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Optimal control of soybean aphid in the presence of natural enemies and the implied value of their ecosystem services☆

Wei Zhang[a,*], Scott M. Swinton[b]

[a] Environment and Production Technology Division, International Food Policy Research Institute (IFPRI), 2033 K Street NW, Washington DC 20006, USA
[b] Department of Agricultural, Food, and Resource Economics, 202 Agriculture Hall, Michigan State University, East Lansing, MI 48824-1039, USA

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ABSTRACT

By suppressing pest populations, natural enemies provide an important ecosystem service that maintains the stability of agricultural ecosystems systems and potentially mitigates producers' pest control costs. Integrating natural control services into decisions about pesticide-based control has the potential to significantly improve the economic efficiency of pesticide use, with socially desirable outcomes. Two gaps have hindered the incorporation of natural enemies into pest management decision rules: 1) insufficient knowledge of pest and predator population dynamics and 2) lack of a decision framework for the economic tradeoffs among pest control options. Using a new intra-seasonal, dynamic bioeconomic optimization model, this study assesses how predation by natural enemies contributes to profit-maximizing pest management strategies. The model is applied to the management of the invasive soybean aphid, the most significant serious insect threat to soybean production in North America. The resulting lower bound estimate of the value of natural pest control ecosystem services was estimated at $84 million for the states of Illinois, Indiana, Iowa, Michigan and Minnesota in 2005.

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). Integrating naturally occurring pest control services into decisions about pesticide-based control has the potential to significantly improve the economic efficiency of pesticide use, with socially desirable outcomes. While ecologically based approaches have long been promoted as alternatives to complement and partially replace current chemically based pest-management practices (NRC, 1996), there has been limited guidance on how to operationalize the concept. Part of the challenge has been insufficient biological knowledge of predator-pest-crop system, with attendant gaps in the ability to measure the economic tradeoffs among pest management options.

Decision rules for pest control using synthetic chemical pesticides typically do not account for the presence of natural enemies. Many synthetic chemical pesticides are broad-spectrum, killing not only arthropod and pathogen pests but also beneficial organisms that keep the pest populations in check (NRC, 1996). Damage to beneficial species 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 can create a hidden opportunity cost to private producers by curtailing natural control services that would have been provided by existing natural enemies if no pesticides had been used. A profit-oriented pesticide use strategy that accounts for biocontrol by natural enemies tends to reduce pesticide use. Reduced pesticide use also mitigates the human health and environmental risks associated with pesticide exposure (Naylor and Ehrlich, 1997; Thomas, 1999).

This study offers three contributions. First, we elucidate how the inclusion of natural enemy predation contributes to optimal pesticide strategies. Those insights emerge from applying a new bioeconomic optimization model of the natural enemy-adjusted economic threshold (NEET) for pest management (Zhang and

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* Corresponding author. Tel.: +202 862 5626; fax: +202 467 4439.
E-mail addresses: w.zhang@cgiar.org, zhangwe9@gmail.com (W. Zhang).

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Swinton, 2009). Second, we evaluate the performance of the dynamic NEET model against comparable static economic threshold models. Third, we calculate a lower bound estimate of the economic value of natural control services to private producers based on the NEET model. In the process, we focus on the management of soybean aphid (SBA), the most important invasive insect threat to soybean production in North America (Ragsdale et al., 2007).

The economic threshold (ET) is a well-known concept in pest management, pioneered by entomologists Stern et al. (1959) as a quantitative approach to integrated pest management. The ET is defined as the pest population density at which action must be taken in order to prevent an increasing pest population from reaching the economic injury level (EIL) at which the expected value of crop damage equals the cost of control (Pedigo et al., 1986).

While the ET has been widely adopted by entomologists as an operational decision rule for pesticide control (Mumford and Norton, 1984), the basic ET approach has three limitations. First, the EIL is static, whereas pest-crop systems are dynamic. Because the EIL model includes only single period decision making, it misses the effect of current actions on future decisions (Brown, 1997). Second, the pest population model that determines the ET typically omits natural pest biocontrol. Important exceptions are Brown (1997) and Musser et al. (2006), who incorporate biological control into an ET. However, both studies build the ET by adjusting a known EIL for single period decision making; neither one models interacting pest and natural enemy population dynamics. Other ecological studies have adjusted the ET for parasitism without explicitly modeling natural enemy population dynamics (e.g., Hoffmann et al., 1990; Walker et al., 2010, and Hamilton et al., 2004) or have developed sampling plans which depend on the ET (e.g., Giles et al., 2003 and Wilson et al., 1985). Third, standard pest population models ignore the effect of natural enemy mortality due to broad-spectrum pesticides (though again, Musser et al., 2006, is an exception).

Dynamic ET's have been developed for rapidly reproducing pest populations that can recover from pesticide spraying, where profitable management may call for multiple treatments. Dynamically optimal decision rules have been developed for multi-stage pest control problems to guide the timing, frequency, and dosage of pesticide treatments (Talpaz and Borosh, 1974; Zacharias and Grube, 1986; Harper et al., 1994; Bor, 1995). A separate thread of dynamic studies has optimized biological pest control via timing the impulsive release of natural enemies of the target pest (Tang et al., 2005; Zhang et al., 2007; Cardoso et al., 2009). However, until very recently, no dynamic study had incorporated the role of natural enemies into pesticide-based optimal pest control.

The recent breakthrough comes from Zhang and Swinton (2009), who explicitly incorporate natural enemies into a dynamic optimization pesticide decision model by offering a new threshold decision rule. Their natural enemy-adjusted economic threshold (NEET) is the pest population density threshold at which pesticide control becomes optimal in spite of the opportunity cost of lost biocontrol due to injury to natural enemies of the target pest. The NEET model allows for multiple treatment opportunities and identifies the optimal expected sequence of pesticide applications.

Natural pest control services are a category of regulating ecosystem service (Millennium Ecosystem Assessment, 2005) that can be valued indirectly via their intermediate contribution to the production of marketed products. Thus, their partial economic value can be inferred from the price of marketed products using the factor input approach (Freeman, 2003). In this study, model results will measure profitability impacts of the NEET model by comparing producer net returns over variable costs of pesticide control with and without accounting for the presence of natural enemies. The results allow us to make a preliminary estimate of the added value from an additional natural enemy in the system. We apply the model to soybean aphid, extrapolating this added value across the U.S. Midwest to estimate the value to farmers of incorporating natural enemy populations into their insecticide use decisions. The estimated values are conservative, because they take into account only farmers' private profitability benefits from optimizing the number and timing of broad-spectrum pesticide applications in the presence of natural enemies. A full accounting of the natural pest control services would also include health, social and environmental benefits, which may justify further reduction of pesticide use and higher monetary value of natural pest control services.

The remainder of the paper begins with background information on the SBA problem and the role of natural enemies in its regulation. We then briefly describe the bioeconomic model of Zhang and Swinton (2009) and present numerical results of optimal control strategies for single season SBA management. These results are extrapolated to estimate the economic value of natural enemies that attack SBA. Finally, we highlight main findings, offer caveats, and suggest future research directions to operationalize the field use of NEET decision support models.

2. Soybean aphid and its natural enemies

SBA is an invasive pest that was first discovered in Wisconsin, USA, in 2000 (Ragsdale et al., 2011). Within four years, it had spread to 21 states and south-central Canada (Landis et al., 2004); within 9 years it had reached 28 states (Ragsdale et al., 2011). 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 (Thompson and German, 2003; RAMP, 2006). Since 2000, SBA has prompted U.S. soybean farmers to perform extensive spraying of soybean acreage, making it one of the key drivers of pesticide 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% in the North Central region before SBA arrived (NASS, 2000 and 2006).

Existing natural enemy communities play a key role in suppressing SBA populations in the North Central region of the United States (Fox et al., 2004; Landis et al., 2004; Costamagna and Landis, 2006; Costamagna et al., 2008). 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) 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 broad-spectrum insecticides used to treat SBA (C.D. DiFonzo, pers. comm., 2006). Evidence from Iowa indicates that insecticides applied early in the season can actually stimulate greater late season SBA infestations (Johnson et al., 2008), presumably due to removing the suppressive control of natural enemies.

While selective insecticides may reduce the risk on natural enemies, broad-spectrum insecticides have been shown to provide greater protection from SBA (Johnson et al., 2008) and are likely to remain important options for farmers. The challenge, therefore, is to choose the optimal strategy for broad-spectrum pesticide use to conserve SBA natural enemies such that the economic benefit to the farmer outweighs the additional cost. Although agricultural pesticide recommendations for SBA control generally stress the need for assessing the presence of natural enemies before spraying (Smith and Pike, 2002; NCPMC, 2005), the implementation of the current extension recommendation of treatment threshold relies solely on observed aphid density. However, the recommendation was developed from field data where natural enemies were present (Ragsdale et al., 2007), so their effect is implicit in the threshold. Until the NEET model (Zhang and Swinton, 2009), producers lacked a decision rule that explicitly accounts for the pest regulation services supplied by ambient natural enemies.

3. Method

3.1. Bioeconomic optimization model

The NEET intra-seasonal SBA management model developed by Zhang and Swinton (2009) links an ecological predator-prey model, a crop plant growth model and an economic decision model in a dynamic optimization framework for optimal, threshold-based pest management. The population dynamics of ambient natural enemies are explicitly modeled along with their suppressive effect on the pest population and their mortality effect due to the use of broad-spectrum SBA pesticides. The NEET decision rule incorporates the opportunity cost of losing these benefits due to pesticide sprays that can kill natural enemies. The model is operationalized using field trial data from Michigan collected during 2003 and 2005. While the estimated technical parameters represent the Michigan soybean field conditions including the pest-predator complex dwelling in those fields, the modeling methodology can be generalized to other crops and pest-predator systems.

The model adopts a stage-based, discrete dynamic framework. It considers the SBA management problem over five time periods that correspond to the five early reproductive stages of soybean plant development, R1 through R5. During these early bloom stages, soybean plants are most susceptible to SBA damage (Jameson-Jones, 2005). Insecticide application decisions are modeled as binary choices at the standard application rate specified on the product label, given constant prices for crop and inputs. The model assumes that a producer chooses the optimal control action (spray or no spray) at each decision point (t) to maximize net return over variable costs of control, subject to three biological constraints that describe: i) population dynamics of SBA (S_t), estimated using simulated SBA growth data generated by a daily time-step model developed by Costamagna et al. (2007b), ii) population dynamics of natural enemies (NE_t), described with a dynamic Lotka-Volterra predator-prey model (Lotka, 1925; Volterra, 1926) and estimated using Michigan field data[1], and iii) crop yield response to surviving SBA pest density ($E_t[y]$), based on the reformulated version of Cousens (1985) rectangular hyperbolic model and estimated using field trial data from Michigan. The solution to this discrete dynamic optimization problem leads to an optimal sequence of control actions or the NEET decision rule.

The profit-maximizing decision over the full time horizon entails spraying in period 1 ($t = 1$) only if the associated cost is no greater than the predicted benefit of reduced pest damage adjusted for the loss of pest control by natural enemies. Depending on the relative magnitude of the biological interactions given the economic parameters, the inclusion of natural enemies can lead to less pesticide use. Although avoiding unnecessary insecticide use can potentially confer a wide range of social and environmental benefits, this model focuses only on the private profitability effect of incorporating natural enemies into farm insecticide decisions.

Estimated values of key parameters from Zhang and Swinton (2009) appear in Table 1. A few points deserve note. First, the model assumes that no more than one spray may occur in each stage and that the predicted yield at the final stage before soybean maturity (R5) is carried through to harvest so that SBA control is only meaningful during earlier plant growth 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* (seven-spotted ladybeetle) adult and larva, *Coleomegilla maculata* (spotted ladybeetle) adult, *Cycloneda munda* (polished ladybeetle) adult and larva, and *Hippodamia convergens* (convergent ladybeetle) adult. Third, natural enemy populations are indexed to the equivalent predation rate of the Asian multi-colored ladybeetle. Based on findings from the biological literature on the mean daily aphid consumption rate by multi-colored Asian ladybeetle adults (Hukusima and Kamei, 1970; Lou, 1987; Hu et al., 1989; Lucas et al., 1997) and the field observation of ladybeetle life stage composition in Michigan, Zhang and Swinton (2009) propose an approximate range of weighted average daily number of aphids eaten per ladybeetle: 17 to 52, for a mean daily consumption rate of 35 aphids 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 1). Fourth, for price and cost parameters, we use a long-term soybean trend price of \$0.26/kg (\$6.90 per bushel) and a treatment cost of \$29.63/ha for threshold-based integrated pest management using Warrior at 0.0947 l/ha.[2] A break-down of the cost includes \$17.28/ha pesticide cost, \$4.94/ha for scouting, and approximately \$7.41/ha for spraying (Song et al., 2006). Finally, the model assumes that SBA pesticide will kill 99% of the population of both aphids ($k_{S,t}$) and natural enemies ($k_{NE,t}$) upon each application during the season.

3.2. Numerical analysis approach

Based on the bioeconomic model described above, this study adopts a numerical dynamic optimization approach comprised of two components: i) a simulation routine to predict the economic outcome of each possible control path (i.e. control strategy,), and ii) a selection routine to choose the control strategy that yields the highest economic outcome. The algorithm of the approach is analogous to that of DDPSOLVE, a dynamic programming computer program developed by Miranda and Fackler (2002), with two major improvements: i) it allows the biological transition equations to contain time period-specific parameters, and ii) it significantly reduces computational expenses by limiting the ranges of the initial values of biological state variables to those that are consistent with Michigan field data.[3] Specifically, the optimization is carried out as follows:

[1] The Lotka-Volterra model presented in Zhang and Swinton (2009) is a simple model for predator-prey dynamics, with the same components and general structure as the original Lotka-Volterra model (Begon et al., 2006), but with some key differences. First, the parameter for intrinsic growth rate of the prey population is not constant, but rather varies over time (Costamagna et al., 2007b), which puts a cap on the aphid population growth. Second, our predation rate per predator in the prey equation is estimated from data for each plant growth stage. This makes it much harder for the prey population *not* to go extinct under predation pressure, as compared to the original Lotka-Volterra model, in which predation rate is reduced as prey become scarcer (van der Werf, 1995). Finally, the original Lotka-Volterra model is a differential equation model, whereas the model presented in Zhang and Swinton (2009) is a discrete time model.

[2] This is a projected 2005 price for soybean by Song et al. (2006). The projection model was estimated using historical US season-average farm-level prices from 1963 to 2004 adjusted for inflation.

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

Table 1
Estimated values of key model parameters.

Parameters	R1	R2	R3	R4	R5
Duration of plant growth stage (day)	3	10	9	9	15
Mortality rate of SBA from pesticides ($k_{S,t}$)	0.99	0.99	0.99	0.99	0.99
Mortality rate of natural enemies from pesticides ($k_{NE,t}$)	0.99	0.99	0.99	0.99	0.99
Natural enemies					
Net decline rate of *NE* (d_t)	−0.59	−0.90[c]	−2.13[b]		
Reproduction rate of *NE* per prey encountered (b_t)	0.002	−0.0001	0.002[a]		
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[b]	0.0003[a]	0.0001[a]	0.0002
Maximum proportional yield loss to pest damage (θ_t)	1	1	1	1	1
Economic parameters					
Output price (p)	\$0.26/kg				
Control cost ($c(x_t)$)	\$29.63/ha				

[a] Significant at 90%.
[b] Significant at 95%.
[c] Significant at 99%. Source: Zhang and Swinton (2009).

- Specify 16 distinct possible control paths, each representing a unique sequence of four control choices made over the periods R1 to R4.
- Define space matrices for the initial values of state variables: i) 31 possible values for the population density of SBA in stage R1 (S_1) (0:5:150, meaning a range of 0–150 aphids on average per plant with an interval of 5), ii) 9 possible values for the population density of natural enemies in stage R1 (NE_1) (0:0.5:4.0, meaning a range of 0–4 natural enemies on average per plant with an interval of 0.5), and iii) 11 possible values for the initial yield potential (or maximum yield potential) that are consistent with the reported soybean yield levels in Michigan ($E_1[y]$) (2688:134:4032, meaning a range of 2688 to 4032 kg/ha (40–60 bu/ac) with an interval of 134 kg/ha (2 bu/ac) (MSU Field Crops AOE Team, 2002).
- Consider 3 possible ladybeetle daily predation rates to account for uncertainty in the parameter value (minimum, mean, and maximum of 17, 35, and 52 aphids consumed per ladybeetle per day, respectively).

We define a scenario as a distinct combination of state variable initial values and key parameter values. In total, we assess 9207 scenarios (31 initial SBA population densities $\times$ 9 initial natural enemy population densities $\times$ 11 initial soybean yield potentials $\times$ 3 ladybeetle daily predation rates). For each scenario, we simulate the model and predict the net returns over variable costs of control for each of the 16 possible control paths. The control path that yields the highest predicted net return is designated the optimal control path for a given scenario. The total number of simulations to run therefore amounts to 147,312 (9207 $\times$ 16) to explore a wide range of possibilities at a sufficiently small incremental margin.

4. Optimal pest control strategies that account for natural enemies

The NEET dynamic optimization model prescribes sharply different pesticide application thresholds according to whether or not natural enemies of pests are present. Those thresholds drive changes in producer net returns. The changed field-level net returns can be aggregated into regional estimates of the value of natural pest control services.

The model's optimal control paths are presented graphically in two-dimensional space described by initial pest population density (S_1) and initial natural enemy population density (NE_1), holding other parameters constant (Fig. 1).[4] The sequence of predicted optimal control actions for the entire season follows deterministically from field scouting information in the initial period. The initial population densities of SBA and natural enemies that trigger the predicted optimal control path are interpreted as the NEET for adopting that particular optimal strategy. For instance, at a daily predation rate of 35 aphids/*NE* and an initial yield potential ($E_1[y]$) of 4032 kg/ha, if there are no natural enemies ($NE = 0$), the model predicts that the optimal control path is to spray only in soybean growth stage R1 with as few as 5 aphids/plant initially ($S_1 = 5$) and to spray in both R1 and R2 and do nothing from R3 to R5 when $S_1 = 125$ aphids/plant (Fig. 1b). The NEET, given that the natural enemy density in R1 is zero, is a pest density of 5 aphids/plant in R1 for a single spray and 125 aphids/plant in stage R1 for two sprays. We explore scenarios that vary the two parameters to which model solutions are most sensitive: yield potential (2688 kg/ha vs. 4032 kg/ha) and the daily aphid predation rates of the natural enemy populations (base case of 35 aphids/day, bracketed by 17 and 52 aphids/day).

Three distinct optimal control paths emerge from the numerical analysis: (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 explicitly model the population dynamics of natural enemies, any control action prescribed by the model remains optimal in spite of the opportunity cost of injury to

[4] Fig. 1 does not represent a normal phase plane, which would depict the relationship between the *x*-axis and *y*-axis variables. Instead, the coordinates in our figures represent the model predicted solutions in terms of the optimal control strategy for each given combination of x and y values.

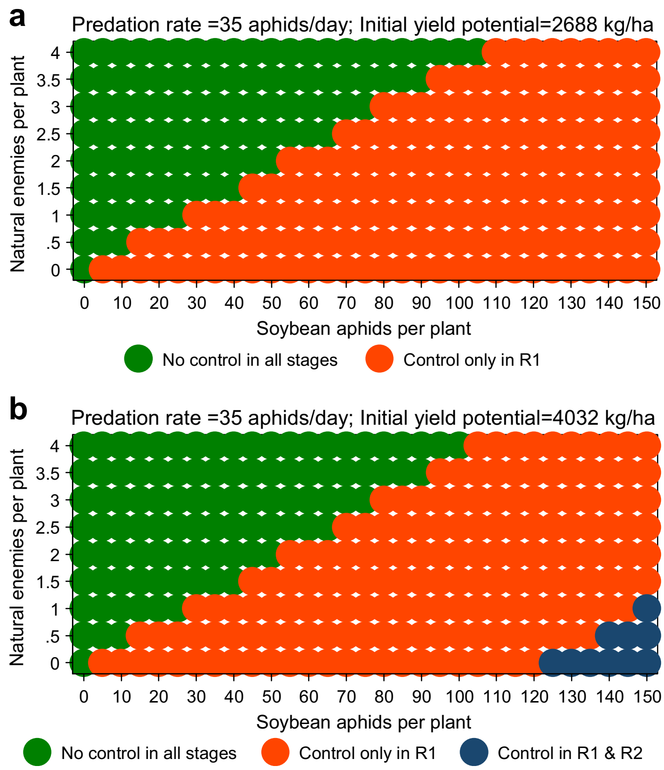

Fig. 1. Optimal control paths for initial yield potentials of 2688 kg/ha (a) and 4032 kg/ha (b) at the mean daily predation rate of 35 aphids per natural enemy.

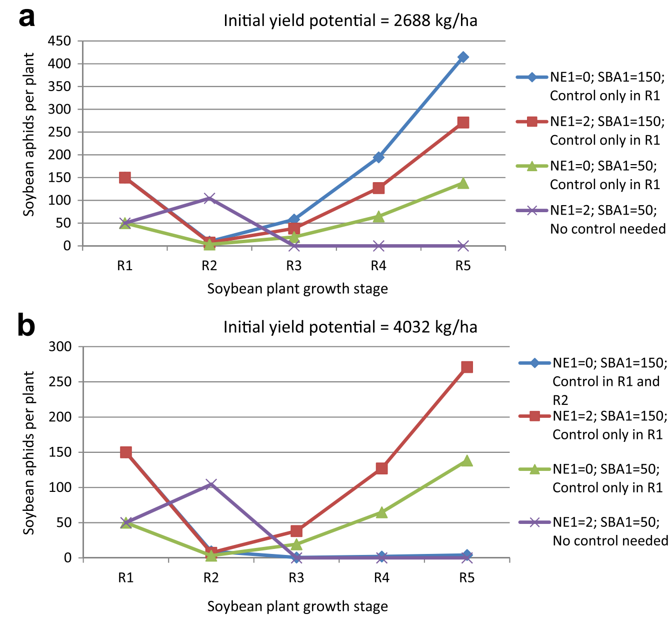

Fig. 2. Soybean aphid density over soybean plant growth stages for four different NEET control trajectories for initial yield potentials of 2688 kg/ha (a) and 4032 kg/ha (b) at the mean daily predation rate of 35 aphids per natural enemy.

natural enemies by the chemical pesticides used to treat SBA. While it is obvious that no pesticide spray is necessary during the last stage (R5), stages R3 and R4 are found to be too late to take 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 spraying in both R1 and R2 has to be justified by a relatively heavy SBA infestation, low natural enemy population (or low predation rate), or high initial yield potential. As Fig. 1 shows, in the absence of natural suppression (i.e., $NE_1 = 0$), "Spray R1+R2" is never optimal when expected soybean yield ($E_1[y]$) is as low as 2688 kg/ha. However, spraying twice becomes desirable in more heavily infested situations ($S_1 \geq 125$) and with higher initial yield potential such as 4032 kg/ha. Our results confirm that for a pest that can reproduce rapidly, like SBA, early treatment is preferred. This is consistent with the current extension recommendation for SBA (Ragsdale et al., 2011).

Compared to a conventional economic threshold, application of the NEET in this model has important effects on the trigger level for pesticide use and producer profitability. The NEET is sensitive to several key parameters. These areas are discussed below.

1) Natural enemies sharply raise the pest density threshold for optimal pesticide use

The dynamic NEET always exceeds the static economic threshold aphid pest population density when natural enemies are present. The effect is clearest compared to the threshold when natural enemies are missing (or ignored). In the absence of natural enemies, as shown in the bottom rows of the two parts of Fig. 1, chemical control is cost-effective for an initial pest density as low as 5 aphids/plant. This zero-natural enemy scenario exemplifies the implied assumption of soybean farmers who ignore natural control services. This level is similar to the 3 aphids/plant action threshold suggested by Olson and Badibanga (2005), who ignored natural enemies in calculating their economic threshold. But with just one natural enemy per plant, the optimal aphid density threshold is sharply increased to 30 aphids/plant (Fig. 1a,b).

The density of natural enemies also reduces the optimal number of sprays when pest populations are high. At a high initial aphid infestation (125 aphids/plant), with no natural enemies and a high yield potential, two sprays are recommended (Fig. 1b). The same aphid pest population density only needs one spray at a natural enemy population of just one per plant. Although this numerical result is specific to the current model parameters, it illustrates how accounting for natural enemies raises the threshold for pesticide use, allowing natural enemies to suppress pest populations and reducing pesticide use.

Fig. 2 further illustrates the relationship between pest density and soybean growth stage for four different NEET control trajectories (based on different initial natural enemy and pest population densities). By construction, each of these trajectories is optimal for grower profitability, given the initial pest and NE conditions. The asymmetry with late pest population increases is to be expected, because soybean yield loss is most severe due to early stage damage.

2) Natural enemies boost producer net return most for moderately infested fields

The effect of natural enemies on producer returns over variable costs is greatest when the ratio of natural enemy density to pest density allows the natural enemies to suppress pest outbreaks, keeping pest populations low and preventing them from inflicting economic damage. Due to the exponential nature of pest population growth, if natural enemy populations are not high enough to keep pest numbers low or if the infesting pest density is too high for the natural enemies to handle, the pest population rapidly multiplies, sharply reducing the value of the natural enemy contribution and making pesticidal control the preferred choice for a profit-maximizing producer.

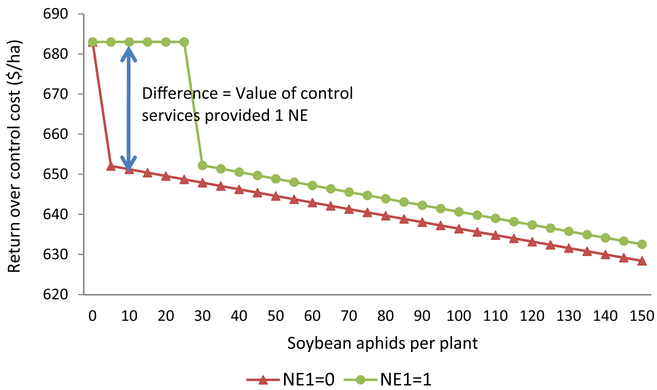

Fig. 3. Value of producer return at initial yield potential of 2688 kg/ha and daily predation rate of 35 aphids per natural enemy.

The patterns that illustrate these observations can be seen in Fig. 3, which plots the producer net return over variable costs of aphid control against initial aphid densities for two initial levels of natural enemy density ($NE_1 = 0$/plant and $NE_1 = 1$/plant) in the baseline scenario with initial yield potential of 2688 kg/ha and the daily predation rate of 35 aphids/*NE*. The curve marked with triangles shows that with no initial natural enemies and no aphid infestation, the producer would earn the maximum net return of $683/ha. However, the presence of just 5 aphids per plant in period R1 would drive down the net return by $31/ha or nearly 5%. By contrast, the curve marked with circles shows that an initial natural enemy population of just one per plant ($NE_1 = 1$/plant) can maintain the maximum net return level of $683/ha, even if the field experiences a moderate infestation of 5–25 aphids per plant in stage R1. However, beyond 30 aphids/plant, the aphid pest infestation would overwhelm the natural enemies' ability to control it, and the value of one initial natural enemy per plant only raises producer net returns by an average of $4.20/ha under dynamically optimal pest management.

3) Optimal control paths and producer net returns are sensitive to output price, predation rate and pest-free crop yield potential

Sensitivity analysis reveals that the optimal control decisions and hence producer net returns are highly responsive to the natural enemy predation rate and the crop yield potential. A higher daily predation rate increases the NEET for pesticide 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. The influence of pest predation rate is illustrated by comparing the two panes of Fig. 4, which holds constant the yield potential at 4032 kg/ha. In the upper pane (Fig. 4a), where the predation rate is 50% below the baseline (17 aphids/*NE*/day), the triangle where no control is optimal runs from 0 aphids at 0 *NE*/per plant to 50 aphids at 4 *NE*/plant. In contrast, in the lower pane (Fig. 4b), where the predation rate is 50% above the baseline (52 aphids/*NE*/day), the triangle where no control is optimal expands to run from the (0, 0) corner up to 150 aphids at 4 *NE*/plant. In parallel with the expansion of the no control area, there is a reduction of the region where it is optimal to spray once in R1 as the daily predation rate increases from 17 to 52 aphids/*NE*. Of course, the 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.

Higher crop yield potential increases the model's propensity to recommend insecticide treatment. For example, Fig. 1b shows that

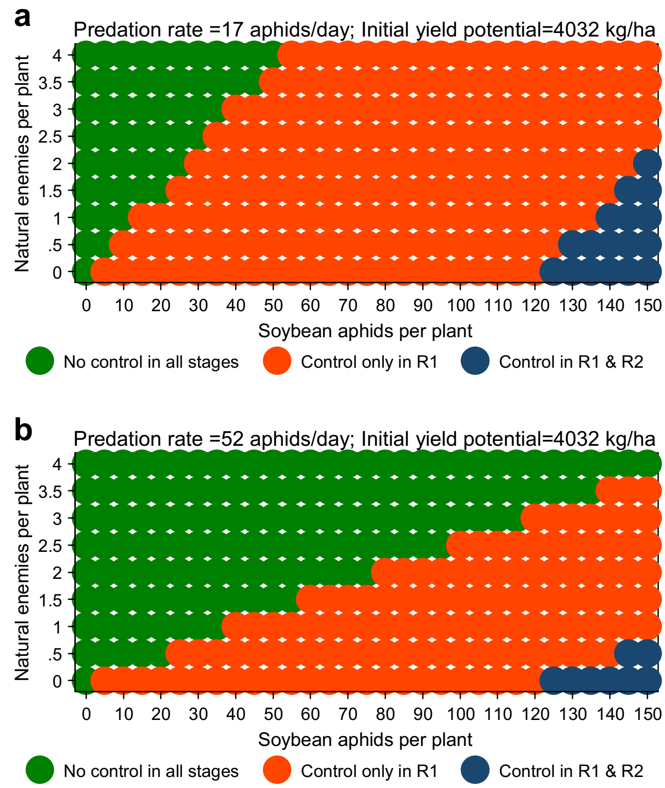

Fig. 4. Optimal control paths for daily predation rates of 17 and 52 aphids per natural enemy at an initial yield potential of 4032 kg/ha.

at a high yield potential (4032 kg/ha) two sprays provide optimal control for high initial aphid infestations when natural enemy populations are low. In contrast, at a low crop yield potential of 2688 kg/ha (Fig. 1a), the same conditions would justify no more than one spray. This result conforms to the general expectation that more productive fields justify more pesticide use because they offer more product to lose.

Sensitivity analysis also shows that the optimal control decisions and producer net returns are highly responsive to soybean output price. A 50% increase in price would induce the same effect on the choice of NEET as the crop yield potential increasing from 2688 kg/ha to 4032 kg/ha. The value of return responds roughly proportionally to the variation in output price. While the current numerical analysis uses the long-term soybean trend price of $0.26/kg estimated by Song et al. (2006), the average soybean price paid to US farmers soared to $0.38/kg in 2007 (Soy Stats, 2008), about 50% higher than the baseline price analyzed here. Given that future soybean prices are likely to remain above $0.26/kg (for example, US season-average soybean price for 2011/121 was projected to be roughly double this level, at $0.46/kg to $0.53/kg in August 2011 (USDA, 2011), our result implies that the producer net return over variable cost of control is likely to be even higher than the levels reported in our numerical analysis.

5. Economic value of natural pest control services

The effect of natural enemy populations on producer net returns can be used to improve upon past estimates of the value of natural pest control ecosystem services. Two prior approaches have been used to measure the economic value of natural pest control services. The first one uses *ex post* project impact assessment of introduced or massively released biological control agents (see review by Hill and Greathead (2000)). The second approach estimates the total cost of averted pest damage due to all pest control practices and then attributes a fraction of the total pest control benefit to natural enemies (e.g., Losey and Vaughan, 2006; Pimentel *et al.*, 1997). While these aggregate values provide snapshots of the possible magnitude of the benefit from natural pest control, they ignore the local context (e.g., pest species, pest pressure, existing natural enemy level, value of protected yield, cost of chemical control, pesticide efficacy). These studies are also subject to the usual critiques of attempts to place aggregate monetary values on entire categories of ecosystem services, such as failing to consider marginal changes and the most likely alternative ways for humans to obtain those services (Bockstael et al., 2000; Pearce, 1998).

The numerical results from the current study can serve as the basis for an indirect estimate of the value of natural control of the soybean aphid in five Midwestern U.S. states using the factor input approach (Freeman, 2003; Swinton and Zhang, 2005). The value is calculated from the incremental gain in producer net returns as a result of an increased initial population of natural enemies, provided that the producer follows the NEET optimal pest management strategy. The estimate constitutes a realistic lower bound for the total economic value of this ecosystem service because i) it omits other important social benefits such as the avoidance of health and environmental risks from pesticide spraying, ii) this analysis assumes a high efficacy rate for soybean aphid pesticides (99%) and a moderate rate of daily pest predation by natural enemies, making pesticide-based control relatively more attractive as compared to natural control, iii) the analysis assumes relatively low soybean initial yield potential, costs of pesticide control and low soybean price, and iv) it assumes the adoption of optimal pesticide use strategies in the presence of natural enemies, which will yield a lower (if more realistic) estimate of total natural enemy value than an estimate that assumes growers relying solely upon natural pest control.

The greatest gain in pest control value from natural enemy populations occurs when they become present instead of absent. Using values from Figs. 3 and 5 illustrates the estimated value of one natural enemy per plant in the initial period as compared to none. Our estimates of the per acre value of one initial natural enemy per plant for moderately infested fields ($5 \leq S_1 \leq 25$) are in line with the estimate of $32/ha reported in Landis et al. (2008). For highly infested fields, however, our results show that Landis et al. (2008) overstate the value of natural control services. This finding highlights the need to address the initial conditions of the field (such as infestation level and natural enemy presence) in assessing the value of the natural control services.

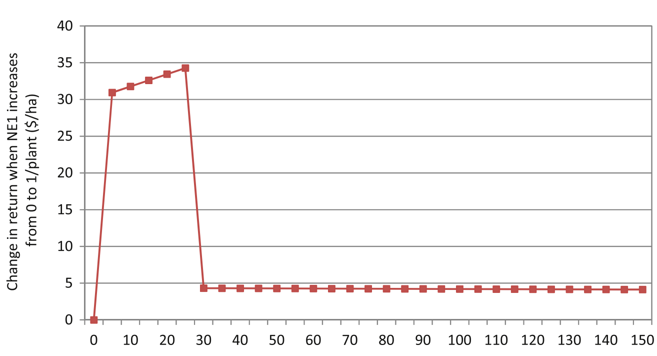

Fig. 5. Value of one natural enemy per plant in stage R1 (as compared to none) at daily predation rate of 35 aphids per natural enemy and initial yield potential of 2688 kg/ha.

Building on assumptions for soybean aphid infestation rates, these micro-level values can be scaled up to estimate the value of pest control services by the natural enemies of soybean aphid at a regional scale. Such regional aggregation is complicated because we do not observe the counterfactual cases of (a) the fields that never reached threshold because of natural enemies, and (b) the fields that were treated but did not need it because natural enemies would have contained SBA damage.

To estimate the regional value of soybean aphid control by natural enemies, we first assume that all insecticides used in the treated soybean acreage in the five states of Iowa, Indiana, Illinois, Michigan and Minnesota were used for controlling soybean aphid. This assumption is justified because the insecticide application rate prior to the arrival of the aphid was close to zero (NASS, 2000). Second, we assume that one natural enemy unit per plant (equivalent to the ladybeetle *H. axyridis*) can represent the value of natural enemies. Third, we assume the baseline daily predation rate of 35 aphids/*NE* and a soybean yield potential of 2688 kg/ha (typical of U.S. average yields since 2000). We consider two ranges of initial SBA densities to illustrate our scaling up analysis: a range representing a moderate SBA infestation case where no insecticide spray is needed when there is one initial natural enemy per plant (5–25 aphids/plant in period R1) and a range representing a relatively more severe infestation where one spray is the optimal action (30–150 aphids/plant in R1). Hence, our fourth assumption is that representative average values of natural enemy pest control corresponding to these two ranges of initial aphid densities are $32.6/ha for the moderate infestation case and $4.2/ha for the more severe infestation case (as in Fig. 5). We calculate the aggregate value of natural biocontrol by multiplying the per hectare value by the total planted area and the percentage of area treated with insecticides in 2005. The estimated aggregate value for the 5-state region, therefore, is $84 million for the moderate infestation case and $11 million for the more severe case (Table 2). Based on field data that the average SBA density was 21 aphids/plant in R1 in Michigan, Wisconsin, Minnesota, and Iowa in 2005, we believe that the level of initial SBA infestation was likely to be moderate (lower than 30 aphids/plant) in this five-state region (M. Gardiner and A. Costamagna, personal communications, 2006 personal communications, 2005).[5] The aggregate value of one natural enemy in R1 as compared to none in 2005 was thus approximately $84 million for the 5-state region, although the value for Michigan might be lower than the regional average because higher SBA density (60 aphids/plant) was observed at the two trial sites there.

The estimated value of $84 million for this region is conservative for four reasons. First, it measures only the incremental profitability benefits from natural pest control in a system where pesticide-based control is the default. In a natural system without pesticides, the value of natural pest control would be far higher (see, e.g., Landis et al., 2008). Second, prophylactic pesticidal control was widely adopted during 2003–2005 in these five states, and Song and Swinton (2009) estimate that it was less profitable than the static economic threshold of 250 aphids/plant. Thus, compared to real soybean grower behavior during this period that actually underperformed the static ET, the dynamic NEET strategy would have greater value than estimated here. Third, the current estimate is based on a conservative soybean price of $0.26/kg, roughly half the price in 2011–12 (USDA, 2011). Fourth, this benefit estimate omits the environmental value of averted pesticide use.

[5] Data were provided by the soybean aphid USDA Risk Assessment and Mitigation Program team members Mary Gardiner and Alejandro Costamagna.

Table 2
Aggregate value of the natural control of SBA by natural enemies for 2005 (Initial yield potential=2688 kg/ha, daily predation rate=35 aphids/*NE*).

	Percentage of area treated with insecticides				
Year	Iowa	Illinois	Indiana	Michigan	Minnesota
1999	0%	0%	0%	0%	0%
2005	16%	9%	18%	42%	30%
Planted area in 2005 (ha)					
2005	4,100,000	3,800,000	2,200,000	800,000	2,800,000
Total acreage	13,700,000				
Initial SBA density in R1	*Value of one NE relative to none ($/ha)*				
$5 \leq S_1 \leq 25$ aphids/plant	32.6				
$S_1 \geq 30$ aphids/plant	4.2				
	State-level aggregate value in 2005 ($)				
	Iowa	Illinois	Indiana	Michigan	Minnesota
$5 \leq S_1 \leq 25$ aphids/plant	21,300,000	11,300,000	12,800,000	11,100,000	27,300,000
$S_1 \geq 30$ aphids/plant	2,700,000	1,500,000	1,700,000	1,400,000	3,500,000
	Regional-level aggregate value in 2005 ($)				
$5 \leq S_1 \leq 25$ aphids/plant	83,900,000				
$S_1 \geq 30$ aphids/plant	10,800,000				

6. Conclusion

The control of pests by their natural enemies represents an important ecosystem service that has the potential to mitigate pest control costs. Neither this important ecosystem service, nor the effect of broad-spectrum pesticides on its value, has 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). Using a new dynamic optimal control model that innovates the natural enemy-adjusted economic threshold (NEET) applied to the soybean aphid pest (Zhang and Swinton, 2009), we compare optimal management with the NEET to a static economic action threshold that ignores the presence of natural enemies. We further apply the model to estimate the value of the natural pest control services of the complex of natural enemies controlling the soybean aphid in the north-central United States.

The NEET model (Zhang and Swinton, 2009) provides a bridge between two prior models for managing soybean aphid. Olson and Badibanga (2005) bioeconomic simulation model ignored natural enemies altogether, resulting in a static economic threshold for soybean aphid control as low as 3 aphids per plant. At the other extreme is the static economic threshold of 250 aphids/plant recommended by Midwestern U.S. extension entomologists based on field experiments (Ragsdale et al., 2007). Because the extension threshold was developed in the field, it implicitly includes average levels of natural enemies, and so benefits from their contributions. The NEET model's optimal control recommendations explicitly depend upon the relative densities of the pest and natural enemy populations. At natural enemy levels of 1–2 *NE*/plant, the model simulations presented here show thresholds for at least one insecticide spray in the range of 30–150 aphids per plant in the soybean's early flowering stage, R1. That these thresholds are much higher than Olson and Badibanga (2005) is due to explicit incorporation of natural enemies. That they are below the Ragsdale et al. (2007) level may be due to unrepresentative parameter levels (e.g., pest densities, natural enemy densities, pest predation rates) or omission of other relevant pest control factors, such as insecticide residual effects on pest populations or migration behavior by pests or their natural enemies. In addition, by ignoring timing of the insecticide application, the extension threshold of 250 aphids/plant implicitly lumps together early season ET values that would optimally be lower with late season ET values that would be higher. As our study shows, timing of control does matter, especially for a species that is capable of rapid reproduction.

The dynamic optimization analysis leads to preliminary estimates of the economic value of natural pest control as an ecosystem service in the management of soybean aphid. Given a conservative soybean output price of $0.26/kg for 2005, these values range from $4.20 to $32.60 per hectare per year, when soybean aphid is present. The low end represents cases where soybean aphid populations are so high that the natural enemies cannot control them, while the high end represents moderate soybean aphid levels that can be suppressed by available natural enemy populations. Based on field data on SBA densities in plant stage R1 in the region, we estimate the value of soybean aphid pest control by natural enemies to be worth $84 million across the states of Iowa, Illinois, Indiana, Michigan and Minnesota in 2005. Caution should be exercised in extrapolating these values due to their context dependence. However, they offer a conservative benchmark for private, monetary benefits because they are based on conservative soybean prices, they presuppose primary reliance on insecticide-based pest control, and they exclude health benefits and benefits external to the farm household. The challenge remains to implement pest management strategies that integrate the value of natural pest control services both in soybean and across other applications.

Future implementation of the NEET approach will require several steps forward. First, since the dynamic optimization model prescribes optimal control paths for the entire growing period based on the assessment of the initial situation, it is important to correctly identify the initial population densities of pest and natural enemies in order to avoid large losses. With the help of training and skillful scouting, reasonably accurate accounting of insect densities may be possible. Second, this study shows that model outcome is sensitive to the natural enemy pest predation rate parameter. Information on species-specific predation rates is currently limited; future research is needed to improve the estimates of this parameter. Third, the parameter sensitivity analysis in Zhang and Swinton (2009) shows that model outcomes are also sensitive to the SBA mortality rate from insecticides. Field data on insecticide efficacy rates will be needed to improve upon the cautious rate of 0.99 assumed in this study. Model outcomes may also be sensitive to the within-stage timing of pesticide application. Fourth, future application of the model in other settings should be tailored to specific soybean varieties, weather conditions and pest-predator populations.

An important caveat is that the NEET model assumes the use of broad spectrum insecticides that kill both the pest and its natural enemies. If selective pesticides become available that reduce collateral damage to natural enemies, the opportunity cost of pesticide use to private producers will decline.

The concept of explicitly modeling the interaction of pest and natural enemy populations in order to predict a NEET threshold that captures the value of biocontrol by natural enemies has the potential for much wider application. This paper explores and extends the NEET model of Zhang and Swinton (2009) that was developed for soybean aphid and its guild of insect predators. The potential for modeling the interactions among natural populations that help to regulate agricultural pests to generate NEET rules is very great. For example, in natural enemy communities led by pathogens or mammals would function very differently than the arthropod natural enemies that regulate soybean aphid populations.

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; Letourneau et al., 2009). Future research should move beyond pesticide use thresholds to develop landscape-scale guidelines for explicit management of habitat for the natural enemies of agricultural pests.

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