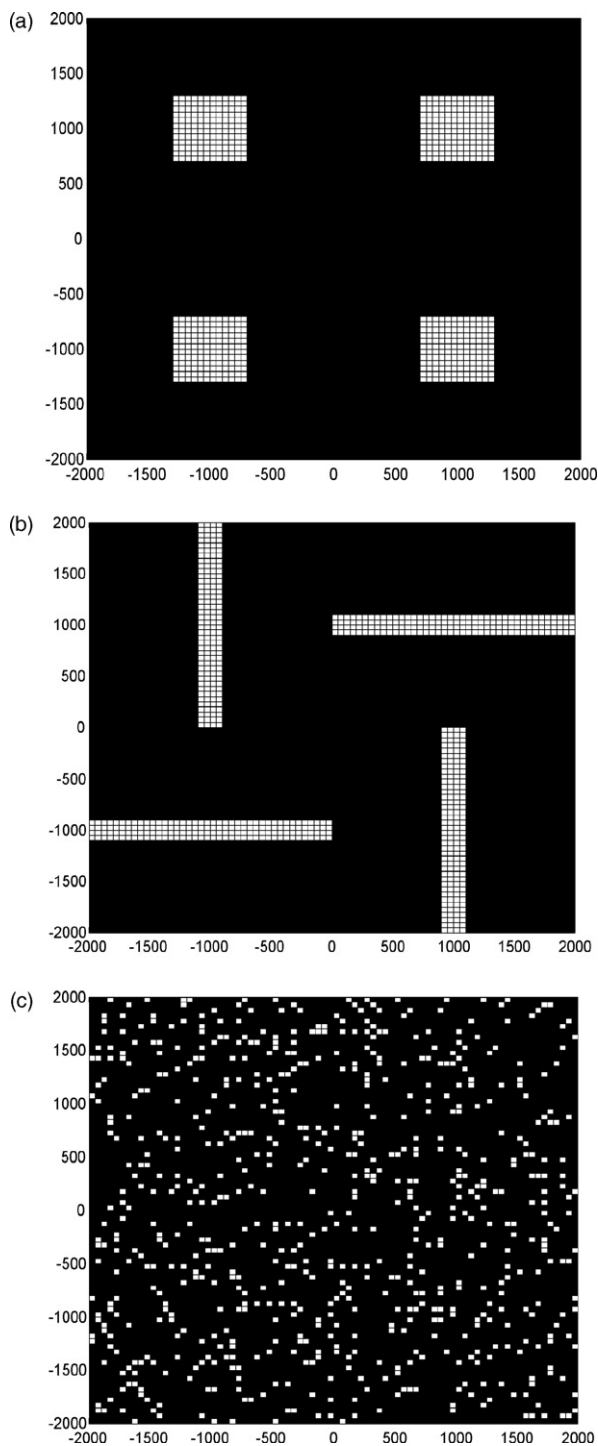


Fig. 1. Illustration of landscape configuration with four farms and three NCH configurations (prepared in 80×80 grid and with $prop_NCH=0.1$): (a) square, (b) strip, and (c) archipelago.

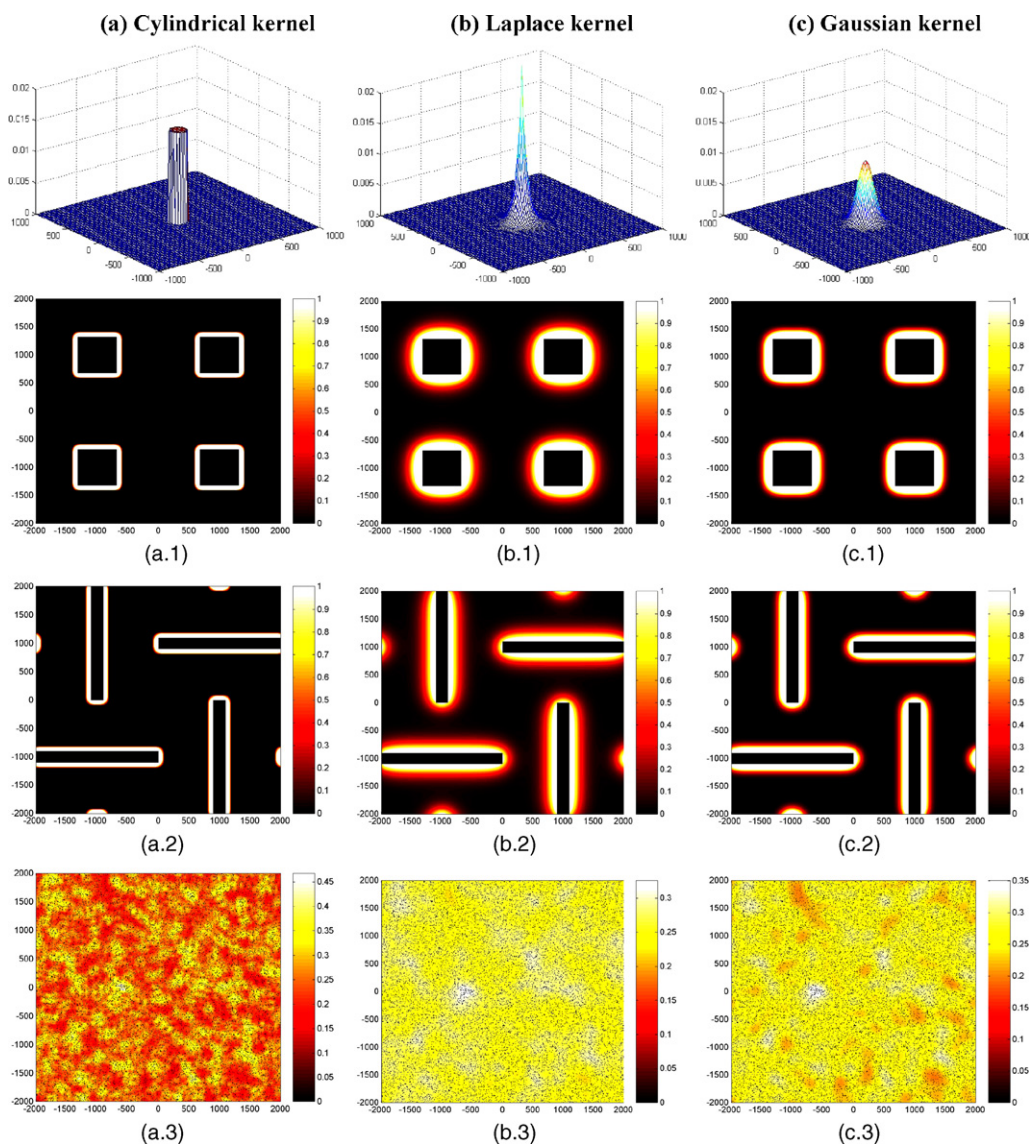


Fig. 2. Illustration of distribution kernels (prepared in 200×200 grid) and distributions of pest control impact (proportion of reduction, prepared with $prop_NCH=0.1$ in a 400×400 grid): (a) cylindrical kernel (radius=100m), (b) Laplace kernel ($\alpha=0.02\text{ m}^{-1}$), and (c) Gaussian kernel ($\theta=80\text{m}$); (1) square, (2) strip, and (c) archipelago.

2. Spatial optimization model

This study develops an agricultural land use choice model that focuses on the function of NCH as the source origin of natural enemies, from which pest regulation services are dispersed into surrounding crop fields, resulting in spatially linked crop yield damage protection at each point in the affected crop fields. For instance, by providing hibernation sites for the seven-spotted lady beetles, NCH act as source of natural control services. The model 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 and (ii) an economic module for evaluating the net return to fixed factors of crop production, given a configuration of crop vs NCH land. The two models are coupled with an optimization method that finds the land configuration that is most economically desirable among the patterns considered.

We apply the model to a simple agricultural landscape composed of 1600 ha ($4000\text{m} \times 4000\text{m}$) of square cells or land parcels, arranged in a 800×800 grid ($n=800$) with each cell being 25m^2 in size (Fig. 1). 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 a size of 400 ha (about 988 acres), arranged in a 2×2 checkerboard (Fig. 1). We assume that rational economic agents would consider only a selected set of land configuration options regarding the shape and location of NCH elements. 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 spillover across the edges of the farm is minimized and the farm enjoys as much of the services as possible.

We consider three shape options: squares, strips, and archipelago. In the square distribution (Fig. 1a), there is a square of s by s NCH cells in the center of each farm. In the strip configuration (Fig. 1b), a strip of width w (counted in cells) runs through the north–south 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 $1-prop_NCH$) (Fig. 1c). Fig. 1 illustrates the case where $prop_NCH$ is set to 0.1, although in the model the proportion is determined endogenously. The use of selected configuration options effectively simplifies the optimization problem, making it possible to focus the optimization on the area of NCH (or $prop_NCH$) and choice among three distribution patterns of NCH elements.

2.1. Ecological module for the distribution of pest control services

We assume predator density (or the services provided) is independent of the area of each NCH element (no scale dependence). Assuming there is one unit 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,

$$\text{Services per NCH element} = (\text{Density of pest control services}) \times (\text{Area of NCH element})$$

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 three options of distribution kernels (Fig. 2): (i) vertical cylinder (Fig. 2a) with a probability density equal to $1/\pi r^2$ within a radius r from the source, and 0 elsewhere

$$K(x, y) = \begin{cases} 1/\pi r^2 & \text{for } \sqrt{x^2 + y^2} \leq r \\ 0 & \text{for } \sqrt{x^2 + y^2} > r \end{cases} \quad (1)$$

(ii) rotated exponential (Laplace) kernel (Fig. 2b)

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

where α is the slope of the decline of allocated services with distance, and (iii) two-dimensional normal (Gaussian) kernel (Fig. 2c)

$$K(x, y) = \frac{1}{2\pi\theta^2} e^{-[(x^2 + y^2)/2\theta^2]} \quad (3)$$

where θ represents the standard deviation. The mean dispersal distance in the plane is $2/3r$ for a cylindrical kernel, $2/\alpha$ for a Laplace kernel, and $\theta\sqrt{\pi/2}$ for a Gaussian kernel (Skelsey et al., 2005). 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 lady beetles (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.

IS pest control impact per unit of NCH is measured in percentage reduction in pest density per unit area of crop area. The impact is proportional to NCH area. We estimate the relationship between the average percentage 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), who modeled the interaction between aphids in wheat and the seven-spotted lady beetle on the basis of a quantitative, process-based account of the underlying dynamic predator prey interaction. The end result of these simulations is presented as a relationship between the proportion of NCH in the landscape, and the total amount of impact (pest pressure reduction) that is allocated to surrounding crops (Fig. 3). The seven-spotted lady beetle is a major contributor to the natural suppression of SBA (Costamagna et al., 2008), and it is assumed here that the results for this predator in the study of Bianchi and van der Werf (2003) provide a useful proxy for natural predator effects in the SBA–lady beetle system. Although the scale of the landscape simulated in Bianchi and van der Werf (2003) is smaller than the one defined in our model, 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 lady beetle predation. Fig. 2 renders graphical illustrations of the distribution of pest control services from various distribution patterns of NCH when the landscape area devoted to NCH is exogenously set at 10%. The axes represent distance (in meters), and the shades indicate the proportion of pest population reduction, with lighter color representing higher level of pest control.

2.2. Economic module for the evaluation of land use decisions

Pest management practices vary by farming system. We consider two farming systems: conventional and organic. Certified organic farms typically rotate at least one other crop with soybean (Delate et al., 2003). We therefore model soybean and corn in alternate-year rotation on both the conventional and the organic farms in order to allow direct comparison between the systems. Our analysis assumes that the farm grows one crop at a time, although the model implicitly treats all cropland as if it were evenly divided between corn and soybean. Among other things, the soybean–corn rotation implies that the opportunity cost of setting aside land to provide pest control services for soybean carries over to the corn crop, making NCH more expensive, especially if the corn does not benefit from the NCH.

In the baseline scenario, we assume that on a conventional farm insecticides are used to control invasive SBA, whereas on an organic farm, the pest goes untreated because synthetic insecticides are not allowed. Under HM, both farming systems rely on NCH to control SBA.

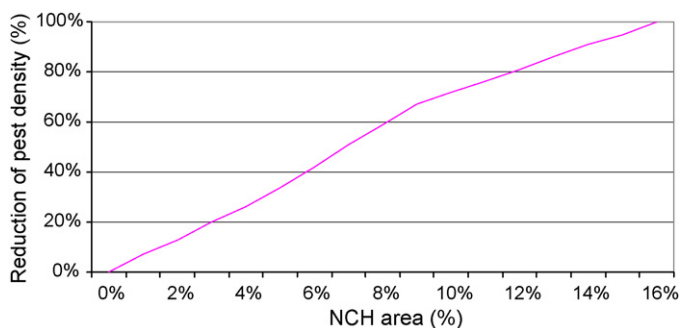


Fig. 3. The relationship between the NCH area and the average pest reduction impact (estimated from Bianchi and van der Werf, 2003).

To assess the land configurations under HM, we refer to relative economic performance of HM as compared to the baseline for each farming system. The economic objective of the farmer is to choose the area and shape of NCH to maximize the proportion of change in net return to fixed factors from the baseline (nr):

$$nr = \frac{NR_{NCH} - NR_{base}}{NR_{base}} = \frac{(NR_{NCH_soy} + NR_{NCH_corn}) - (NR_{base_soy} + NR_{base_corn})}{(NR_{base_soy} + NR_{base_corn})} \quad (4)$$

where the net returns to fixed factors (NR) for one soybean–corn rotation cycle are given as follows:

$$\text{Baseline : } NR_{base} = NR_{base_soy} + NR_{base_corn} \quad (5)$$

$$\text{HM : } NR_{NCH} = NR_{NCH_soy} + NR_{NCH_corn} \quad (6)$$

We define the baseline net return for soybean as

$$NR_{base_soy} = [p_{soy} \times y_{base_soy} - VC_{soy} - TCost_{spray}] \times Area_{total} \quad (7)$$

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 $TCost_{spray}$ represents the cost of SBA control ($TCost_{spray} = Cost_{spray} \times Number_of_sprays$). 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 hyperbolic yield function (Cousens, 1985):

$$y_{base_soy} = y_{soy_max} \left(1 - \frac{\eta[(1 - Efficacy_{spray}) pest_{initial}]}{1 + \eta[(1 - Efficacy_{spray}) pest_{initial}]/\mu} \right) \quad (8)$$

where y_{soy_max} is the maximum (pest-free) yield potential, $Efficacy_{spray}$ is the efficacy rate of SBA insecticides measured in terms of percent of pests killed by each spray, $pest_{initial}$ is the average untreated initial infestation pest density level, 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 across crop cells, y_{base_soy} is a scalar. Similarly, the baseline net return for corn is given by:

$$NR_{base_corn} = [p_{corn} \times y_{base_corn} - VC_{corn}] \times Area_{total} \quad (9)$$

The net return for soybean under HM is:

$$NR_{NCH_soy} = \sum_{l=1}^{Area_{soy}} [p_{soy} \times y_{NCH_soy,l} - (1 + \lambda) \times VC_{soy}] \quad (10)$$

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, $Area_{soy}$ denotes the area of land devoted to soybean production, and $Area_{soy} = (Area_{total} - Area_{NCH})$, where $Area_{NCH}$ denotes the area of NCH (represented by the number of NCH cells). The summation operator in Eq. (10) 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 Eq. (8). Soybean yield in crop cell l (ton/cell), $y_{NCH_soy,l}$, thus is described by the hyperbolic yield function (Cousens, 1985):

$$y_{NCH_soy,l} = y_{soy_max} \left(1 - \frac{\eta[(1 - \omega_l) pest_{initial}]}{1 + \eta[(1 - \omega_l) pest_{initial}]/\mu} \right) \quad (11)$$

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:

$$NR_{NCH_corn} = [p_{corn} \times y_{base_corn} - (1 + \lambda) \times VC_{corn}] \times (Area_{total} - Area_{NCH}) \quad (12)$$

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 of the enduring 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 in Eqs. (5)–(12) 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.

3. Numerical analysis

3.1. Parameters

Table 1 summarizes parameters used in the numerical analysis along with their sources, including statistical estimations from field and secondary data, as well as values drawn from the literature. We use the simulation model developed by Costamagna et al. (2007b) to calculate average predation-free SBA population densities (aphids/plant) for the five soybean plant growth stages after flowering begins (denoted R1–R5). The model was run using three levels of pest density starting values (30, 47 and 73 aphids/plant at the beginning of stage R1) from Michigan field observations in 2005–2006.¹ 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 (12,000 aphids/plant). The assumption is made based on results from Zhang (2007), which suggest that when predators are absent, soybeans be sprayed twice for mean aphid density in stage R1 that is greater than or equal to 120 per plant, and once otherwise. This study rounds that value to 100, which corresponds to average density of 12,000 aphids/plant for the entire period of stages R1–R5.

Reliance on NCH imposes two important kinds of costs. The opportunity cost of foregone income from cropland that could be producing a marketable crop can be estimated as the product of NCH area and net return per unit area, had the land been used for crop production. The variable cost of managing more fragmented cropland is more complicated. Central to the increased cost of fields containing fragmented NCH is 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 m per crop strip (consistent with a 6 row planter), we first estimate the number of crop strips based on the assumed field area and strip width to approximate the number of turns needed with and without NCH for all configurations and values of $prop_NCH$ considered.² Assuming that 15% of machinery field time is spent on turning when no NCH is present, any change in the number of turns made to accommodate NCH can be converted to a change in the total amount of machinery time.

Using production cost data for each crop reported in UIUC (2003) (Table 1), we estimate the change in variable costs of production (λ) due to change in machinery field time, accounting also for cost savings from averted crop planting costs on NCH. The custom hire machinery cost includes repair, fuel, and hire cost (UIUC, 2003). Field re-configuration can induce both positive and negative changes in the variable costs of production, depending on the configuration 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. For example, at 1% of NCH, variable costs scarcely change for the square and strip shapes of NCH. By contrast, for the archipelago configuration, 1% of NCH raises variable costs by 37% for organic soybean production, 24% for organic corn production, 12% for conventional soybean production, and 8% for conventional corn production.

3.2. Optimal configuration of non-crop habitat (NCH)

In the baseline, pesticide control proves to be cost-effective for conventional farms, saving 95–91% of the pest-free level of net return to fixed factors for the soybean–corn rotation. By contrast, organic farms suffer a significant 38–50% reduction in net returns, depending on the level of uncontrolled pest infestation. The organic farms have a much higher stake than the conventional

¹ Data provided by A. Costamagna, graduate research assistant, and C.D. DiFonzo, associate professor, Department of Entomology, Michigan State University.

² 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.

Table 1
Values of parameters used in the numerical analysis.

| Parameters | Values | Sources |
|---|---|---|
| η : proportion of yield lost per unit of pest population | 0.00026 | Estimated from Michigan field data for 2005 provided by C.D. DiFonzo |
| μ : maximum allowable yield loss | 1 | Model restriction |
| p_{soy} conventional | \$247.9/ton ^a | 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_{soy_max} conventional | 3.08 ton/ha | UIUC (2003) Food-Grade |
| y_{soy_max} organic | 2.45 ton/ha | UIUC (2003) Food-Grade |
| y_{corn_max} conventional | 10.85 ton/ha | UIUC (2003) Regular hybrid |
| y_{corn_max} 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–R5) | 5000 (low), 8000 (medium), and 12,000 (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 and Swinton (2008) |
| $Number_of_sprays$ | 1 for low, medium infestation; 2 for high infestation | Adapted from results in Zhang (2007) |
| $Efficacy_{spray}$: efficacy rate of soybean aphid insecticides | 0.99 | Assumed |
| r : radius of cylindrical kernel | 150 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 Fig. 3 | Estimated from simulation results from Bianchi and van der Werf (2003) |
| λ : proportion of change in variable costs due to the establishment of NCH | | Estimated using cost data from UIUC (2003) and estimate of the amount of machinery field time spent on turning (Bowers, 1992) |
| Machinery cost (repair, fuel, and hire) | Soybean: \$162.5/ha (organic), \$52.5/ha (conventional) Corn: \$187.5/ha (organic), \$70/ha (conventional) | UIUC (2003) |
| Seed cost | Soybean: \$47.5/ha Corn: \$75/ha (organic), \$87.5/ha (conventional) | UIUC (2003) |

^a 1 metric ton=36.74 (37) bushels soybeans (60 pound bu) and 1 bushel/acre=0.0673 (0.07) metric ton/ha (Weiland and Smith, 2007). 1 ha=2.471 (2.5) acres.

farms in considering HM as a potential pest control mechanism in the face of the new soybean pest. In the absence of the invasive SBA pest, organic systems earn almost twice the net return of conventional systems for two reasons. First, organic products fetch a price premium, making yield losses more valuable. Second, the variable cost of producing organic corn is slightly less than that of conventional corn. This advantage exists in spite of the lower yields associated with both organic soybean and corn (Table 1).

Our presentation of key results is focused on the medium infestation level and Laplace distribution kernel. Devoting 1% of land to NCH ($prop_NCH=0.01$) with small NCH elements scattered in an archipelago was the optimal habitat configuration controlling SBA among all configuration options

considered. For organic farmers, this land configuration pattern leads to a 59% increase in net return over the no-control baseline. For conventional farms, insecticide-based pest control offers the best net return. However, among HM options, the smallest profitability loss comes from devoting 1% of land to NCH, configured in an archipelago pattern. This system decreases net returns by 4% from the insecticide-based control baseline under the conventional system.

The key results are driven by a tradeoff between increased pest control around many small areas of NCH and increased cost of managing fragmented fields. As shown in Fig. 4, the first 1% of NCH scattered as an archipelago generates significant profitability gains over no control. Beyond 1% areas, however, the marginal costs outstrip the benefits, with a decreasing returns-to-scale effect for 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. Beyond its 1% NCH peak, the performance of the archipelago pattern declines at a much faster rate under the organic system than the conventional system as *prop_NCH* increases, because the organic system relies on repeated tillage for weed control, and tillage costs increase dramatically with more turns in the field.

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 (Fig. 4). Under the conventional system, the optimal size of NCH is 16% and 9% of total area for square and strip, respectively, with a decrease in net return of around 32% for both patterns. By contrast, under the organic system, the optimal size of NCH is 15% and 5% of total area for square and strip, with increases in net returns of 22% and 27%, respectively.

Overall, the adoption of HM for SBA control is unattractive on a conventional farm, resulting in at least a 4% reduction in net returns below the insecticide control baseline (Fig. 4). In sharp contrast, the organic system gains significantly in economic performance after establishing NCH. Specifically, an organic farm would be better off by setting aside any 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 peak level of 59%.

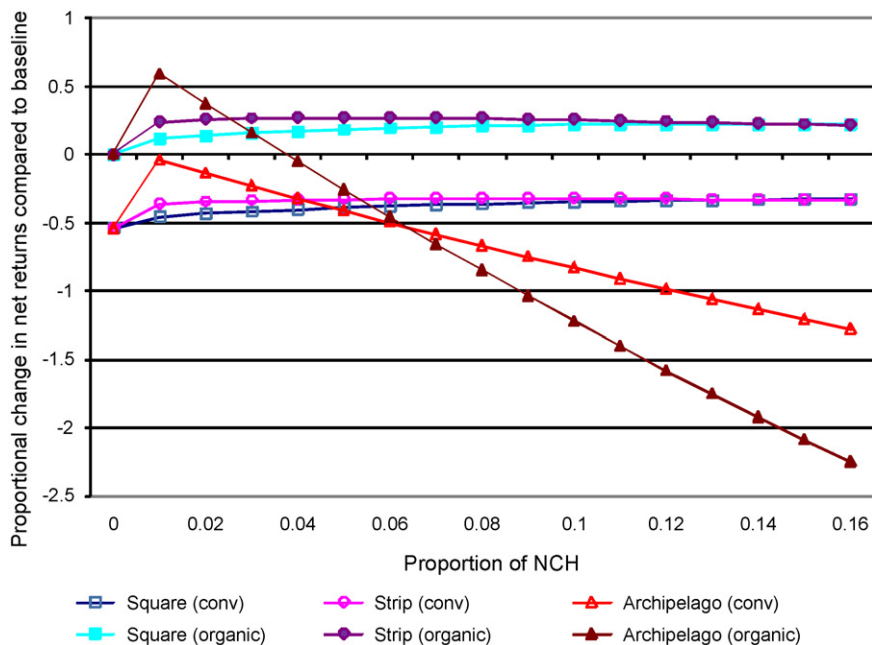


Fig. 4. Proportional change in net returns to fixed factors as compared to the baseline (i.e., pesticide control for the conventional farms and no control for the organic farms) (Medium pest infestation, Laplace kernel).

3.3. Infestation pressure effects

The level of pest infestation does not significantly influence the optimal choices of NCH shape and area. However, it does play a role in determining the performance of HM relative to the baseline management. Under the conventional system with 1% of NCH arranged in an archipelago pattern (and assuming a Laplace distribution kernel), HM becomes more valuable as compared to baseline management when SBA infestation is high. For example, net returns increase by 0.3% from the baseline under the high infestation scenario but fall by 5% and 4% from the baseline under the low and medium infestation scenarios. The increased benefits to NCH under high infestation can be attributed to both the higher insecticide control cost under the high infestation scenario and the higher soybean yield loss as more pests initially mean more pests escape control. Under the organic system, infestation levels have an even greater impact on the relative performance of HM: Net returns increase over no control by 41%, 59%, and 77% for low, medium, and high infestation levels, respectively (assuming 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 effect for NCH area. On conventional farmland, the gap between HM and chemical control gets smaller as infestation level increases, up to a minimum gap at NCH = 13%. Likewise, under the organic system, the higher the pest level, the better HM performs on areas of NCH up to 9% of all land. These results follow from the archipelago's superior ecological benefit and extraordinarily high production cost compared to the square and strip patterns. When the proportion of 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.

3.4. Sensitivity analysis

Although model results were somewhat sensitive to the distribution kernel selected, the choice of distribution kernel did not affect the ranking of NCH configurations across the two farm types. In general, the Laplace kernel displayed the strongest effects. The most important effect on net returns came from natural enemy access to cropped area, which was greatest for the archipelago configuration under all distribution kernels and both farm types.

The sensitivity of the model's rankings and net return estimates was evaluated for 5–10% perturbations of a wide range of spatial, ecological, and economic parameters. Overall, model results are robust to parameter variations for the conventional system, except for efficacy rate of SBA insecticides and natural enemy mean dispersal distance. 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.

4. Conclusion and future research directions

The spatial bioeconomic model developed here for managing the habitat of natural enemies of crop pests builds on special characteristics of invasive species that have established themselves as agricultural pests. In particular, invasive agricultural pest species cause production loss in marketed goods. This creates a direct incentive for private action to limit pest damage. Broad-spectrum chemical pesticides represent one important means for pest management, but they can lead to environmental and human health risks (Thomas, 1999). By establishing habitats to enhance the ambient populations of predators, farmers can protect crops from invasive pest damage. Their management is especially relevant for established, widely dispersed invasives for which eradication is impractical. This study explores the economically optimal spatial configuration of natural enemy habitat in agricultural landscapes, using the seven-spotted lady beetle to model predator habitat management for control of the invasive soybean aphid in North America soybeans.

Not all invasive agricultural pest species are amenable to control by natural enemies. In some settings, a foreign pest will become established in a new territory free of natural enemies, including

those from its native range. For the approach developed here to be helpful, natural enemies of the invasive species must be both present and responsive to changes in habitat resources in agricultural landscapes. Note that the natural enemies need not be native species; they may be introduced and are often enemies of the pest in its native range. For example, the soybean aphid migrated to North America along with both its winter host plant, buckthorn, and its major predator, the Asian multicolored lady beetle (Jones and Boggs, 2008). While the lady beetle was actually introduced in the United States for control of other pests, prior to the arrival of the soybean aphid, its presence met the preconditions for feasible management of soybean aphid as an agricultural invasive species.

Our findings emerge from a spatial optimization model to explore spatial manipulation of non-crop habitats in a simulated landscape. The model 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 has the potential to become a win–win option for organic systems (beneficial to both society and private producers). While any amount of habitat in square and strip shapes would improve net returns over the organic no-control baseline, a small area of habitat scattered as an archipelago results in the best outcome. Under an organic system, the higher the pest pressure, the greater the advantage of habitat management over no control (except when more than 3% habitat is arranged in the high-cost archipelago pattern).

In a conventional soybean–corn system, however, the adoption of habitat management tends to reduce farm net returns. 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 a wider range of beneficial insects (e.g., pollinators) and other 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 configurations 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 foregone crop income and the 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. Assuming equal mean dispersal distance of 100m, we find a positive association between the spatial extent of natural pest control services 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 influence on the model results.

Several issues deserve future attention. First, while not considered in the current study, species scale dependence (Hambaeck and Englund, 2005) may have important implications for spatially

explicit models involving land use choices. If natural enemy density increases exponentially with the area of contiguous habitat, the aggregation of patchy habitats may become desirable through coordinated action among multiple land managers. 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, improved parameter estimates (such as the efficacy rate of insecticides by species and species-specific spatial distribution scale parameters) would refine this bioeconomic modeling approach. 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. The spatial distribution of pests was assumed homogeneous in this model, but research into developing pest spread functions is needed, particularly for pests (like SBA) that can travel long distances under certain conditions.

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 examining spillover effects at the landscape scale, that work remains to be done. 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 spatial factors are particularly important for socially optimal land use choices: the distribution of natural enemies in space and the scale dependence effect. Longer dispersal distance ensures that biocontrol services reach more crop fields. As for scale dependence, if species population increases disproportionately with its habitat area, then a larger contiguous non-crop habitat offers a potential gain in total biocontrol services. When natural biocontrol can be projected at such larger scales (or when farms are small), coordinating habitat configuration across neighboring farms becomes optimal. In the world of pest control, this incentive for coordination is analogous to the policy incentive for coordinated habitat management explored by Parkhurst and Shogren (2007). In both cases, the incentive for coordination arises from private gains that are increased by spatially coordinated habitat management because of the range and scale dependence of the species of interest.

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