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

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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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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