Development of integrated pest management techniques: Insect pest management on soybean

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Development of integrated pest management techniques:
Insect pest management on soybean

By

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A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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2010

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CHAPTER 1.
GENERAL INTRODUCTION
AND LITERATURE REVIEW

Dissertation organization

This dissertation is organized into six chapters. Chapter one contains a general introduction, including a review of the literature on the biology, damage caused, and control of soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae). In addition to soybean aphid biology and management, this chapter will also include a review of integrated pest management (IPM) theory including plant injury responses and insect threshold development. The chapters reporting the original research conducted through the course of study will progress from the applied to the basic: Chapter two will detail the effects of insecticide application techniques on soybean aphid management. Chapter three will report on the applicability of the current soybean aphid threshold on soybean grown in narrow-rows. Chapter four will compare the economic probability of net profit comparing preventive soybean aphid management programs to IPM. Chapter five will detail several soybean yield response models to two common sources of injury (e.g. assimilate removal and defoliation). Chapter five will also discuss how assimilate removal and defoliation interact in a common yield loss model, and how this information could aid in the development of comprehensive soybean aphid thresholds. Finally, chapter six will provide a brief overview of the conclusions of this original research and is followed by an acknowledgments section.
SOYBEAN APHID IMPACT

SOYBEAN APHID BIOLOGY

The soybean aphid is an invasive species which is native to Southeast Asia. The soybean aphid was first discovered in North America (Wisconsin) in July of 2000 (Hodgson et al. 2004, Ragsdale et al. 2004). By July 2002 soybean aphids were found in every county of Iowa (Lang 2003), and by 2004, soybean aphids were reported in 24 states and three provinces of Canada (Losey et al. 2002, Ragsdale et al. 2004, Voegtlin et al. 2004a, Rutledge and O'Neil 2005, 2006). The importance of understanding soybean aphid biology in North America was so great that the Annals of the Entomological Society of America dedicated a special issue to the biology of soybean aphid in North America and its management (Heimpel and Shelly 2004).

Prior to the arrival of soybean aphid in the Midwestern United States, no aphids were known to colonize soybean fields, or cause yield losses in soybean due to feeding injury (Turnipseed and Kogan 1976, Kogan and Turnipseed 1987, Higley and Boethel 1994). Only the cotton aphid, *Aphis gossypii* Glover (Hemiptera: Aphididae) could be found and reproduce on soybean in the Midwestern United States. However, the cotton aphid did not cause yield damage (Blackman and Eastop 2000). The fact that cotton aphid was the only aphid in North American known to feed on soybean partially explains why initial reports of aphids colonizing soybean were incorrectly identified as the cotton aphid (Voegtlin et al. 2004b). In addition to having a common summer host, there are many morphological similarities between the two species. Cotton aphid and soybean aphid are approximately the same size and shape (0.9 mm to 1.9 mm for apterous (wingless) females and 1.1 mm to 1.9 mm for alate (winged) females). They have similar coloration and patterns (Blackman and Eastop 2000). The morphological similarities are so similar that, “It may not be possible to
determine every specimen collected on soybean with complete certainty” (Voegtlin et al. 2004b).

The soybean aphid has a heteroecious, holocyclic life cycle (Ragsdale et al. 2004). Heteroecious organisms require two different plant hosts to complete development (Blackman and Eastop 2000), and holocyclic organisms undergo parthenogenesis reproduction for much of their lifecycle. In North America, soybean aphid overwinter as an egg on buckthorn (*Rhamnus* spp.) (Ragsdale et al. 2004, Voegtlin et al. 2004a, 2004b, McCormack et al. 2005, Voegtlin et al. 2005, Yoo et al. 2005). Each spring, apterous, asexual, females hatch and feed on the overwintering host for several generations, before the first alate generation migrates to the secondary host plant (soybean). Once established on soybean, soybean aphid undergoes multiple overlapping generations where both apterous and alate asexual females are produced. This biology makes soybean aphid capable of rapid population growth. Studies have shown population doubling times of as low as 1.5 days (McCornack et al. 2004, Myers et al. 2005b). Although much longer doubling times are seen in the field (Ragsdale et al. 2007, Schmidt et al. 2007, Gardiner 2009).

In the fall, asexual soybean aphids emigrate from soybean in search of *Rhamnus* spp. where they give birth to ovipara (sexually reproducing females). Male soybean aphids are produced on soybean after female emigration to buckthorn, the apterous males also emigrate from soybean in search of the ovipara developing on *Rhamnus* spp. where they mate (Blackman and Eastop 2000). The eggs are oviposited around lateral buds of *Rhamnus* spp. (McCornack et al. 2004, Ragsdale et al. 2004, Venette and Ragsdale 2004, Voegtlin et al. 2004a, Voegtlin et al. 2005).

In Asia and North America, soybean aphids use plants in the genera *Glycine* as a secondary host, soybean (exotic to North America) is the only *Glycine* spp. in the
North American agro-ecosystem to have a significant distribution and there are no *Glycine* spp. native to North America (Ragsdale et al. 2004, Wu et al. 2004). In addition to plants in the genus *Glycine*, soybean aphid have shown some survivorship and fecundity on non-*Glycine* spp. (Hill et al. 2004). Soybean aphids are also capable of surviving for a period of time on numerous leguminous host including: *Trifolium* spp, *Medicago* spp, and *Phaseolus* spp. (Hill et al. 2004). Although this phenomenon has not been observed in the field, both *Trifolium praetense* (L.) and *Medicago sativa* L. are present both spatially and temporally in soybean producing-areas of North America. The only recorded non-leguminous secondary host of soybean aphid is horsenettle, *Solanum carolinense* L. (Clark et al. 2006).

In North America, the ‘preferred’ primary host, common buckthorn, *Rhamnus cathartica*, is exotic to the North America, while both *Rhamnus alnifolia* and *Rhamnus lanceolata* (‘expectable’ hosts) are native to North America, as is *Rhamnus caroliniana* (‘potential’ host), while *Rhamnus frangula* (‘potential’ host) is exotic (Voegtlin et al. 2004a, Voegtlin et al. 2005). Although exotic to North America, the invasive nature of *R. cathartica* makes it prevalent across a large portion of the soybean-producing areas. Both *R. alnifolia* and *R. lanceolata* have a limited distribution across the soybean producing areas of North America (Voegtlin et al. 2004a, Voegtlin et al. 2005). *Rhamnus caroliniana* is fairly abundant in the North Central region of the United States (Stewart and Graves 2005), and *R. frangula* has a limited in distribution in soybean producing areas of North America (Possessky et al. 2000).
SOYBEAN APHID MANAGEMENT

Insecticidal management of insect pests is one of the most effective means of reducing insect pest populations quickly. Previous reviews of insect pest management in soybean have focused on pyrethroid and organophosphate classes of chemistry (Turnipseed and Kogan, 1976, Kogan and Turnipseed, 1987). In recent years insecticides with new modes of action have been developed with multiple benefits including; reduced human toxicity, increased pest efficacy per gram of active ingredient, plant mobility, and pest selectivity (Harrewijn and Kayser 1997, Elzen 2001, Kraiss and Cullen 2008, 2008b, Brück et al. 2009, Ohnesorg et al. 2009).

Plant-systemic insecticides move primarily through either, xylem (apoplastic movement), or phloem (symplastic movement) tissues. Plant-systemic insecticides effective against soybean aphid primarily consist of two modes of action; nicotinic acetylcholine receptor agonists (neonicotinoids) and lipid synthesis inhibitors (spirotetramat). Although there are also examples of acetylcholinesterase inhibitors that exhibit plant systemic movement (i.e. the organophosphate insecticide acephate), this is not true for all members of this class of chemistry. Neonicotinoids were first commercialized in the 1990’s and were one of the first insecticidal classes to consistently exhibit systemic (apoplastic) movement. Neonicotinoids may be applied to the soybean seed at planting or as a foliar product (Elzen 2001, Buchholz and Nauen 2002). Common neonicotinoid insecticides include thiamethoxam, imidacloprid, and clothianidin. Neonicotinoid seed treatments are toxic against both leaf-feeding insect such as bean leaf beetle, Cerotoma trifurcata (Förster) (Coleoptera: Chrysomeloidea) and phloem-feeding insects such as soybean aphid and white fly, Bemisia tabaci (Gennadius) (Hemiptera: Aleyrodidae). However, their impact is limited for insect pests that colonize soybeans later in the season. For
example, bean leaf beetles colonize soybean fields in North America as the plants emerge, and seed treatments have been very effective in reducing defoliation in the plants early vegetative stages (Bradshaw et al. 2008). However, in much of North America, soybean aphid does not colonize soybean fields until nearly two or three months after plants emerge, and the utility of a seed treatment for soybean aphid management is very limited (Johnson et al. 2008, McCormack and Ragsdale 2006).

Ecological backlash in the form of pest resurgence and replacement should be major concerns of any pest management program (Stern et al. 1959). Insecticides that remove beneficial insects from the ecosystem may cause these two forms of ecological backlash. Systemic and selective insecticides may limit occurrence of resurgence and replacement, which reduces the exposure of non-target organisms. *In vitro* assays have shown that neonicotinoids have a low degree of selectivity, however when neonicotinoid insecticides are applied as seed treatments, non-target impacts are limited to insects that either feed on treated plants or consume intoxicated prey (Nauen et al. 2002). Other studies have demonstrated the efficacy of selective insecticides which utilize modes of action specific to soybean aphid, and closely related species (Kraiss and Cullen 2008, Ohnesorg et al. 2009). Such insecticides, some of which are biopesticides or reduced-risk insecticides, are effective against soybean aphid but have limited impacts on natural enemies. (Kraiss and Cullen 2008, Ohnesorg et al. 2009).

*Orius insidiosus* (Say), which has been documented to reduce establishment and slow population growth of soybean aphid (Rutledge and O'Neil 2005). The natural control of soybean aphid (Schmidt et al. 2007, 2008, Gardiner et al. 2009) increases the possibility that insecticides may cause soybean aphid populations to flair by affecting the natural enemy community adversely (Kraiss and Cullen 2008a, 2008b, Ohnesorg et al. 2009). Insecticides applied before soybean colonization by soybean aphid may not provide protection from soybean aphid, and may facilitate the establishment and subsequent outbreaks of soybean aphid (Kraiss and Cullen 2008a, 2008b, Ohnesorg et al. 2009), by removing natural enemies. Therefore the use of insecticides as a preventative management technique for soybean yield protection from soybean aphid may not be effective over large portions of the Midwestern United States (McCornack and Ragsdale et al. 2006, Johnson et al. 2008, 2009, Ohnesorg et al. 2009).

We are now aware that foliar insecticides labeled for control of soybean aphid in North America can reduce natural enemy populations (Kraiss and Cullen 2008a, 2008b, Ohnesorg et al. 2009). However, there is a potential that chemical insecticides could complement the natural enemy community through the use of reduced-risk insecticides. The Environmental Protection Agency (EPA) defines a reduced-risk pesticide as one which "may reasonably be expected to accomplish one or more of the following: 1) reduces pesticide risks to human health; 2) reduces pesticide risks to non-target organisms; 3) reduces the potential for contamination of valued, environmental resources; or 4) broadens adoption of IPM or makes it more effective" (EPA 1998). Pyrethrin, although not labeled for use in soybean, is a plant-systemic insecticide with a specific mode of action (causing paralysis of the cibarial pump) that is effective against soybean aphid (Ohnesorg et al. 2009) while limiting the impacts on beneficial insects, including aphidophagous predators (Harrewijn and
Additionally, tetronic acid derivatives are plant-systemic insecticides (Brück et al. 2009) with a selective mode of action (inhibiting lipid syntheses). This selectivity allows tetronic acid derivatives to control specific to members of the insect order Hemiptera, while having limited impacts on beneficial insects, including aphidophagous predators (Brück et al. 2009).

There has also been much work on host plant resistance for soybean aphid. Host plant resistance against insects comes in three different forms; antixenosis, antibiosis, and tolerance (Painter 1958). Antixenosis is the inability of an insect pest to find or feed on a plant. Injury caused by potato leafhopper, *Empoasca fabae* can greatly reduce soybeans growth in the United States (Metcalf and Luckmann 1994). However the use of antixenosis by selecting for greater pubescence on leaves and stems on soybean reduced leafhopper injury to soybeans.

Antibiosis reduces the ability of the pest species to survive and reproduce on the host plant. Evidence for soybean lines exhibiting antibiosis against soybean aphid has been reported by several groups of plant breeders (Hesler et al. 2007, Hill et al. 2006, Mensah et al. 2005). When soybean aphids are placed on these plants, they produce fewer offspring. The source of antibiosis in soybeans is attributed to a single, dominant gene (*Rag1*) (Hill et al. 2006). Beginning in 2009, this gene has been available on a limited commercial basis in North America. However, the usefulness of this gene may be limited, as a biotype of soybean aphid that is capable of surviving on *Rag1*-containg soybeans has already been discovered in North America (Kim et al. 2008).

The last form of host plant resistance is tolerance which is defined as the ability of a plant to produce high yields despite insect feeding. Tolerance is difficult to test in the laboratory because tolerant plants will continue to support large insect
populations thus plant yields must be allowed to mature and their yield measured for verification.

**INTEGRATED PEST MANAGEMENT THEORY**

Tactics that mitigate insect pest damage in agricultural settings have recently changed. Starting with the publication of “The Integrated Control Concept” (Stern et al. 1959) and “Management of Insect Pests” (Geier 1966) pest management has replaced pest eradication as the goal of mitigating crop damage (yield loss). A key tenet of pest management is that low levels of injury (pest activity) are tolerable (Geier 1966, Pedigo et al. 1986, Peterson and Higley 2001). Pest mitigation tactics such as pesticide applications are warranted, only after pest populations reach an economic threshold (Pedigo et al. 1986).

Integrated Pest Management (IPM) programs are essential for efficient and economical pest management. A cost-benefit analysis (Poston et al. 1983) is the foundation of any IPM program (Stone and Pedigo 1972). In order for the cost benefit analysis to be effective, it should include not only the control cost, cost associated with implementation, and crop value, but also crop response to pest activity (injury) (Poston et al. 1983).

The injury per individual pest is a key piece of information for any cost benefit analysis to take place. Pedigo et al. (1986) has defined injury as the physiological response of a plant to a pest activity and damage as the measurable injury caused by a pest activity. This response is characterized by the damage curve (Fig. 1). The damage curve has six distinct regions; 1) tolerance (no damage per unit injury), 2) overcompensation (negative damage per unit injury), 3) compensation (increasing damage per unit injury, this where the Db is first crossed), 4) linearity (constant
damage per unit injury), 5) desensitization (decreasing damage per unit injury), and 6) inherent impunity (no additional damage per unit injury) (Pedigo et al. 1986).

Once the injury response (crop response to pest injury) has been characterized, an economic injury level (EIL) and an economic threshold (ET) can be calculated. Pest management thresholds may be categorized into one of four threshold levels; no threshold, nominal, simple, and comprehensive (Pedigo and Rice 2008). The first threshold level, “No threshold”, is usually reserved for very high-value crops such as fresh market produce where cosmetic considerations are important. Nominal thresholds exist where there is some anecdotal or limited experimental data showing that yield loss is being caused by an insect but insufficient data exists to calculate an economic injury level. Nominal thresholds are communally used when a new pest species first invades the system. Simple thresholds exist when sufficient data exists, for a single pest species to predict how much yield loss will occur at a given level of pest activity (Stone and Pedigo 1972, Peterson and Higley 2001, Ragesdale et al. 2007). With comprehensive thresholds, yield predictions could be made when multiple pest species are active (Ostlie and Pedigo 1985, Hutchins et al. 1988, Peterson and Higley 2001). The techniques for developing a single pest EIL and ET are well-studied and used (Stone and Pedigo 1972, Peterson and Higley 2001, Ragsdale et al. 2007), however the development of comprehensive thresholds for insect management has not progressed beyond assuming additive effects of injury caused by insects of the same feeding guild (Hutchins et al. 1988). Six main feeding guilds of insects have been described: stand reducers, leaf-mass consumers, assimilate removers, turgor reducers, fruit feeders, and architecture modifiers (Boote 1981, Pedigo et al. 1986). When insects from multiple feeding guilds, such as bean leaf beetle (fruit feeder and leaf-mass consumer), *Cerotoma trifurcata* (Förster)
(Coleoptera: Chrysomelidae), and the soybean aphid (assimilate remover), are present at the same time we must defer to nominal thresholds for management decisions even though simple thresholds exist for both pests on reproductive stage soybean *Glycine max* (L.) plants (Smelser and Pedigo 1992, Ragsdale et al. 2007).

To advance the science of insect management when multiple insect feeding guilds are present, we must first increase our understanding of plant responses to multiple sources of injury, and how those sources of injury interact to cause damage. There are five ways injuries could interact; additive, synergistic, antagonistic, enhancing (Akobundu et al. 1975), and as a safener (Hoffman 1953). An additive injury response would mean that the two sources of injury cause the same physiological response and that the two sources are replaceable with one another. Synergism exists when one source of injury increases the amount of damage caused by the second source of injury. Antagonism exists when one source of injury lessens the damage of the second source of injury. Enhancers and safeners are special cases where one component causes no damage but the presence of this component either increases the damage caused by the other source of injury (enhancement), or decreases damage caused by the other source of injury (saftener) (Hoffman 1953, Akobundu et al. 1975). Understanding how multiple sources of injury interact to cause yield loss will allow pest managers to more effectively apply injury mitigation techniques.
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FIGURE CAPTIONS

Figure 1. The damage curve as reproduced from Pedigo et al. (1986). Major regions of the damage curve; damage boundary (Db, is the injury level at which yield loss is first detectable), tolerance (no damage per unit injury), overcompensation (negative damage per unit injury), compensation (increasing damage per unit injury, this where the Db is first crossed), linearity (constant damage per unit injury), desensitization (decreasing damage per unit injury), and 6) inherent impunity (no additional damage per unit injury) (Pedigo et al. 1986).
Figure 1.
CHAPTER 2.

INSECTICIDE APPLICATION TECHNIQUES FOR SOYBEAN APHID (HEMIPTERA: APHIDIDAE) MANAGEMENT

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ABSTRACT

Soybean aphid, *Aphis glycines* Matsumura, is one of the most damaging insect pests of soybean, *Glycine max* (L.) Merrill, in the Midwestern United States and soybean producing Canadian provinces. Although significant advances in soybean aphid management have occurred using biological control (classical and conservation) and aphid resistant varieties, most growers continue to rely on insecticides for aphid management. Many groups have evaluated the efficacy of different insecticides. However, few if any have addressed the effect of insecticide application techniques on insecticide efficacy. We compared the effect of three insecticide application techniques on soybean aphid populations in Iowa over a three-year time period (2005-2007). Foliar contact insecticides (a pyrethroid, an organophosphate, both alone and in combination) were applied to naturally occurring soybean aphid populations. The insecticides were applied using techniques that varied the coverage. Coverage was varied by nozzle selection (TeeJet® 8002 XR and 11002 TJ), pressure (138 Kpa and 276 Kpa), and carrier volume (181 and 362 L per ha) to achieve
medium, fine, and very fine droplets, as defined by the American Society of Agricultural & Biological Engineers. The results indicate that application techniques that produced small droplets at higher volumes had a greater reduction in soybean aphid populations and increased yield protection by 108 kg per ha (1.6 bu per ac). Our results indicate that proper application techniques can increase the efficacy of a contact insecticide without increasing rates of application.

**INTRODUCTION**

SOYBEAN APHID, *Aphis glycines* (Matsumura), is the most significant insect pest of soybean production in North America (Ragsdale et al. 2007). While advances in host plant resistance (Hill et al. 2004a, Hill et al. 2004b, Liu et al. 2004, Mensah et al. 2005), conservation biological control (Schmidt et al. 2007, Schmidt et al. 2008, Gardiner et al. 2009), and classical biological control (Heimpel et al. 2004) may make significant contributions to soybean aphid management in the future, soybean producers in North America currently rely on insecticides to prevent yield loss caused by soybean aphid. Ragsdale et al. (2007) showed that insecticides applied during soybean aphid outbreaks on reproductive stages (flowering through seed development) of the plants protect soybean yield. Consistent protection of soybean yield with a single application of a foliar insecticide has been demonstrated by multiple researchers (Myers et al. 2005, Hodgson et al. 2006, Ragsdale et al. 2007, Johnson et al. 2009). Populations that exceed 674 aphids per plant are required to reduce soybean yield below the gain threshold (Pedigo et al. 1986) based on the following assumptions: control cost of $24.51 per ha, market value of $238.83 per ton, and a yield potential of 4.04 ton per ha (Ragsdale et al. 2007). To prevent this economic injury level (EIL) from being
reached, growers are recommended to apply a foliar insecticide when soybean aphid populations exceed an economic threshold (ET) of 250 aphids per plant (assuming a 4 day lag-time before the EIL is reached) between flowering (R1) (Pedersen 2004) and early seed development (R5). Left untreated, phloem feeding by soybean aphid can result in significant yield losses that can exceed 40% (Myers et al. 2005, Ragsdale et al. 2007, Johnson et al. 2009).

Soybean aphid management is primarily through the use of foliar-applied, pyrethroid (λ-cyhalothrin, β-cyfluthrin, ζ-cypermethrin, bifenthrin, etc.) and organophosphate (chlopyrifos, acephate) insecticides (Myers et al. 2005, Ragsdale et al. 2007, Johnson et al. 2009, Ohnesorg et al. 2009). There are many ways in which pesticides can be classified; application type (soil, foliar), class of chemistry, mode of action, site of action, etc. Another way pesticides are classified is by the mobility of the pesticides within the plant. Broadly the two categories of pesticide mobility are contact (not mobile) and systemic (mobile). Contact insecticides require that the insecticide and the insect come into physical contact in order to induce mortality. Systemic insecticides such as neonicotinoids (imidacloprid, thiamethoxam, clothianidin, etc.) and tetramic acid inhibitors (spirotetramat) among others are available or may soon be available for aphid control in soybean production, but most growers continue to rely on contact insecticides.

Contact fungicides and herbicides only affect parts of the plant that they contact, while systemic fungicides and herbicides are able to affect an entire plant. Due to these differences contact pesticides generally require application techniques that increase the surface area covered by the pesticide (Miller and Ellis 2000).
Coverage is important concept in pesticide application, and this is especially true of contact insecticides. Coverage refers to the percentage of the plant surface area that is covered with the pesticide application. Of the many factors that affect coverage are three that can be easily controlled by the applicator: nozzle selection, spray pressure, and carrier volume. Nozzle selection and spray pressure affect droplet size and distribution pattern where nozzle selection, specifically orifice size, is positively correlated to droplet size and spray pressure is negatively correlated to droplet size. A smaller orifice and higher spray pressure produce small droplets and a larger orifice and lower pressure produce large droplets. Wolf and Bretthauer (2009) suggest that droplet size is a more important parameter than carrier volume when calibrating spray equipment. Small droplet size is considered important for increasing leaf surface coverage for contact pesticides, however, small droplet size by its self does not ensure good coverage (Wolf and Daggupati 2009). Finally, carrier volume is directly correlated with the number of droplets at a given size. If systemic pesticides replace contact pesticides, their performance will be optimized with an increase in amount of surface area covered by the pesticide (i.e. many small droplets). While pesticide performance may increase with a decrease in droplet size, smaller droplet sizes increase the risk of off-target movement of pesticides through drift (Nuyttens et al. 2007). In addition to coverage there is also the potential that some insecticides (chlorpyrifos) could volatilize, reducing the impact of application technique (French et al. 1992). However this phenomenon is difficult to predict as the local environment affects the volatilization of a given compound such as barometric pressure, temperature, and humidity (Getzin 1981).

In Iowa, soybean aphid populations rarely reach the EIL before soybeans reach reproductive growth stages (Johnson et al. 2009), which is typically after later than soybean
canopy closure. As the soybean canopy increases in density, a lower percentage of droplets of any size are able to penetrate to the lower canopy levels (Uk and Courshee 1982). Thus, closure of the soybean canopy may affect the efficacy of contact insecticides applied for soybean aphid management. Our objective was to compare different application techniques across the two main classes of contact insecticides (pyrethroid and organophosphate) to determine if application techniques influence insecticide efficacy. We conducted this experiment across a range of locations in Iowa where soybean aphid is established and can potentially cause considerable damage.

**MATERIALS AND METHODS**

In 2005, 2006, and 2007 a common experimental design was used at two locations (Story County and Floyd County) in Iowa. At each location, a soybean variety appropriate for that area was planted from late April to late May, depending on weather conditions (Table 1). Plots measured 10 m by 15 m in size with a row-spacing of 76 cm. Conventional production practices and a glyphosate-based weed control program were employed at all locations.

To evaluate the impact of the varied application techniques, seven treatments and two controls (untreated and aphid-free) were arranged in a randomized block design and replicated four to six times within each location-year, depending on available space. Naturally occurring aphid infestations were allowed to reproduce throughout the season in the untreated control. The broad-spectrum insecticides λ-cyhalothrin (Warrior II with Zeon Technology® Syngenta Crop Protection, Greensboro, NC) and chlorpyrifos (Lorsban 4E®, Dow AgroSciences, Indianapolis, IN) at 225 ml per ha and 570 ml per ha respectively, were
applied whenever aphids were found in the aphid-free control. By comparing yield differences between these controls we have an indication of the total yield loss attributed to the soybean aphid. Treatments were to be applied when aphid population densities reached an ET of 250 aphids per plant (Ragsdale et al. 2007). However, the timing of treatment applications varied among locations and years, depending largely on the level of aphid infestation in any given location-year (Table 1). All insecticide application techniques were applied using backpack sprayer equipment. Insecticide application techniques were designed to achieve varying levels of coverage. To achieve the desired levels of coverage both volume and droplet sizes were varied. Varying nozzles (Spraying systems, Wheaton, IL) and pressures (Table 2), as defined by the American Society of Agricultural & Biological Engineers (ASABE 1999), to achieve differing droplet sizes of medium (181 L per ha, 138 Kpa, 8002 XR), fine (181 L per ha, 276 Kpa, 8002 XR), and very fine (362 L per ha, 276 Kpa, 11002 XR).

We selected a common contact insecticide from the pyrethroid class of chemistry, λ-cyhalothrin (Warrior II® at 225 ml per ha), and a common contact insecticide from the organophosphate class of chemistry, chlorpyrifos (Lorsban 4E® at 1,700 ml per ha), and included a tank-mix of the pyrethroid and organophosphate classes of chemistry, λ-cyhalothrin and chlorpyrifos (Warrior II® at 225 ml per ha and Lorsban 4E® at 570 ml per ha). All treatments were applied with the range of labeled rates for control of the soybean aphid in accordance with manufacturers recommendations.

We employed an incomplete factorial design to compare the different insecticide classes, both alone and in combination, with the varied application methods (Table 3). We recognized that the very fine application technique would be a higher cost to growers due to
lost efficiency (increased time spent loading equipment). This prompted the inclusion of the intermediate (fine) application technique. However this treatment was only applied using the pyrethroid class of chemistry due to resource constraints.

**Aphid sampling and soybean yield.** Plots were sampled once a week using *in situ* whole-plant counts to enumerate the total number of aphids per plant within each plot. In all three years, the number of plants sampled ranged from five to 20, determined by the proportion of infested plants during the previous sampling date. When 0% to 80% of plants were infested with soybean aphids, 20 plants were counted; when 81% to 99% of plants were infested, ten plants were counted; at 100% infestation, five plants were counted. The seasonal exposure of soybean to soybean aphid was reported in units of ‘cumulative aphid-days’ (CAD), calculated based on the number of aphids per plant between two sampling dates (Hanafi et al. 1989). Summing aphid days accumulated during the growing season, or CAD, provided a measure of the seasonal aphid exposure that a soybean plant experienced (Hodgson et al. 2004). Cumulative aphid days were calculated for the entire season. Plots were harvested once plants reached full maturity (R8). Entire plots were harvested with a small combine, and seed moisture was corrected to 13% before seed yields were estimated.

**Data analysis.** To determine the effectiveness of the application techniques, we compared plant exposure to aphids and yield data using PROC GLM procedures in SAS statistical software (V9.1, SAS Institute, Cary, NC). Average aphid-days accumulated each week were calculated for each treatment throughout the growing season. The effect of treatments on accumulation of aphid-days was determined using natural log-transformed data to meet the assumptions for analysis of variance (ANOVA). Differences in aphid exposure were determined by analyzing cumulative aphid days in a one-way ANOVA in PROC GLM.
(SAS Institute reference here) and \( F \)-protected least-squares means test for mean separation. Yield differences were analyzed in the same way. The statistical model for both aphid exposure and yield considered treatment and location as fixed effects, while year and blocks (nested within both year and location) were considered random effects.

**RESULTS**

Across the three years of the study, soybean aphid significantly reduced yield as evidenced by comparing the untreated controls to the aphid free controls (12% yield protection, Fig. 1). Across location-years, we observed significant differences in CAD amongst the application techniques in terms of soybean exposure to aphids \( (F = 26.6, \, df = 8,155, \, P < 0.0001) \). All application techniques reduced aphid populations compared to the untreated control (Table 4). All three, insecticide groups included in the study significantly reduced aphid exposure as the application technique changed from the medium to very fine application techniques (Table 4).

All insecticide applications, regardless of insecticide type or technique, protected soybean yield compared to the untreated control \( (F = 9.4, \, df = 8,155, \, P < 0.0001) \) (Table 5). Only the pyrethroid applied using the medium application technique failed to protected yield as well as multiple insecticide applications in the aphid free control treatment (Fig. 1). Only the pyrethroid insecticide exhibited significant additional yield protection as the application technique changed from medium to very fine, and the fine application technique resulted in a true intermediate which was not significantly different from either the medium or very fine application techniques (Fig. 1). Although insignificant, there was a trend of greater yield protection as droplet size decreased (Fig. 1). In the main effect analysis no differences in
yield protection due to insecticide were detected (Fig. 2). However, a significant \( F = 15.14, \ df = 4, 171, P < 0.0001 \) increase in yield protection of 108 kg per ha (1.6 bushels per acre) was detected when comparing the medium application technique to very fine application technique (Fig. 3).

**DISCUSSION**

The value of managing soybean aphid with insecticide applications based on scouting and the soybean aphid population reaching an ET (Ragsdale et al. 2007) is well supported by research (Johnson et al. 2009, Song and Swinton 2009) and growers are currently relying on insecticides to control soybean aphid accordingly (Olson et al. 2008).

Although proper application of pesticides has long been understood as a critical component of pesticide use, it is sometimes overlooked. The goal of any pesticide application should be to ensure that the pesticide contacts the pest with limited contact to non-target organisms. We found that the contact insecticides applied using application techniques that are commonly recommended for other contact pesticides (herbicides and fungicides) had a greater reduction in aphid populations and provided improved yield protection. This improvement was probably due to the increased levels coverage achieved by those application techniques.

We also observed little difference between the insecticides even though they represented different chemical classes. The lack of soybean yield differences between insecticide treatments is consistent with other insecticide evaluations (Myers et al. 2005, Johnson et al. 2009, Ohnesorg et al. 2009). Our results suggested proper pesticide application would increase the efficacy of a pesticide thus increasing the value of the
insecticide to the grower by increasing yield protection or possibly allowing for a reduction in application rates. We also recognize that the application techniques we are recommending for soybean aphid management may increase the potential of pesticide drift (Nuyttens et al. 2007), which is why pesticide applicators should always be aware of conditions such as wind, temperature, and relative humidity that are conducive to pesticide drift or volatization.

It is important to confirm the basic principles of pesticide application, and pesticide coverage are important considerations in pest management decisions. With the emergence of plant systemic insecticides more research should address pesticide application techniques that could reduce off target movement of pesticides and maximize the efficiency of the applied pesticides. This research has shown that efficiently applying insecticides could increase the efficacy and yield protection of a contact insecticide by 108 kg per ha (1.6 bu per ac) when insecticide application is warranted per an economic threshold. The additional yield protection would represent a significant value ($76 to $114 per ha) to growers at current the price levels of $8.00 to $12.00 per 27.2 kg (1 bushel).

ACKNOWLEDGMENTS

This journal paper of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 5032, was supported by Hatch Act and State of Iowa funds. In addition to the state of Iowa, we thank the Iowa Soybean Association and North Central Soybean Research Program for financial support of our research and Dow ArgoSciences and Syngenta Crop Protection for supplying insecticides. We would also like to thank Dr. Micheal Owen, Dr. Larry Pedigo, and Dr. Erin Hodgeson for help reviewing this manuscript. Finally, we would like to thank the Iowa State University farm managers Kenneth...
Pecinovsky, Dave Starret, and their respective staffs for assistance with management of the soybean plots.

LITERATURE CITED


Table 1. Experimental locations, dates of planting and application, aphid populations, and soybean varieties

<table>
<thead>
<tr>
<th>Year</th>
<th>Iowa County</th>
<th>Planting date</th>
<th>Application date</th>
<th>Aphid population at application</th>
<th>Soybean variety</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Story</td>
<td>23 May</td>
<td>7 Aug</td>
<td>161 ± 26</td>
<td>Prairie Brand 2494</td>
</tr>
<tr>
<td></td>
<td>Floyd</td>
<td>5 May</td>
<td>8 Aug</td>
<td>313 ± 56</td>
<td>Pioneer 93M90</td>
</tr>
<tr>
<td>2006</td>
<td>Story¹</td>
<td>11 May</td>
<td>NT</td>
<td>NT</td>
<td>Prairie Brand 2494</td>
</tr>
<tr>
<td></td>
<td>Floyd</td>
<td>28 April</td>
<td>7 Aug</td>
<td>168 ± 46</td>
<td>Pioneer 93M95</td>
</tr>
<tr>
<td>2007</td>
<td>Story</td>
<td>3 May</td>
<td>18 July</td>
<td>394 ± 172</td>
<td>Prairie Brand 2490</td>
</tr>
<tr>
<td></td>
<td>Floyd</td>
<td>15 May</td>
<td>31 July</td>
<td>280 ± 79</td>
<td>Pioneer 93M95</td>
</tr>
</tbody>
</table>

¹ Story County not treated in 2006 due to low aphid populations.
² Seed was obtained through Prairie Brand (Story City, IA) and Pioneer Hi-Bred International (Johnston, IA).
Table 2. Application parameters for droplet size ratings

<table>
<thead>
<tr>
<th>Droplet rating(^1)</th>
<th>VMD(^2) range (microns)</th>
<th>Pressure (Kpa)</th>
<th>Nozzle(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>226-325</td>
<td>138</td>
<td>8002 XR</td>
</tr>
<tr>
<td>Fine</td>
<td>145-225</td>
<td>276</td>
<td>8002 XR</td>
</tr>
<tr>
<td>Very fine</td>
<td>&lt;144</td>
<td>276</td>
<td>11002 TJ</td>
</tr>
</tbody>
</table>

\(^1\)As defined by American Society of Agricultural & Biological Engineers Standard 572.

\(^2\)Volume Median Diameter (VMD) the value where 50% of the total volume of liquid sprayed is made up of larger droplets and 50% of the total volume is made up of smaller droplets.

\(^3\)TeeJet\(^®\) (Spraying Systems, Wheaton, IL) nozzles single orifice extended range (XR) or double orifice twin jet (TJ).
<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Droplet rating&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Application rate (l per ha)</th>
<th>Pressure (Kpa)</th>
<th>Nozzle&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ-cyhalothrin&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Medium</td>
<td>181</td>
<td>138</td>
<td>8002 XR</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>181</td>
<td>276</td>
<td>8002 XR</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>362</td>
<td>276</td>
<td>11002 TJ</td>
</tr>
<tr>
<td>chlorpyrifos&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Medium</td>
<td>181</td>
<td>138</td>
<td>8002 XR</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>362</td>
<td>276</td>
<td>11002 TJ</td>
</tr>
<tr>
<td>λ-cyhalothrin and chlorpyrifos</td>
<td>Medium</td>
<td>181</td>
<td>138</td>
<td>8002 XR</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>362</td>
<td>276</td>
<td>11002 TJ</td>
</tr>
</tbody>
</table>

<sup>1</sup> As defined by American Society of Agricultural & Biological Engineers Standard 572.

<sup>2</sup> TeeJet® (Spraying Systems, Wheaton, IL) nozzles single orifice extended range (XR) or double orifice twin jet (TJ).

<sup>3</sup> Warrior II with Zeon Technology®, Syngenta Crop Protection, Greensboro, NC.

<sup>4</sup> Lorsban 4E®, Dow AgroSciences, Indianapolis, IN.
Table 4. Effect of application parameters on cumulative aphid day exposure post insecticide application

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Droplet rating</th>
<th>CAD²</th>
<th>Yield³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Control</td>
<td>NA</td>
<td>8,691 ± 3</td>
<td>3,830 ± 94</td>
</tr>
<tr>
<td>Aphid free control⁴</td>
<td>Very fine</td>
<td>98 ± 48*</td>
<td>4,280 ± 47*</td>
</tr>
<tr>
<td>λ-cyhalothrin⁵</td>
<td>Medium</td>
<td>2,618 ± 5*</td>
<td>3,944 ± 108*</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>1,998 ± 4*</td>
<td>4,065 ± 74*</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>1,901 ± 3*</td>
<td>4,213 ± 67*</td>
</tr>
<tr>
<td>Chlorpyrifos⁶</td>
<td>Medium</td>
<td>1,236 ± 5*</td>
<td>4,092 ± 114*</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>973 ± 6*</td>
<td>4,112 ± 74*</td>
</tr>
<tr>
<td>λ-cyhalothrin and chlorpyrifos</td>
<td>Medium</td>
<td>1,480 ± 5*</td>
<td>4,045 ± 81*</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>1,437 ± 4*</td>
<td>4,085 ± 81*</td>
</tr>
</tbody>
</table>

¹ASABE (American Society of Agricultural & Biological Engineers) Standard 572.
²Cumulative aphid day (CAD) post insecticide application ± Stand Error of the Mean.
³Yield in kg per hectare ha corrected to 13% moisture ± Stand Error of the Mean.
⁴Aphid free control was applied when aphids exceeded 10 aphids per plant, which resulted in multiple applications.
⁵Warrior II with Zeon Technology®, Syngenta Crop Protection, Greensboro, NC.
⁶Lorsban 4E®, Dow AgroSciences, Indianapolis, IN.
* Significantly different from the untreated control P ≤ 0.05.
FIGURE CAPTIONS

Figure 1. Effect of treatments on soybean yield (kg per ha ± Stand Error of the Mean) across all location-years. All three of the insecticide groups had improved soybean yield protection compared when applied using contact pesticide application techniques. Means labeled with a unique letter were significantly different ($P \leq 0.05$).

Figure 2. The main effect of insecticide types on soybean yield (kg per ha ± Stand Error of the Mean) across all location-years and application techniques. Means were not significantly different ($P \leq 0.05$).

Figure 3. The main effect of application type on soybean yield (kg per ha ± Stand Error of the Mean) across all location-years and insecticides. Application techniques in line with other contact pesticides produced a yield advantage of 108 kg per ha (1.6 bu per ac). Means labeled with a unique letter were significantly different ($P \leq 0.05$).
Figure 1.
Figure 3.
CHAPTER 3.

PROBABILITY OF COST-EFFECTIVE MANAGEMENT OF SOYBEAN APHID (HEMIPTERA: APHIDIDAE) IN NORTH AMERICA


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ABSTRACT

Soybean aphid, *Aphis glycines* Matsumura, is one of the most damaging pests of soybean, *Glycine max* (L.) Merrill, in the Midwestern United States and Canada. We compared three soybean aphid management techniques in three Midwest states (Iowa, Michigan, and Minnesota) for a three year time period (2005-2007). Management techniques included an untreated control, an insecticidal seed treatment, an insecticide fungicide tank-mix applied at flowering (i.e. a prophylactic treatment), and an Integrated Pest Management (IPM) treatment (i.e. an insecticide applied based on a weekly scouting and an economic threshold). In 2005 and 2007, multiple locations experienced aphid population levels that exceeded the economic threshold, resulting in the application of the IPM treatment. Regardless of the timing of the application, all insecticide treatments reduced aphid populations as compared to the untreated, and all treatments protected yield as compared to the untreated. Treatment efficacy and cost data were combined to compute the probability of a positive economic return. The IPM treatment had the highest probability of cost effectiveness, when compared to the prophylactic tank-mix of fungicide and insecticide. The probability of surpassing the gain threshold was highest in the IPM treatment, regardless of the scouting cost assigned to the treatment (ranging from $0.00 to $19.76 per ha). Our study further confirms that a single insecticide application can enhance the profitability of soybean production at risk of a soybean aphid outbreak if used within an IPM based system.
INTRODUCTION

SOYBEAN APHID, *Aphis glycines* Matsumura, is a significant insect threat to soybean production in North America (Ragsdale et al. 2007). Advances in host plant resistance (Hill et al. 2004a, b, Liu et al. 2004, Mensah et al. 2005) and importation biological control (i.e. classical biological control; Heimpel et al. 2004) may make significant contributions to soybean aphid management in the future. However, current soybean production in North America relies on chemical control to prevent yield loss due to the soybean aphid. Consistent protection of soybean yield can be achieved with a single application of a foliar insecticide (Myers et al. 2005) applied during soybean aphid outbreaks (>500 aphids per plant) that occur in the reproductive stages of the plants growth. Approximately 423 aphids per plant are required to reduce soybean yield below an economic injury level (EIL) based on the following assumptions: control cost of $24.51 per ha, market value of $238.83 per ton, and a yield potential of 4.04 ton per ha (Ragsdale et al. 2007). To prevent this EIL from being reached, growers are recommended to apply a foliar insecticide when soybean aphid populations exceed an economic threshold (ET) of 250 aphids per plant (assuming a 4 day lag-time before the EIL is reached) between flowering (R1) and early seed set (R5). Left untreated, soybean aphid herbivory can result in yield losses exceeding 40% (Ragsdale et al. 2007).

Before the discovery of the soybean aphid in North America, there was limited use of insecticides for soybean production in the Midwest (NASS 1999). Since the arrival and establishment of the soybean aphid to the North Central region of the U.S., the use of insecticides has increased (NASS 2005). Currently soybean aphid management is primarily through the use of foliar-applied pyrethroid and organophosphate insecticides.
Neonicotinoid insecticide seed treatments are available to North America soybean growers to manage bean leaf beetle, *Cerotoma trifurcata* ( Förster), as well as soybean aphids. However, a limitation of seed treatments is the loss of insecticidal activity between 35 to 42 days after planting (V2-V4), prior to when soybean aphid outbreaks or colonization typically occur in North America (McCornack and Ragsdale 2006, Johnson et al. 2008). However, given the ease of use and the occasional need for protection from early season insect pests (Bradshaw et al. 2008), the adoption of seed treatments is increasing.

In addition to increased insecticide use, interest in fungicide application to soybeans has also increased with the discovery of Asian soybean rust (*Phakopsora pachyrhizi* Sydow) in North America. *Phakopsora pachyrhizi* is an invasive fungal disease that can significantly reduce soybean yield (Kawuki et al. 2003, Miles et al. 2003). In the absence of *P. pachyrhizi*, inconsistent but positive yield responses are possible with the application of fungicide (Hanna et al. 2008) through control of various (or multiple) fungal pathogens present in North America soybeans (Dashiell and Akem 1991). As a result, growers are increasingly exposed to marketing promotions that advise the application of tank-mixed pesticides (fungicides and insecticides) based on a calendar date or plant growth stage. Such an approach to pest management is inconsistent with integrated pest management (IPM) approach for soybean aphid, which relies on scouting and insecticide application only when an aphid population exceeds the ET. It is not clear how a prophylactic approach (either tank-mixes or insecticidal seed treatments) compares to use of IPM in managing soybean aphid outbreaks and protecting yield.

The occurrence of soybean aphid outbreaks in North America is highly variable, with orders of magnitude difference in aphid populations occurring among years and locations.
Aphid outbreaks can be suppressed by a community of predatory insects (Fox et al. 2004, Fox et al. 2005, Costamagna and Landis 2006, Schmidt et al. 2007, Schmidt et al. 2008, Gardiner et al. 2009), but this predator community is easily disrupted by the application of insecticides (Jeffries and Lawton 1984, Ohnesorg et al. in press). Broad-spectrum insecticides applied for soybean aphid control in a prophylactic approach may flair secondary pest populations, or allow rapid re-colonization of the primary pest, due to the creation of enemy-free space (Jeffries and Lawton 1984). Prophylactic insecticide applications for soybean aphid management may not protect yield if applied before aphid colonization, and may instead cause resurgence in aphid populations or secondary pests such as two-spotted spider mite *Tetranychus urticae* Koch (Gerson and Cohen 1989, Johnson et al. 2008). The intensity and frequency of soybean aphid, colonization, summer migratory flights, and outbreaks are temporally and spatially variable. As a result, it is not clear that prophylactic applications of insecticide are effective in preventing yield losses from soybean aphids over several growing seasons. Our objective was to compare prophylactic soybean aphid management strategies to an IPM approach, determining which resulted in the most consistent reduction in plant exposure to soybean aphids and soybean yield, while maintaining overall profitability. We conducted this experiment across multiple of locations in the North Central region of the U.S. where soybean aphids are established and cause considerable damage to soybeans.

**MATERIALS AND METHODS**

In 2005, 2006, and 2007, a common experimental approach was used at two locations each year in three states (Iowa, Michigan, and Minnesota). At each location, a soybean
variety adapted for that area was planted between late April to late May, depending on weather conditions (Table 1). Plots were 0.20 to 0.40 ha (0.50 to 1.0 acres) in size with a row spacing of 76.2 cm (30 inches). Conventional production practices and a glyphosate-based weed control program were employed at all locations. Three management approaches were compared to an untreated control: 1) an insecticidal seed treatment (the ‘seed treatment' was included at all locations in 2006 and 2007), 2) a preventative tank-mix of an insecticide with a fungicide, applied regardless of aphid abundance (the ‘prophylactic treatment’), and 3) an IPM-based approach which employed scouting and an economic threshold of 250 aphids per plant (Ragsdale et al. 2007) to time a foliar-applied insecticide (referred to as the ‘IPM treatment’).

Treatments were arranged in a randomized block design and replicated four to six times within each location-year, depending on available space. The timing of treatment applications varied among locations and years, depending largely on planting date and the level of aphid infestation in any given location-year (Table 1). The seed-treatment was thiamethoxam at 56.3 g A.I. per 100 kg seed (CruiserMaxx®, Syngenta Crop Protection, Greensboro, NC) applied commercially to the seed. The prophylactic treatment was a tank mix of the insecticide lambda-cyhalothrin at 28.0 g A.I. per ha (Warrior with Zeon Technology®, Syngenta Crop Protection, Greensboro, NC), and the fungicide pyraclostrobin at 89.6 g A.I. per ha (Headline®, BASF Corporation, Research Triangle, NC). The prophylactic treatment was applied regardless of aphid pressure once the reproductive growth stage (R1-R2) was reached (averaged across all blocks). Soybean growth stages (Pedersen 2004) were noted each week in all plots. The IPM treatment was scouted weekly (see below) and was treated with the foliar insecticide lambda-cyhalothrin at 28.0 g A.I. per ha once the
ET (250 aphids per plant) was crossed (aphids per plant averaged across all blocks at a given location). The prophylactic treatment was applied as plants reached the predetermined growth stage and the IPM treatment was applied within 5 days after reaching 250 aphids per plant. All foliar insecticides were applied using ground-based equipment.

**Aphid Sampling and Soybean Yield.** Soybean aphid populations at all locations originated from natural populations. Plots were sampled once a week using either in situ or destructive whole-plant counts to estimate the average number of aphids per plant in each plot. In 2005, 10 plants were randomly selected from locations in each plot. The aphid sampling protocol was modified in 2006 because our understanding of how spatial distribution of soybean aphids varied with population density improved (Hodgson et al. 2004). In 2006 and 2007, the number of plants sampled ranged from 5 to 20, determined by the proportion of infested plants on the previous sampling date. When 0% to 80% of plants were infested, 20 plants were counted; when 81% to 99% of plants were infested, 10 plants were counted; at 100% infestation, 5 plants were counted. The seasonal exposure of soybean to soybean aphid was reported in units of ‘cumulative aphid-days’, calculated based on the number of aphids per plant between two sampling dates (Hanafi et al. 1989). Summing aphid days for the growing season, or cumulative aphid-days (CAD), provided a measure of the seasonal aphid exposure to soybean plants in a treatment (Hodgson et al. 2004). Yield was estimated either by harvesting the entire plot with a small combine, or by harvesting a randomly selected two row section with a two row plot combine, and adjusting seed moisture to 13%. For analysis, treatment averages of season long cumulative aphid-days and yield were compared.
**Data analysis.** To determine the effectiveness of the soybean aphid management approaches, we compared plant exposure to aphids and yield data using the PROC MIXED procedure in SAS statistical software (V9.1, SAS Institute, Cary, NC). The statistical model for both aphid exposure and yield considered treatment and location as fixed effects, while year and blocks (nested within both year and location) were considered random effects. Average aphid-days accumulated each week were calculated for each treatment throughout the growing season. The effect of insecticide treatments on accumulation of aphid-days was determined using natural log-transformed data to meet the assumptions for analysis of variance (ANOVA). Differences in aphid exposure were determined by analyzing cumulative aphid days in a one-way ANOVA in PROC MIXED and using F-protected least-squares means test for mean separation. Yield differences were analyzed in the same way.

The effectiveness of each management plan was also analyzed based on break-even yield gain analysis. A yield gain threshold (GT) was calculated based on insecticide and application costs, expected crop price, and expected yield. The GT is expressed in kg per ha and calculated as estimated control costs (C) [$ per unit area] divided by expected crop price (P) [$ per unit sold] (Pedigo et al. 1986), which is equivalent to

\[
GT = \frac{C}{P}. \tag{1}
\]

Average retail price of pesticides and their associated application costs were obtained from an informal phone survey of multiple elevators from across the three states in which the experiment was conducted (Table 2). Treatment costs were remarkably consistent across the three participating states with the exception of scouting cost, which ranged from $0.00 to $19.76 per ha, depending on the scouting service. Low-cost scouting ($0.00 per ha) was
provided to growers by some firms contingent on the purchase of inputs, while higher-cost scouting ($19.76 per ha) was provided by full-service firms which scouted weekly for insects, weeds, and diseases for the full season. Four soybean prices ranging from $6.00 to $12.00 per 27.2 kg (one U.S. bushel) were selected to represent the range of recent futures prices (Table 2).

Without clear understanding of how combinations of insecticides and fungicides would interact to affect yield, we analyze the cost effectiveness using Bayesian statistical methods to calculate the probability that an aphid management strategy is cost effective rather than using a traditional analysis of variance. Bayesian statistical methods provide intuitive and meaningful inferences, which are well suited for decision-making problems (Ellison 1996, Johnson 1999). The Bayesian approach to statistical analysis is that a parameter (e.g. the difference in mean yields between two treatments) has a probability distribution. A hypothesized prior distribution describes the knowledge about the parameter before the data are collected. The posterior distribution describes the knowledge about the parameter after the data are collected. Following Munkvold et al. (2001), we present the probability that the yield gain from a treatment exceeded the GT at each of the four soybean prices. Given an appropriate choice of prior distributions, the posterior distribution of the difference in yield is a rescaled t-distribution (Box and Tiao 1973). The probability that the yield difference exceeds a specified gain threshold is the integral of the posterior distribution of yield difference from the gain threshold to infinity. This probability can be calculated using SAS software by calculating a recentered t-quantile, t(GT):
\[
t(GT) = \frac{GT - (\bar{y}_t - \bar{y}_c)}{s \sqrt{\frac{1}{n_t} + \frac{1}{n_c}}}
\]

then calculating the one-tailed probability that a random variable with a T distribution exceeds \( t(GT) \). This can be calculated in SAS by:

\[
P_{\text{net}} = 1 - \text{PROBT}[t(GT), df_e]
\]

where \( df_e \) is the error d.f. associated with the pooled standard deviation, \( s \). Replacing \( GT \) with \( \Delta GT \) in equation 2 gives the probability that yield gains from one treatment exceed those from a second treatment.

**RESULTS**

**Aphid exposure and yield.** Across location-years, we observed significant differences in CAD among the management approaches in soybean exposure to aphids (Table 3). All three management approaches reduced aphid exposure compared to the untreated control (\( df = 3,211, F = 24.25, P = <0.0001 \)). Despite a significant difference in aphid exposure between the IPM (807 CAD’s) treatment and both the prophylactic (402 CAD’s) and seed treatment (471 CAD’s) approaches there was no evidence of a difference in soybean yield among the management treatments (Table 3, \( df = 2,211, F = 12.68, P = <0.0001 \)).

Aphid populations and consequent aphid exposure varied significantly from year to year with the highest levels of aphid exposure to soybean aphids in 2005 and 2007 (Table 4). Among the locations, Minnesota farms consistently experienced high aphid populations compared to Iowa and Michigan (Table 5), and applied the IPM treatment with greater frequency (Table 1). The abundance of aphids in 2005 and 2007 resulted in 50 percent of the
locations in 2005 and 33 percent of the locations in 2007 reaching the ET, leading to an application of the IPM treatment.

Significant treatment differences in both aphid exposure and yield were observed among treatments. Over all locations and years, soybeans treated with thiamethoxam or the prophylactic treatment had the lowest levels of aphid exposure. The IPM treatment had an intermediate level of aphid exposure, and the untreated control had the highest levels of aphid exposure (Table 3). Soybean yield varied significantly among treatments, years, and locations (Tables 3, 4, 5). Differences in soybean yield were less variable with only two levels of separation being detected with significantly lower yields in the untreated control treatment overall (Table 3), as well as across locations and years (Tables 4, 5).

Cost effectiveness analysis. Overall, as crop price increased, the probability of recouping the cost of any given treatment increased (Table 6). Although there was little difference in yield among the three insecticide treatments, there was a large difference among the probability of recouping treatment costs. The Bayesian break-even yield gain analysis indicates that regardless of scouting cost, the IPM treatments had the highest probability of recouping treatment cost (Table 6). The seed treatment (thiamethoxam) consistently had the lowest probability of recouping its cost with between 43% probability (at $6.00 per 27.2 kg) and 51% probability (at $12.00 per 27.2 kg) of exceeding the cost of the treatment. The IPM treatment was more likely to give a higher yield gain than either the prophylactic treatment or the thiamethoxam seed treatment, even at the higher scouting cost (Tables 6, 7). As the crop price increased, the cost-effectiveness of the IPM treatment declined as compared to the prophylactic treatment (Table 7).
DISCUSSION

Soybean aphid management should be based on scouting and applying an insecticide only when populations exceed the ET. Our data supports this recommendation (Ragsdale et al. 2007) that soybean fields be scouted weekly until aphid populations exceed an economic threshold. Preventative applications of insecticides, either applied to the seed or foliage, did not significantly reduce soybean exposure to soybean aphids or prevent yield lost compared to insecticides applied in an IPM approach. Our results are consistent with previous studies that show seed treatments do not provide significant protection against yield loss caused by soybean aphids (McCornack and Ragsdale 2006, Johnson et al. 2008). Although seed treatments are convenient and have limited impact to natural enemies (Ohnesorg et al. in review), colonization by the soybean aphid usually occurs after the activity of the neonicotinoid-based seed treatments residual activity has declined. Due to the variability of soybean aphid phenology within the North Central region, timing the application of a foliar insecticide with a potential outbreak is critical for effective soybean aphid management. Locations in this study did not experience injury from early-season insect pests, such as white grubs and bean leaf beetle. Such insects could justify the use of seed-applied insecticides (Bradshaw et al. 2008).

We defined our prophylactic application insecticide with a fungicide applied at the start of flowering (R1). As discussed earlier, the interest in fungicide use in soybeans has increased with the arrival of *P. pachyrhizi* to North America, had influenced our decision to include a second class of pesticide. The application of herbicide, typically glyphosate, is a common practice by growers throughout the Midwest due to the rapid adoption of glyphosate tolerant soybeans. We are aware of no evidence that co-application of glyphosate and
insecticide are incompatible, and this practice is likely commonly used by growers interested in a preventative approach to soybean aphid management. The timing of such an application could vary due to weed-management needs of a grower. Glyphosate applications are typically based on crop and weed development (Coulter and Nafziger 2007), and the application varies within a range from late May to early July in the Midwest. Johnson et al. (2008) explored if the application of an insecticide timed with the emergence of the first generation of *C. trifurcata* protected soybeans from *Soybean aphid*. They found little impact to *Soybean aphid* when insecticides were applied from mid June to early July and no yield protection. With the application of a fungicide we anticipated some yield protection and a potential economic benefit. Therefore, we elected to include a fungicide-insecticide combination timed to potential fungal pathogen as our preventative treatment. However, the application of pesticides does not insure yield improvement and ecological backlash may work counter to crop production.

The objective of this study was to determine the economic viability of management practices targeting the soybean aphid, and not the ecological consequences due to these practices. Collectively referred to as ecological backlash (Pedigo and Rice 2008), there are three types of negative consequences of insecticide use: resistance to the active ingredient, resurgence of the target pest, and replacement of the target pest by a insect that previously did not have significant pest status (Stern et al. 1959).

Regarding resurgence, this form of ecological backlash is possible within soybeans. The insecticides used in soybeans are toxic to soybean aphid natural enemies (Ohnesorg et al. in review) and interfere with the biological control these beneficial insects provide. While the effects of predatory insects on soybean aphid are well documented (Brown et al. 2003,
Fox et al. 2004, Rutledge et al. 2004, Fox et al. 2005, Rutledge and O’Neil 2005, Brosius et al. 2007, Schmidt et al. 2007, Schmidt et al. 2008, Gardiner et al. 2009), the effects of entomopathogenic fungi are not. Latteur and Jansen (2002) demonstrated that many fungicides reduce the infectivity of *Erynia neoaphidis*, observed as a source of mortality of soybean aphid in North America (Nielsen and Hajek 2005). At one location (2007, Story County, IA) we observed higher populations of soybean aphid in plots treated with the prophylactic treatment 31 days after the treatment was applied. This was remarkable, given that the IPM treatment was applied at the same time, and showed no such increase. This suggests that the fungicidal component of the tank-mix may have prevented mortality from entomopathogenic fungi. Across our entire study, an increase in aphid populations in the prophylactic treatment was only observed at one location. Because this study was focused on issues of management and not ecology, it is not clear how much risk soybean growers face when employing a preventative approach for soybean aphid management. We did not evaluate the risk of resurgence across the full range of products available to soybean growers in the North Central Region of the U.S. Furthermore, we did not control for the biotic and abiotic factors (temperature, humidity) that are additional aspects of the disease triangle required for epizootics to occur.

The risk of pest resurgence from a prophylactic approach is not limited to the soybean aphid, but could also include other potential insect pests of soybeans such as spider mite and green cloverworm *Plathypena scabra* (Fabricius) whose populations may be limited by entomopathogenic fungi (Higley and Boethel 1994). However, we argue that this uncertainty only further supports the current IPM-based recommendations for soybean aphid management.
Willingness of growers to adopt any pest management approach could be increased if the cost of the treatment is reduced such that the gain threshold is more likely to be reached. The occurrence of any ecological backlash from a preventative approach would effectively increase the cost of the prophylactic treatment, further decreasing the probability of profitable soybean pest management. As our probability analysis indicates, the cost effectiveness of an IPM approach is revealed only over time. It may require several location-years before all forms of ecological backlash become apparent to a grower. We recommend the risk associated with a preventative approach to soybean aphid be communicated to growers in order to prevent growers from experiencing such events.

Integrated pest management approaches based on economic cost-benefit analyses are recognized for effectively managing pest populations (Stern 1973, Pedigo et al. 1986, Pedigo 1995, Ragsdale et al. 2007). This study shows that a single insecticide application can enhance the profitability of soybean production if used properly in an IPM based system. In particular, the IPM treatment was most likely to provide yield protection that exceeded the gain threshold, covering the treatment cost. This finding held even at the high scouting cost of $19.76 ha$^{-1}$, which shows it to be highly robust, as this scouting fee substantially exceeds the $5.00 ha$^{-1}$ rate reported by Song et al. (2006) as the proportion of a typical crop consultant commercial scouting fee in Michigan that is attributable to soybean aphid scouting visits. The finding is consistent with Song and Swinton’s (in review) analysis, which finds that timely insecticide application resulted in soybean yield protection that fully offset yield loss when the soybean aphid population exceeded the economic threshold. It is important to mention that grower benefit from the $19.76 ha$^{-1}$ was not limited to information on aphid populations. The services provided for this fee at full service scouting agencies included
monitoring all insect pest densities, weed densities, disease pressure, soil nutrient analysis, and offering management advice. Even using the conservative scouting fee of $19.76 ha\(^{-1}\) the likelihood of exceeding the gain threshold was less with the prophylactic approach than with the IPM approach. The IPM approach was clearly the most profitable in our breakeven analysis, which fits with findings across broad range of U.S. crops where IPM practices have been adopted (Fernandez-Cornejo et al. 1998).

**ACKNOWLEDGMENTS**

We thank the United States Department of Agriculture’s Risk Assessment and Mitigation Program (“Soybean Aphid in the North Central U.S.: Implementing IPM at the Landscape Scale”, USDA CSREES 2004-04185), the Iowa Soybean Association, Syngenta Crop Protection, and BASF Corporation for financial assistance and support for fieldwork conducted in the participating states. We also thank the many individuals in the three states that collected data, counted aphids, managed field plots and assisted in all aspects of this study.

**LITERATURE CITED**


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Table 1. Experimental locations, dates of planting and treatment applications

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Planting</th>
<th>Prophylactic</th>
<th>IPM</th>
<th>Variety</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Story, IA</td>
<td>23 May</td>
<td>7 July</td>
<td>NA</td>
<td>Prairie Brand 2494</td>
</tr>
<tr>
<td></td>
<td>Lucas, IA</td>
<td>5 May</td>
<td>8 July</td>
<td>NA</td>
<td>Pioneer 93M90</td>
</tr>
<tr>
<td></td>
<td>Kalamazoo, MI</td>
<td>23 May</td>
<td>19 July</td>
<td>NA</td>
<td>Pioneer 92M70</td>
</tr>
<tr>
<td></td>
<td>Saginaw, MI</td>
<td>10 May</td>
<td>13 July</td>
<td>13 July</td>
<td>Pioneer 91B64</td>
</tr>
<tr>
<td></td>
<td>Redwood, MN</td>
<td>31 May</td>
<td>13 July</td>
<td>27 July</td>
<td>Asgrow 2007</td>
</tr>
<tr>
<td></td>
<td>Dakota, MN</td>
<td>24 May</td>
<td>13 July</td>
<td>4 Aug</td>
<td>Pioneer 91B91RR</td>
</tr>
<tr>
<td>2006</td>
<td>Story, IA</td>
<td>11 May</td>
<td>11 July</td>
<td>NA</td>
<td>Prairie Brand 2494</td>
</tr>
<tr>
<td></td>
<td>Lucas, IA</td>
<td>28 April</td>
<td>12 July</td>
<td>NA</td>
<td>Pioneer 93M95</td>
</tr>
<tr>
<td></td>
<td>Kalamazoo, MI</td>
<td>26 May</td>
<td>26 July</td>
<td>NA</td>
<td>Asgrow AG2703</td>
</tr>
<tr>
<td></td>
<td>Saginaw, MI</td>
<td>4 May</td>
<td>14 July</td>
<td>NA</td>
<td>Pioneer 91M60</td>
</tr>
<tr>
<td></td>
<td>Redwood, MN</td>
<td>22 May</td>
<td>18 July</td>
<td>27 July</td>
<td>NK S19-L7</td>
</tr>
<tr>
<td></td>
<td>Dakota, MN</td>
<td>19 May</td>
<td>27 July</td>
<td>NA</td>
<td>NK S19-R5</td>
</tr>
<tr>
<td>2007</td>
<td>Story, IA</td>
<td>3 May</td>
<td>18 July</td>
<td>18 July</td>
<td>Prairie Brand 2494</td>
</tr>
<tr>
<td></td>
<td>Lucas, IA</td>
<td>15 May</td>
<td>20 July</td>
<td>NA</td>
<td>Pioneer 93M95</td>
</tr>
<tr>
<td></td>
<td>Kalamazoo, MI</td>
<td>15 May</td>
<td>24 July</td>
<td>NA</td>
<td>Dekalb 27-53</td>
</tr>
<tr>
<td></td>
<td>Saginaw, MI</td>
<td>7 May</td>
<td>13 July</td>
<td>NA</td>
<td>Pioneer 91M61</td>
</tr>
<tr>
<td></td>
<td>Redwood, MN</td>
<td>28 May</td>
<td>6 July</td>
<td>7 August</td>
<td>NK S19-L7</td>
</tr>
<tr>
<td></td>
<td>Dakota, MN</td>
<td>19 May</td>
<td>23 July</td>
<td>NA</td>
<td>Pioneer 92M02</td>
</tr>
</tbody>
</table>

1 County and state
2 The IPM treatment was only applied if naturally-occurring soybean aphid populations exceeded an average of 250 aphids per plant.
Table 2. Treatment costs and yield gain thresholds at four soybean prices.

<table>
<thead>
<tr>
<th>Management tactic</th>
<th>Cost(^3)</th>
<th>$6.00</th>
<th>$8.00</th>
<th>$10.00</th>
<th>$12.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated Control</td>
<td>$0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IPM (lowest scouting cost)</td>
<td>$35.82(^4)</td>
<td>162</td>
<td>121</td>
<td>101</td>
<td>81</td>
</tr>
<tr>
<td>scouting (low)</td>
<td>$0.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>lambda-cyhalothrin application</td>
<td>$19.76</td>
<td>90</td>
<td>67</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>lambda-cyhalothrin application</td>
<td>$16.06</td>
<td>73</td>
<td>54</td>
<td>47</td>
<td>34</td>
</tr>
<tr>
<td>IPM (highest scouting cost)</td>
<td>$55.58(^4)</td>
<td>252</td>
<td>188</td>
<td>155</td>
<td>121</td>
</tr>
<tr>
<td>scouting (high)</td>
<td>$19.76</td>
<td>90</td>
<td>67</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>lambda-cyhalothrin application</td>
<td>$19.76</td>
<td>90</td>
<td>67</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>lambda-cyhalothrin application</td>
<td>$16.06</td>
<td>73</td>
<td>54</td>
<td>47</td>
<td>34</td>
</tr>
<tr>
<td>Prophylactic</td>
<td>$58.06(^4)</td>
<td>263</td>
<td>196</td>
<td>161</td>
<td>135</td>
</tr>
<tr>
<td>lambda-cyhalothrin application</td>
<td>$19.76</td>
<td>90</td>
<td>67</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>pyraclostrobin</td>
<td>$22.24</td>
<td>101</td>
<td>74</td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>application</td>
<td>$16.06</td>
<td>73</td>
<td>54</td>
<td>47</td>
<td>34</td>
</tr>
<tr>
<td>thiamethoxam</td>
<td>$23.47</td>
<td>106</td>
<td>81</td>
<td>67</td>
<td>54</td>
</tr>
</tbody>
</table>

\(^1\) In kg per ha
\(^2\) Soybean prices in U.S. dollars per 27.2 kg (1 U.S. bushel)
\(^3\) Cost in U.S. dollars per ha
\(^4\) Includes the cost of both pesticides and application
Table 3. Overall treatment effects on aphid exposure and yield\(^1\)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Cumulative Aphid days(^2)</th>
<th>Yield(^2,3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1582 ± 5.0 c</td>
<td>1271 ± 52 a</td>
</tr>
<tr>
<td>Prophylactic</td>
<td>402 ± 5.0 a</td>
<td>1380 ± 52 b</td>
</tr>
<tr>
<td>Seed-treatment</td>
<td>471 ± 5.1 a</td>
<td>1366 ± 52 b</td>
</tr>
<tr>
<td>IPM</td>
<td>807 ± 5.0 b</td>
<td>1369 ± 52 b</td>
</tr>
</tbody>
</table>

\(^1\) Means and Standard Errors are from least squares means in Proc Mixed.
\(^2\) Mean ± Standard Error. Means labeled with a unique letter were significantly different (\(P < 0.05\)).
\(^3\) Yield in kg per ha
<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Cumulative aphid days</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Control</td>
<td>15214 ± 1.2 c</td>
<td>1225 ± 30 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>3569 ± 1.2 a</td>
<td>1407 ± 30 b</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>5825 ± 1.2 b</td>
<td>1393 ± 30 b</td>
</tr>
<tr>
<td>2006</td>
<td>Control</td>
<td>98 ± 1.4 c</td>
<td>1423 ± 19 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>20 ± 1.4 a</td>
<td>1434 ± 19 a</td>
</tr>
<tr>
<td></td>
<td>Seed-treatment</td>
<td>27 ± 1.4 a</td>
<td>1437 ± 19 a</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>58 ± 1.4 b</td>
<td>1410 ± 19 a</td>
</tr>
<tr>
<td>2007</td>
<td>Control</td>
<td>2940 ± 2.2 c</td>
<td>1148 ± 14 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>1098 ± 2.2 a</td>
<td>1285 ± 14 b</td>
</tr>
<tr>
<td></td>
<td>Seed-treatment</td>
<td>936 ± 2.2 a</td>
<td>1268 ± 14 b</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>1716 ± 2.2 b</td>
<td>1295 ± 14 b</td>
</tr>
</tbody>
</table>

1 Means and Standard Errors are from least squares means in Proc Mixed.
2 Mean ± Standard Error. Means labeled with a unique letter were significantly different ($P < 0.05$).
3 Yield in kg per ha
Table 5. Treatment effects on aphid exposure and yield by state

<table>
<thead>
<tr>
<th>State</th>
<th>Treatment</th>
<th>Cumulative aphid days</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean ± SEM</td>
<td>Mean ± SEM</td>
</tr>
<tr>
<td>Iowa</td>
<td>Control</td>
<td>1703 ± 4 c</td>
<td>1467 ± 117 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>962.9 ± 4 ab</td>
<td>1557 ± 114 b</td>
</tr>
<tr>
<td></td>
<td>Seed-treatment</td>
<td>750 ± 4 a</td>
<td>1584 ± 117 b</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>1012 ± 4 b</td>
<td>1611 ± 109 b</td>
</tr>
<tr>
<td>Michigan</td>
<td>Control</td>
<td>478 ± 19.7 c</td>
<td>1119 ± 177 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>67 ± 19.7 a</td>
<td>1227 ± 177 b</td>
</tr>
<tr>
<td></td>
<td>Seed-treatment</td>
<td>119 ± 19.7 ab</td>
<td>1225 ± 177 b</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>290 ± 19.7 b</td>
<td>1187 ± 177 a</td>
</tr>
<tr>
<td>Minnesota</td>
<td>Control</td>
<td>5167 ± 1.6 c</td>
<td>1217 ± 95 a</td>
</tr>
<tr>
<td></td>
<td>Prophylactic</td>
<td>1054 ± 1.6 a</td>
<td>1334 ± 95 b</td>
</tr>
<tr>
<td></td>
<td>Seed-treatment</td>
<td>1097 ± 1.6 a</td>
<td>1279 ± 98 a</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>1901 ± 1.6 b</td>
<td>1306 ± 95 a</td>
</tr>
</tbody>
</table>

1 Means and standard errors of the mean are from least squares means in Proc Mixed.
2 Mean ± SEM, and means labeled with a unique letter were significantly different ($P < 0.05$).
3 Yield in kg per ha
Table 6. Probability of yield gain from treatments exceeding the gain threshold at four soybean prices

<table>
<thead>
<tr>
<th>Scouting cost</th>
<th>Treatment</th>
<th>Probability by soybean price per 27.2 kg&lt;sup&gt;1&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$6.00</td>
<td>$8.00</td>
</tr>
<tr>
<td>$0.00 per ha</td>
<td>IPM</td>
<td>0.81</td>
</tr>
<tr>
<td>$19.76 per ha</td>
<td>IPM</td>
<td>0.69</td>
</tr>
<tr>
<td>NA</td>
<td>Prophylactic</td>
<td>0.51</td>
</tr>
<tr>
<td>NA</td>
<td>Seed-treatment</td>
<td>0.43</td>
</tr>
</tbody>
</table>

<sup>1</sup> 27.2 kg (one US bushel)
Table 7. Probability of yield gain from the IPM treatments exceeding the prophylactic and seed-treatments at four soybean prices

<table>
<thead>
<tr>
<th>IPM treatment</th>
<th>Probability by soybean price per 27.2 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$6.00</td>
</tr>
<tr>
<td>Scouting cost</td>
<td></td>
</tr>
<tr>
<td>$0.00 per ha</td>
<td></td>
</tr>
<tr>
<td>Prophylactic</td>
<td>0.81</td>
</tr>
<tr>
<td>Seed-treatment</td>
<td>0.84</td>
</tr>
<tr>
<td>$19.76 per ha</td>
<td></td>
</tr>
<tr>
<td>Prophylactic</td>
<td>0.67</td>
</tr>
<tr>
<td>Seed-treatment</td>
<td>0.75</td>
</tr>
</tbody>
</table>

1 27.2 kg (one US bushel)
CHAPTER 4.

SOYBEAN APHID (HEMIPTERA: APHIDIDAE) MANAGEMENT ON NARROW-ROW SOYBEAN

A paper submitted to The Journal of Economic Entomology

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ABSTRACT

Soybean aphid *Aphis glycines* Matsumura (Hemiptera: Aphididae), is one of the most damaging insect pests of soybean, *Glycine max* (L.) Merrill, in the Midwestern United States. While considerable progress has been made in understanding how soybean aphid injury relates to yield loss, the work contributing to this understanding was done almost exclusively in wide-row (76 cm) soybean production. To better understand the effects of soybean aphid injury in narrow-row (25-20 cm) widths, we used a split plot experiment to determine if soybeans were more at risk for soybean aphid outbreaks and resultant yield loss from aphid herbivory when grown in narrow rows compared to wide rows. This experiment was conducted at multiple locations across Iowa and South Dakota from 2007 - 2009. Soybean aphid populations were manipulated within this experiment with insecticides based on three
treatment levels: aphid-free, treated once when populations reached 250 aphids per plant, and untreated. We found no evidence of a difference in soybean exposure to aphids across the two row widths. Additionally, there was no evidence of a difference in yield across the two row widths at any level of aphid exposure. The lack of interactions between soybean exposure to aphids and row width indicate that the current soybean aphid management recommendations are applicable for soybean produced using narrow-row production practices.

INTRODUCTION

SOYBEAN APHID, Aphis glycines Matsumura (Hemiptera: Aphididae), is the most significant insect pest of soybean production in North America (Ragsdale et al. 2007). Multiple studies have found that a single application of a properly-timed foliar insecticide can consistently protect soybeans from yield loss from aphid herbivory (Myers et al. 2005, Ragsdale et al. 2007, Johnson et al. 2009). An insecticide applied during soybean aphid outbreaks (>400 aphids per plant) when soybeans are in reproductive stages will protect soybean yield. The justification of an insecticide application is based on 423 aphids per plant, which will reduce soybean yield below a calculated economic injury level (EIL). The EIL of 423 aphids per plant is based on the following assumptions: aphid control cost of $24.51 per ha, soybean market value of $238.83 per ton, and a yield potential of 4.04 ton per ha (Ragsdale et al. 2007). To prevent this EIL from being reached, growers are advised to apply a foliar insecticide when soybean aphid populations exceed an economic threshold (ET) of 250 aphids per plant (based on the assumption of a 4 day lag-time before the EIL is reached) between flowering (R1) (Pedersen 2004) and early seed set (R5) (Myers et al. 2005, McCormack and Ragsdale 2006, Ragsdale et al. 2007, Rhainds et al. 2007, Johnson et al.
2009, Ohnesorg et al. 2009). The current soybean aphid threshold has become so widely accepted that 17 land grant institutions have published soybean aphid management recommendations based on the economic threshold developed by Ragsdale et al. (2007) (K.J.T., unpublished data).

The current soybean aphid management recommendations have become widely adopted. Although one possible limitation is that the entirety of the research used to calculate the current ET and the EIL values has been conducted using soybean planted in wide-rows (76 cm) (Ragsdale et al. 2007, Rhainds et al. 2007, Johnson et al. 2009, Ohnesorg et al. 2009). Many growers have begun to employ narrow-row soybean production practices (38 cm to 20 cm) (Norsworthy 2003, De Bruin and Pedersen 2008) for a variety of reasons such as increased yield (Bullock et al. 1998) and improved weed management (Wax et al. 1968, Weiner et al. 2001).

Altering the spacing between rows affects soybean morphology, which in turn could produce an interaction with soybean aphid population dynamics. Row spacing has been shown to alter the plant architecture (Legere and Schreiber 1989) and canopy microclimate (Sojka and Parsons 1983). The changes in the microclimate could impact soybean aphid population dynamics by moderating the temperature to levels more closely to those optimal for soybean aphid growth (McCornack et al. 2004). Differences in plant architecture from row spacing have been shown to impact predator development and populations (Mayse 1978); several studies have shown that insect predators can suppress soybean aphid population growth (Van den Berg et al. 1997, Fox et al. 2004, Schmidt et al. 2007, 2008, Noma and Brewer 2008, Gardiner et al. 2009).
In addition to differences in arthropod development, epizootics could also be impacted as microclimatological differences (Ekesi et al. 1999). Pathogens have been observed to affect soybean aphid population growth (Nielson and Hajek 2005), but to the extent they regulate soybean aphid populations is not clear. Additionally, soybean aphid is known to vector plant viruses (Clark and Perry 2002, Burrows et al. 2005, Davis et al. 2005, Davis and Radcliffe 2008), and change in plant architecture could enhance trivial movement of apterous (wingless) aphids. This may lead to increased rates of virus transmission in narrow-row soybean (Rose 1978).

For those reasons it is not known if the current recommendations developed for soybean aphid management in wide-row production are applicable to narrow-row soybean production. For example, differences in soybean responses to insect injury due to variable row spacing have been observed with defoliation injury. Hammond et al. (2000) found that defoliation reduced soybean yields at different rates across row spacings. However, it was determined that differences in total light interception were determining yield loss, and when controlled for light interception yield loss was similar across different row spacings. However, the physiological response to soybean aphid injury is very different from that of defoliation injury (Macedo et al. 2003). These findings indicate that soybean yield loss may not be correlated with light interception for assimilate-removing insects, leading to possible interactions between soybean aphid injury and row spacing. The goal of this experiment was to determine whether the existing soybean aphid economic threshold, developed in wide-row soybean production (Ragsdale et al. 2007), is also appropriate for narrow-row production, or whether refinement of the existing threshold is needed to better describe the EIL and ET levels for narrow-row soybean production.
MATERIALS AND METHODS

Over three years (2007, 2008, and 2009), a common experimental protocol was used at multiple locations in Iowa (Story, Neal, and Floyd Counties), and South Dakota (Brookings County). At each location, a soybean variety adapted for that area was planted in late April to late May, depending on weather conditions at a given location. Soybeans were planted within a corn-soybean rotation using conventional production practices and a glyphosate-based weed control program. We employed a split-plot design, alternating 5 m strips of narrow and wide-row soybeans (split effect). Soybeans assigned to the wide-row treatment were planted in 76 cm wide-rows. Soybeans assigned the narrow-row treatment were planted in either 25 cm or 20 cm wide rows (depending on available equipment at a location). The main effect treatment consisted of three levels of naturally-occurring soybean aphid populations, which were randomly assigned to plots measuring 10 m by 15 m. The main effect plots straddled the two row spacings with 5 m narrow-row soybean and 5 m wide-row soybean within each main effect plot. Naturally occurring aphid populations were allowed to reach one of three levels; (1) an untreated control where aphid populations were allowed to grow unimpeded (referred to as ‘untreated’), (2) an aphid-free control that received an insecticide every time aphids exceeded five per plant (referred to as ‘aphid-free’), and (3) an integrated pest management treatment which only received an insecticide if aphid populations exceeded 250 aphids per plant (referred to as ‘IPM’). We applied the broad-spectrum insecticides λ-cyhalothrin (Warrior II with Zeon Technology®, Syngenta Crop Protection, Greensboro, NC) and chlorpyrifos (Lorsban 4E®, Dow AgroSciences, Indianapolis, IN) at 225 ml per ha and 570 ml per ha respectively, whenever soybean aphids were found in the aphid-free control. By comparing the soybean yield difference between
the untreated control and the aphid-free the total yield loss attributed to the soybean aphid can be calculated (Ragsdale et al. 2007). An interaction between row spacing and the IPM treatment would support the hypothesis that the current soybean aphid management recommendations, which were developed in wide-row culture, are inadequate for soybean aphid management in narrow-row soybean.

**Aphid Sampling and Soybean Yield.** Soybean aphid populations at all locations originated from naturally occurring populations. Plots were sampled once a week throughout the growing season using nondestructive *in situ* whole-plant counts to estimate the average number of soybean aphids per plant. The number of soybean plants sampled ranged from 5 to 20 per plot. The proportion of infested plants during the previous sampling date was used to determine the number of plants to be sampled. When 0% to 80% of plants were infested with soybean aphids, 20 plants were counted; when 81% to 99% of plants were infested, 10 plants were counted; at 100% infestation, 5 plants were counted (Hodgson et al. 2004). The seasonal exposure of soybean to soybean aphid was reported in units of ‘cumulative aphid-days,’ calculated based on the number of aphids per plant between two sampling dates (Hanafi et al. 1989). Summing aphid days accumulated during the growing season, or cumulative aphid-days (CAD), provided a measure of the seasonal aphid exposure that a soybean plant experienced (Hodgson et al. 2004). Cumulative aphid days were calculated for the entire season. We harvested whole plots with a small combine and adjusted seed moisture to 13 percent before yield was estimated.

**Data analysis.** To determine the effect of soybean row spacing on soybean aphid populations, and soybean injury response, comparisons of plant exposure to soybean aphids and yield using PROC MIXED procedures in SAS statistical software (V9.2, SAS Institute,
The effect of treatments on accumulation of aphid-days was determined using natural log-transformed data to meet the assumptions for analysis of variance (ANOVA). Differences in aphid exposure were determined by analyzing cumulative aphid days in a one-way ANOVA in PROC Mixed and $F$-protected least-squares means test for mean separation. Soybean yield differences were analyzed in the same way, however yield data did not need to be transformed to meet the assumptions of ANOVA. The statistical model for both soybean aphid exposure and soybean yield considered row spacing, soybean aphid exposure, state, and year, as fixed effects, with location and blocks (nested within both year and county) considered as random effects. Location was treated as a random effect due to variation in experimental locations from year to year.

RESULTS

Soybean aphid pressure on soybeans (as measured in CAD) did not vary between narrow and wide row spacings (Table 1; Fig. 1). Soybean aphids significantly reduced soybean yield in both narrow and wide-row soybean in the untreated control (Table 1; Fig. 2), compared to both the aphid-free and IPM treatments.

Over all locations and years CAD exposure resulted in significantly reduced soybean yield ($df = 2, 215, F = 122.88, P < 0.0001$) as soybean aphid exposure increased. The IPM treatment and the aphid-free control had significant yield protection of 544 ± 14 kg per ha (mean ± SE), and 561 ± 13, respectively, when compared to the untreated control (Table 1; Fig. 2). Additionally, there was no significant difference between the IPM treatment and the aphid-free control (Table 1; Fig. 2).
Over all locations and years we observed no significant differences attributed to row spacing on CAD exposure (df = 1, 215, \( F = 0.05, P = 0.96 \)) or yield (df = 1, 215, \( F = 2.00, P = 0.16 \)) (Table 1). Additionally, there was no interaction between row spacing and cumulative aphid day exposure (df = 2, 215, \( F = 0.08, P = 0.91 \)), or between row spacing and yield (df = 2, 215, \( F = 1.20, P = 0.30 \)) (Table 1).

The effect of row spacing on both CAD exposure was consistent across all years (Table 2) and locations (Table 3). Furthermore, there were no interactions between row spacing and CAD exposure, row spacing and yield (Tables 2-3). In 2007 across both states wide-row soybeans demonstrated better yields than the narrow-row soybean by 145 ± 59 kg per ha (df = 1, 95, \( F = 6.15, P = 0.0015 \)) (Table 2) and in South Dakota wide-row soybeans yielded more than the narrow-row soybean by 430 ± 147 kg per ha (df = 1, 55, \( F = 7.91, P = 0.0068 \)) (Table 3). However these differences in soybean yield were not caused by differences in soybean aphid exposure (Tables 2-3).

**DISCUSSION**

Integrated pest management (IPM) tactics based on economic cost-benefit analyses are recognized for effectively managing pest populations (Stern 1973, Pedigo et al. 1986, Ragsdale et al. 2007). Insecticides applied for insect pest management should only be used when populations exceed the economic threshold (Stern 1973). Without a clear understanding of the plant injury response to growers would be forced to rely on nominal thresholds for pest management decisions (Pedigo and Rice 2008). There has been extensive work defining the economic cost-benefit analyses for soybean produced in wide-row production (Song et al. 2006, Ragsdale et al. 2007, Johnson et al. 2009, Song and Swinton.
The soybean injury response to aphid feeding has been well described in wide-row soybean production (Ragsdale et al. 2007), and it has been validated in subsequent studies (Johnson et al. 2009, Ohnesorg et al. 2009). There still exists the possibility that an interaction could occur between soybean aphid populations and row spacing or plant yield and row spacing due to altered plant architecture (Legere and Schreiber 1989) and canopy microclimate (Sojka and Parsons 1983).

Soybean growers are continuing to utilize narrow-row production practices (38 cm to 20 cm) (Norsworthy 2003, De Bruin and Pedersen 2008) with increased frequency for a variety of reasons including increased yield (Bullock et al. 1998, De Bruin and Pedersen 2008) and improved weed management (Wax et al. 1968, Weiner et al. 2001). Average row spacing for soybean production in Iowa is now 57 cm with the majority of acres planted using row spacings of 19 cm (14%), 38 cm (31%), and up to 76 cm (50%). Iowa has seen slower adoption of narrow-row soybean production compared to surrounding states (De Bruin and Pedersen 2008).

Our findings did not suggest any significant interactions between row spacing and soybean aphid populations, or row spacing and soybean aphid injury. We did occasionally observe difference in soybean yield due to row spacing. However, these differences were not caused by differences in aphid exposure measured in CAD, and may have been due to increased disease incidence (white mold, *Sclerotinia sclerotiorum*) which is attributed to a more humid microclimate in narrow-row soybeans compared to wide-rows. The current soybean aphid management recommendations call for weekly scouting of soybean fields and only applying insecticides when soybean aphid populations exceed the ET (Ragsdale et al. 2007, Johnson et al. 2009). Our findings tend to validate the current soybean aphid
management recommendations for soybean produced using narrow-row practices (Ragsdale et al. 2007). The consistency of our findings in narrow-row soybean with research conducted in wide-row soybean supports a single soybean aphid management threshold that can be recommended across a greater range of soybean row widths. The validation of the current soybean aphid management recommendations in narrow-row soybean will allow soybean producers to confidently adopt the current recommendations across a broader range of soybean production practices.

ACKNOWLEDGMENTS

This journal paper of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 5032, was supported by Hatch Act and State of Iowa funds. In addition to the state of Iowa, we thank the Iowa Soybean Association and North Central Soybean Research Program for financial support of our research and Syngenta Crop Protection for supplying insecticides. We would like to thank Dr. Micheal Owen, Dr. Larry Pedigo, and Dr. Erin Hodgeson for reviewing this manuscript. Additionally, we would like to thank the Iowa State University farm managers Kenneth Pecinovsky, Dave Starret, Ryan Rusk and their respective staffs, for assistance with management of the soybean plots. Finally, we would also like to thank Ana Micijevic, Doug Doyle, and Matt Caron at South Dakota State University for data collection and assistance with plot management.

LITERATURE CITED


Table 1. Effect of treatments at the main and split effect levels on cumulative aphid day exposure and yield

<table>
<thead>
<tr>
<th>Effect level</th>
<th>Treatment</th>
<th>CAD $^{1,3}$</th>
<th>Yield $^{2,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>Untreated control</td>
<td>10,938 ± 3,106 A</td>
<td>3,067 ± 322   B</td>
</tr>
<tr>
<td></td>
<td>Aphid-free control</td>
<td>446 ± 126     C</td>
<td>3,647 ± 324   A</td>
</tr>
<tr>
<td></td>
<td>IPM</td>
<td>1,998 ± 593   B</td>
<td>3,600 ± 323   A</td>
</tr>
<tr>
<td>Split</td>
<td>Narrow row</td>
<td>2,208 ± 599   a</td>
<td>3,399 ± 324   a</td>
</tr>
<tr>
<td></td>
<td>Wide row</td>
<td>2,321 ± 629   a</td>
<td>3,477 ± 323   a</td>
</tr>
</tbody>
</table>

1 CAD, cumulative aphid days ± standard error.
2 Yield in kilograms per hectare ± standard error.
3 Main effect treatments labeled with a unique capital letter are significantly different, and split effect treatments labeled with a unique lowercase letter are significantly different at $(P \leq 0.05)$. 
Table 2. Effect of treatments at the main and split effect levels on cumulative aphid day exposure and yield by year

<table>
<thead>
<tr>
<th>Year</th>
<th>Effect level</th>
<th>Treatment</th>
<th>CAD $^{1,3}$</th>
<th>Yield $^{2,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Main</td>
<td>Untreated control</td>
<td>9,897 ± 5,938 A</td>
<td>3,346 ± 295 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphid-free control</td>
<td>544 ± 326 B</td>
<td>3,903 ± 295 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPM</td>
<td>699 ± 451 B</td>
<td>3,890 ± 295 A</td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Narrow-row</td>
<td>1,422 ± 830 a</td>
<td>3,641 ± 235 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide-row</td>
<td>1,635 ± 955 a</td>
<td>3,930 ± 235 a</td>
</tr>
<tr>
<td>2008</td>
<td>Main</td>
<td>Untreated control</td>
<td>12,008 ± 4,300 A</td>
<td>2,956 ± 436 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphid-free control</td>
<td>181 ± 94 C</td>
<td>3,594 ± 436 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPM</td>
<td>3,640 ± 214 B</td>
<td>2,956 ± 436 A</td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Narrow-row</td>
<td>2,208 ± 1,283 a</td>
<td>3,346 ± 434 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide-row</td>
<td>1,808 ± 1,200 a</td>
<td>3,399 ± 434 a</td>
</tr>
<tr>
<td>2009</td>
<td>Main</td>
<td>Untreated control</td>
<td>12,088 ± 4,066 A</td>
<td>2,479 ± 537 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphid-free control</td>
<td>735 ± 247 C</td>
<td>3,151 ± 537 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPM</td>
<td>3,294 ± 1,108 B</td>
<td>3,010 ± 537 A</td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Narrow-row</td>
<td>3,294 ± 1,064 a</td>
<td>2,909 ± 530 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide-row</td>
<td>2,980 ± 963 a</td>
<td>2,922 ± 530 a</td>
</tr>
</tbody>
</table>

$^{1}$ CAD, cumulative aphid days ± standard error.

$^{2}$ Yield in kilograms per hectare ± standard error.

$^{3}$ Main effect treatments labeled with a unique capital letter are significantly different, and split effect treatments labeled with a unique lowercase letter are significantly different at ($P \leq 0.05$).
Table 3. Effect of treatments at the main and split effect levels on cumulative aphid day exposure and yield by state

<table>
<thead>
<tr>
<th>State</th>
<th>Effect level</th>
<th>Treatment</th>
<th>CAD $^{1,3}$</th>
<th>Yield $^{2,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iowa</td>
<td>Main</td>
<td>Untreated control</td>
<td>12,000 ± 4,726</td>
<td>A 3,153 ± 382 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphid-free control</td>
<td>270 ± 105</td>
<td>C 3,799 ± 382 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPM</td>
<td>1,808 ± 706</td>
<td>B 3,771 ± 382 A</td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Narrow-row</td>
<td>1,800 ± 657</td>
<td>a 3,594 ± 376 a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide-row</td>
<td>1,990 ± 726</td>
<td>a 3,554 ± 376 a</td>
</tr>
<tr>
<td>S. Dakota</td>
<td>Main</td>
<td>Untreated control</td>
<td>8,950 ± 941</td>
<td>A 2,674 ± 107 B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aphid-free control</td>
<td>812 ± 94</td>
<td>C 3,151 ± 120 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPM</td>
<td>2,208 ± 375</td>
<td>B 2,674 ± 161 A</td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Narrow-row</td>
<td>2,980 ± 313</td>
<td>a 2,754 ± 107 b</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wide-row</td>
<td>2,440 ± 254</td>
<td>a 3,157 ± 107 a</td>
</tr>
</tbody>
</table>

$^{1}$ CAD, cumulative aphid days ± standard error.
$^{2}$ Yield in kilograms per hectare ± standard error.
$^{3}$ Main effect treatments labeled with a unique capital letter are significantly different, and split effect treatments labeled with a unique lowercase letter are significantly different at ($P \leq 0.05$).
FIGURE CAPTIONS

Figure 1. Cumulative aphid day exposure across treatments for soybean planted in wide (76 cm) and narrow-rows (20 cm or 25 cm). There were no significant differences in soybean cumulative aphid day exposure due to row-width within any treatment. Treatments labeled with a unique capital letter are significantly different, and split effect treatments labeled with a unique lowercase letter are significantly different at $(P \leq 0.05)$.

Figure 2. Soybean yield in kilogram per hectare across treatments for soybean planted in wide (76 cm) and narrow-rows (20 cm or 25 cm). There were no significant differences in soybean yield due to row-width within any treatment. Treatments labeled with a unique capital letter are significantly different, and split effect treatments labeled with a unique lowercase letter are significantly different at $(P \leq 0.05)$. 
Figure 1.
Figure 1.
CHAPTER 5.

MODELING SOYBEAN YIELD RESPONSE TO MULTIPLE TYPES OF INSECT INJURY

A paper intended for submission to The Journal of Economic Entomology

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ABSTRACT

The development of comprehensive thresholds encompassing multiple types of insect injury has remained an elusive goal of Integrated Pest Management (IPM). This is an especially important goal with the addition of the soybean aphid, *Aphis glycines* Matsumura (Aphididae: Hemiptera). The soybean aphid represents a damaging feeding guild (assimilate removal) that was previously of little importance in the Midwestern soybean agroecosystems. In 2008 and 2009 the injury response of soybean to two sources of injury: assimilate removal in the form of cumulative aphid day (CAD) exposure to soybean aphids, and leaf-mass removal (simulated insect herbivory) was determined. Treatments were applied in a five-by-five factorial design with all experimental units experiencing one of five levels of CAD exposure (0, 20,000, 40,000, 60,000, and 80,000 CAD), and one of five levels of defoliation (0, 20, 40, 60, and 80 percent). There was no evidence of an interaction between plant exposure to soybean aphids and
defoliation on seed yield. Therefore, a common linear regression describes the yield response of soybean to aphid exposure at all levels of defoliation within a single year. In 2008, yield declined at a rate of 5.2 percent per 10,000 CAD at all levels of defoliation, and in 2009 yield declined at a rate of 3.2 percent per 10,000 CAD at all levels of defoliation. When the model was restricted to CAD levels lower than 60,000 and defoliation levels below 60 percent, no interaction was observed between year and injury type on soybean yield. In the restricted model yield was reduced at a rate of 4.5 percent per 10,000 CAD and 2.7 percent per 10 percent defoliation indicating an additive interaction between assimilate removal and defoliation.

INTRODUCTION


In addition to the soybean aphid, Midwestern soybean production experiences injury from bean leaf beetle (*Cerotoma trifurcata* (Förster) (Coleoptera: Chrysomelidae) (Smelser and Pedigo 1992), the two spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae) (Hildebrand et al. 1986), and several other insects that infrequently damage soybeans (Turnipseed and Kogan 1976, Kogan and Turnipseed 1987). The soybean herbivore community represents many different injurious feeding guilds (Boote 1981). Combinations of different types of injury lend themselves to many possible interactions, complicating models for explaining yield loss due to the presence of multiple-herbivores.

The key tenet of insect pest management is that low levels of injury (the effect of pest activities on crop physiology) are tolerable (Geier 1966, Pedigo et al. 1986, Peterson and Higley 2001). Only after the injury caused by insect pest activity reaches an economic threshold (ET) that an injury mitigation tactic such as a pesticide application is warranted (Stern 1973, Pedigo et al. 1986). Typically, thresholds are developed for individual species of pest. The creation of thresholds that include multiple pest species have been proposed. However, this has not progressed beyond injury equivalency, in which injury is combined from pest who cause the same type of injury and this injury is equal and additive (Hutchins et al. 1988). Such equivalency would occur when herbivores of similar feeding guilds co-occur,
like leaf feeders. To advance pest management when multiple sources of insect injury are present we must not only have an understanding of how plants respond to different sources of injury (leaf feeding versus phloem feeding), but we must also understand how multiple sources of injury interact to cause damage.

There are at least five ways injuries could interact: additive, synergistic, antagonistic, enhancer (Akobundu et al. 1975), and safener (Hoffman 1953). An additive injury response would mean that the two sources of injury cause the same physiological response and that the two sources are interchangeable with one another. Synergism exists when one source of injury increases the amount of damage caused by the second source of injury. Antagonism exists when one source of injury lessens the damage of the second source of injury. Enhancers and safeners are special cases where one component causes no damage but the presence of this component either increases the damage caused by the other source of injury (enhancer), or decreases damage caused by the other source of injury (safener) (Hoffman 1953, Akobundu et al. 1975).

We are just starting to understand the complexities of organismal interactions in agroecosystems. However, the concept of interactions has been well-studied in chemistry, pesticide development, pharmacy, and toxicology (Hoffman 1953, Akobundu et al. 1975, Davis and Caseley 1999, Gennings et al, 2005). We use statistical and experimental design techniques from these disciplines to advance our understanding of how herbivores from different feeding guilds interaction to impact a crop. The goal of our research was to characterize the yield response of soybean to two common sources of injury, defoliation and assimilate removal.
MATERIALS AND METHODS

Soybeans (Prairie Brand 2940 RR) were planted in central Iowa during the 2008 (Boone County) and 2009 (Story County) growing seasons. Conventional production practices were utilized with a row spacing of 76 cm (30 in), and weeds were controlled as needed with a glyphosate (Roundup Weather Max®, Monsanto, St Louis, MO) weed control program. Treatments were arranged in a randomized complete block design and were assigned one of 28 treatments (five-by-five factorial plus 3 additional treatments), and all treatments were replicated once in a total of six blocks.

Following soybean emergence, exclusion cages were erected over the rows with three meters between cages in alternating rows of soybeans. Cage frames were constructed using 2.54 cm (1.0 inch) schedule 40 PVC tubing (Lowe’s, North Wilkesboro, NC). The finished cages measured 76 cm wide by 76 cm deep and stood 110 cm tall. Cages were covered with no-see-um netting (Quest Outfitters, Sarasota, FL), which was buried in the soil, and nets were opened at the top for infesting with soybean aphids and counting throughout the season (Fig. 1). Cages were erected and closed before naturally-occurring soybean aphid populations infested the plants.

Within each cage, soybeans were thinned to three evenly-spaced plants (subsamples) per cage (experimental unit). Treatments (defoliation and aphid infestation) were “applied” during the flowering growth stages of soybeans (R1-R2) (Fehr and Caviness 1977). Treatments were applied to flowering growth stages of soybeans for two reasons. First, it has been noted that early reproductive stage soybeans are more sensitive to defoliation injury than vegetative and late reproductive stage soybeans (Stone and Pedigo 1972, Higgins et al. 1984, Ostlie and Pedigo 1985). Additionally, in the US and Canada, soybean aphid

The seasonal exposure of soybean to soybean aphid (assimilate removal) was reported in units of ‘cumulative aphid-days’ (CAD) and was calculated based on the number of soybean aphids per plant between two sampling dates (Hanafi et al. 1989). The CAD provided a measure of the seasonal soybean aphid exposure that soybeans experienced (Hodgson et al. 2004). Soybean aphid populations were manipulated to five levels (0, 20,000, 40,000, 60,000, and 80,000 CAD). Caged plants were infested with field-reared soybean aphids and re-infested as needed to achieve targeted CAD levels. Soybean aphid colonies used to supplement the treatments were maintained in field cages same soybean variety within 20 m of the experiment location. Soybeans were infested with soybean aphids by placing infested trifoliates from the field colonies into the canopy of the caged plants. Soybean aphid populations were counted two to three times a week following infestation until all treatments had achieved the targeted CAD levels. Once the targeted CAD levels within a treatment were reached, an insecticide (λ-cyhalothrin, Warrior II with Zeon Technology® Syngenta Crop Protection, Greensboro, NC) was applied to individual cages preventing soybean aphid exposure from exceeding targeted levels. When all treatment levels of CAD exposure were reached, nets were removed and the treatments were maintained as insect-free with bi-weekly applications of λ-cyhalothrin and chlorpyrifos (Lorsban 4E®, Dow AgroSciences, Indianapolis, IN).

Defoliation injury was achieved using simulated herbivory. Defoliation was based on the number of leaflets on intact plants, and was applied at 0, 20, 40, 60, and 80 percent
defoliation. Entire leaflets were removed by hand to reach the assigned defoliation levels. Leaflets were removed the same day as the initial soybean aphid infestations occurred.

Leaflet removal was selected as the simulated herbivory technique based on the results of previous research studies. In a comparison of simulated herbivory techniques and actual insect defoliation it was found that leaf removal was an acceptable simulation of actual insect herbivory (Ostlie and Pedigo 1984).

In addition to total defoliation an attempt was made to measure total light interception. In previous studies soybean yield has been shown to be more closely correlated with total light interception than total defoliation (Hammond et al. 2000). However, attempts to measure light interception within the cages proved problematic due to the small cage size.

There were three treatments included in addition to the factorial treatment levels described above. The first additional treatment was an uncaged control (no netting over the cage) at the 0 percent defoliation and 0 CAD level to determine the impact, if any, of the netting on soybean growth and yield. The other two treatments were a 100 percent defoliation treatment and a soybean aphid exposure of 120,000 CAD. These treatments were included to measure plant yield response under extreme injury scenarios. In the Midwest, soybeans rarely experience injury as high as 100 percent defoliation and 120,000 CAD (Haile et al 1998, Ragsdale et al. 2007). However, these treatments contributed to our understanding of extreme soybean injury responses. The information gained by having a larger range of injuries is particularly important for detecting non-additive injury interactions (Gennings et al. 2005). This information is also of great value in the case of assimilate removal caused by soybean aphid feeding because most studies have only exposed soybean to CAD levels below 60,000 (Ragsdale et al. 2007, Johnson et al. 2008, Johnson et al. 2009).
Once 95 percent of the pods had reached full color (R8), plots were hand-harvested to determine yield. In the laboratory, seeds were removed from pods and dried at 40° C for 6 to 8 h and dry seed weight was measured for final yield. Yield data was analyzed using both PROC GLM (single year analysis) and PROC MIXED (combined analysis of the two years) procedures in SAS statistical software (V9.2, SAS Institute, Cary, NC) to detect treatment differences. The combined analysis included random effects for blocks, which were nested within years. Differences in seed yield between uninjured plants and the sham control were determined by analyzing seed yield in a one-way ANOVA in PROC GLM. Due to variation between targeted and observed CAD values, all regression models were calculated using observed CAD values rather than the targeted CAD levels. When comparing regression models, linear and quadratic models were considered and tested for lack of fit using an ANOVA lack of fit test. No data transformations were needed as comparisons of residual values indicated that there was no evidence that either normality or equality of variances had been violated.

RESULTS

The two sources of injury significantly reduced soybean yield compared to the untreated controls (Fig. 2). There was no affect of the treatment cages in 2008 (df = 1, 130, $F = 0.90, P = 0.37$). However, there was a significant cage effect in 2009 (df = 1, 130, $F = 2.56, P = 0.011$) with the cage treatments yielding more by 15 percent (14 grams per plant). Regression analyses indicate that the injury pattern was similar in 2008 and 2009 (Fig. 2). However, there was a strong year-by-treatment interaction, with plants exhibiting a greater sensitivity to aphid exposure in 2008 than 2009 (df = 1, 282, $F = 19.24, P = <0.0001$) (Fig.
2). Soybean aphid exposure significantly reduced seed yield in the absence of defoliation (df = 1, 282, $F = 284.85$, $P = <0.0001$) (Figs. 2A, and 2C). Also, defoliation reduced seed yield significantly in the absence of soybean aphids (df = 4, 282, $F = 10.54$, $P = <0.0001$) (Figs. 2B and 2D).

We did not detect interactions between soybean aphid exposure and defoliation (df = 4, 282, $F = 1.55$, $P = 0.19$) (Fig. 3), which led to the use of a single linear response model of soybean aphid exposure for defoliation treatments within years (Table 1 and Fig. 3). Overall, there was a five percent reduction in seed yield per 10,000 CAD in 2008, and three percent reduction in seed yield per 10,000 CAD in 2009. The within year models for 2008 and 2009, respectively, were estimated as:

$$y_{2008} = 1.1 - 0.011d - 0.0033d^2 - 0.051c,$$  \hspace{1cm} \text{Equation [1]}

$$y_{2009} = 0.90 - 0.019d - 0.084d^2 - 0.031c,$$  \hspace{1cm} \text{Equation [2]}

where the seed yield ($y$) was equal to defoliation ($d$) and cumulative aphid exposure ($c$) (Table 1, Figs 4, 5).

The year-to-year variability of injury responses led to the development of a model that excluded injury levels that reduced seed yield by more than 25 percent. When we focused on the injury levels in the upper quartile of seed yield (0 to 60,000 CAD and 0 to 60 percent defoliation), we did not observe an interaction between year and source of injury. Therefore we developed a common model explaining yield loss in the upper quartile of seed yield for both years. The injury response to defoliation was linear at 0 to 60 percent defoliation while the best-fit model was quadratic when 0 to 100 percent defoliation was analyzed. The resulting combined model for 2008 and 2009 was:

$$y_{combined} = 1.0 - 0.0027d - 0.045c,$$  \hspace{1cm} \text{Equation [3]}
where seed yield \((y_{combined})\) was equal to the damage caused by defoliation \((d)\), and cumulative aphid exposure \((c)\) (Table 2, Fig. 6).

**DISCUSSION**

Pest management thresholds may be categorized into one of four threshold levels; no threshold, nominal, simple, or comprehensive (Pedigo and Rice 2008). The first threshold level, “No threshold”, is usually reserved for very high value crops such as fresh market produce where cosmetic considerations are important. Nominal thresholds are used where there is some anecdotal or limited experimental data indicating that injury causes yield loss but insufficient data exists to calculate an economic injury level (EIL) or an ET. Nominal thresholds are commonly used when a new pest species first invades the system. Simple thresholds exist when sufficient data exists for a single pest species to predict how much yield loss will occur at a given level of pest activity (Stone and Pedigo 1972, Peterson and Higley 2001, Ragsdale et al. 2007). The final threshold type is a comprehensive threshold. With comprehensive thresholds, yield predictions could be made when multiple pest species are present and active (Ostlie and Pedigo 1985, Hutchins et al. 1988, Peterson and Higley 2001).

To determine an economic threshold (either simple or comprehensive) we must understand how the plant yield varies in response to insect injury (Stone and Pedigo 1972, Stern 1973, Pedigo et al. 1986). The techniques for developing a single pest EIL and ET are well-studied and have been employed many times (Stone and Pedigo 1972, Peterson and Higley 2001, Ragsdale et al. 2007), however the development of comprehensive thresholds for insect management has not progressed beyond assuming additive effects of injury caused
by insects of the same feeding guild (Hutchins et al. 1988). Six main feeding guilds of herbivorous insects have been described; stand reducers, leaf-mass consumers, assimilate removers, turgor reducers, fruit feeders, and architecture modifiers (Boote 1981, Hutchins et al. 1988, Peterson and Higley 2001). When insects from multiple feeding guilds such as bean leaf beetle (fruit feeder and leaf-mass consumer), Cerotoma trifurcata (Förster) (Coleoptera: Chrysomelidae), and the soybean aphid (assimilate remover), Aphis glycines, Matsumura (Hemiptera: Aphididae), are present at the same time we must defer to nominal thresholds for management decisions even though simple thresholds exist for both pests on reproductive stage soybean Glycine max (L.) plants (Smelser and Pedigo 1992, Ragsdale et al. 2007).

Cage studies have several limitations and their use for generating field recommendations is controversial (Poston et al. 1976, O’Neal et al. 2009). The cages may influence soybean yield, as evidenced in the 2009 data. Additionally, cages reduce trivial plant-to-plant movement of insects, and this change in behavior could limit soybean aphid-vectored virus (Burrows et al. 2005, Davis et al. 2005). The cage could also influence soybean yield due to differences in microclimatic conditions as evidenced in 2009 when the uncaged treatment had lower yield than the cage treatment. This increase in yield may be attributed to a greenhouse effect. Temperatures in central Iowa were below average in 2009 (Iowa Mesonet 2010), and other researchers have documented a greenhouse effect in cage studies (Fox et al. 2004).

Previous studies of soybean aphid impact on soybean yield have been done with naturally occurring aphid populations. This is in contrast to our study that employed soybeans artificially infested with soybean aphid within a narrow window of the growing
season. However, yield loss was consistent with other published studies for both simulated herbivory (defoliation) (Stone and Pedigo 1972, Poston et al. 1976) and exposure to aphids (Ragsdale et al. 2007, Rhainds et al. 2007, Johnson et al. 2009).

There has been a debate among IPM practitioners as to the applicability of simulated herbivory to actual leaf-mass removal by insects (Poston et al. 1976). Often leaf feeding insects only remove portions of leaf tissue, and this may influence photosynthetic rates (Poston et al. 1976, Pederson and Higley 2001). Despite differences in physiological responses to different defoliation techniques these differences do not seem to affect yield (Ostlie and Pedigo 1984).

Considering the limitations of using cages and artificial insect infestations, the use of cages were deemed necessary due to the low probability that naturally-occurring soybean aphid populations would achieve the desired injury levels. Field studies demonstrated that natural soybean aphid infestations rarely exceed 40,000 CAD (Ragsdale et al. 2007, Rhainds et al. 2007, Johnson et al. 2009). Additionally, there was a concern that natural enemies of the soybean aphid could further confound the study by preventing the desired injury levels. Even in simple corn and soybean landscapes natural enemies have been shown reduce soybean aphid populations when soybean aphids are not protected from predation (Fox et al. 2004, 2005, Schmidt et al. 2007, Gardiner et al. 2009).

Given the limitations of cages and artificial infestations, the similarity in yield response due to soybean aphid injury between our data and other field research is remarkable (Ragsdale et al. 2007, Rhainds et al. 2007, Johnson et al. 2009). Cage studies should not replace field studies when the practicality of the treatment structure is manageable.
However, these similarities support the use of cage techniques in this and future injury response studies, provided researchers are aware of the limitations.

The year by injury interactions reported in this study can impact data interpretation and limit the potential to develop thresholds. However, when the model developed from the above reported data was restricted to CAD levels lower than 60,000 and defoliation levels below 60 percent, the year-by-injury interactions were not a factor and overall yield was reduced by 4.5 percent per 10,000 CAD and 2.7 percent per 10 percent defoliation (equation 3). The lack of interactions between soybean aphid feeding and defoliation indicated that the two sources of injury interact in an additive manner.

Some researchers have proposed additivity when similar types of insect injury occur simultaneously (Hutchins et al. 1988). However, to our knowledge this assumption has not been experimentally verified, and there may be physiological differences in plant responses to actual herbivory due to plant-insect interactions caused by salival components (Maffei et al. 2007). Additionally, there has been a dearth of evidence describing how different injuries interact.

This study finds that two types of injury (defoliation and assimilate removal) can interact in an additive manner. However, other interaction responses are possible, including: synergism, antagonism, and the special cases of enhancers and safeners. With a synergistic interaction one source of injury increases the damage caused by the second source of injury. In an antagonistic interaction one source of injury decreases the damage caused by the second source of injury. One example of this would be injury caused by aphid feeding inducing as systemic acquired resistance response that reduced the damage caused by pathogen injury (Walling 2000). There may even be examples of the special case injury
interactions of enhancers and safeners where one component causes no damage but the presence of this component either increases the damage caused by the other source of injury (enhancer), or decreases damage caused by the other source of injury (safener). Dean et al. (2009) showed that different strains of the nitrogen-fixing soil bacteria (rhizobia) could influence soybean aphid populations on the above ground portions of the plant inducing a safener effect. Another possible way to achieve a safener effect would be to have a predator whose presence influences herbivore behavior in a way that reduces the injury per insect. Although, Losey and Denno (1998), did not measure yield loss, their predator-aphid research clearly showed that predators can influence herbivore behavior.

Integrated pest management tactics based on economic cost-benefit analyses describe how to effectively manage insect pest populations (Stern 1973, Pedigo et al. 1986, Ragsdale et al. 2007), and insecticides applied for insect pest management should only be used when insect populations exceed the ET (Stern 1973, Pedigo et al. 1986). When insufficient data exist for the development of ETs, growers must rely on imprecise nominal thresholds for treatment decisions, which may lead to overuse of insecticides. Growers currently rely on nominal thresholds for treatment decisions when multiple insect feeding guilds are simultaneously present and active. With a better understanding of plant-insect-injury interactions, EIL’s could be calculated for multiple insect herbivores representing different feeding guilds. Once multi-pest EIL’s have been calculated, economic cost-benefit analyses, coupled with other biological data would facilitate the development of comprehensive multi-pest ET’s.
The results of this research could be utilized to calculate a multi-pest EIL. By first calculating a yield gain threshold (GT) based on control costs, expected crop price, and expected yield.

\[
GT = \frac{C}{P}.
\]  

Equation [4]

The GT is expressed in yield units per unit area and is calculated using estimated control costs (C) [$ per unit area] divided by expected crop price (P) [$ per unit area] (Pedigo et al. 1986). The GT could then be subtracted from seed yield \(y_{\text{combined}}\), equation three) and solving for defoliation \(d\), and cumulative aphid exposure \(c\). The applicability of the equation for decision-making (such as an ET) is greatly complicated by the differential population growth rates of pests representing the sources of injury.

Growers currently rely on nominal thresholds for treatment decisions when multiple insect feeding guilds are simultaneously present and active. With a better understanding of plant-insect-injury interactions, EIL’s could be calculated for multiple insect herbivores representing different feeding guilds. Once multi-pest EIL’s have been calculated would facilitate the development of comprehensive multi-pest ET’s.

ACKNOWLEDGMENTS

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to financial support. Finally, we would like to thank the Iowa State University research managers Brent Pringnitz, Dave Starret, and their respective staffs for assistance with management of the soybean plots.

LITERATURE CITED


Table 1. Yield regression slopes for cumulative soybean aphid day exposure and intercepts for defoliation level by year

<table>
<thead>
<tr>
<th>Year</th>
<th>Defoliation(^1)</th>
<th>Intercept(^2) ± SE(^3)</th>
<th>Slope(^4) ± SE</th>
<th>R square value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.0</td>
<td>1.07 ± 0.04</td>
<td>-5.2 ± 0.40</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>1.03 ± 0.03</td>
<td>-5.2 ± 0.40</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.98 ± 0.03</td>
<td>-5.2 ± 0.40</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.89 ± 0.03</td>
<td>-5.2 ± 0.40</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.77 ± 0.03</td>
<td>-5.2 ± 0.40</td>
<td>0.45</td>
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<tr>
<td></td>
<td>1.0</td>
<td>0.63 ± 0.06</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2009</td>
<td>0.0</td>
<td>0.90 ± 0.03</td>
<td>-3.1 ± 0.28</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.90 ± 0.02</td>
<td>-3.1 ± 0.28</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.84 ± 0.02</td>
<td>-3.1 ± 0.28</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.71 ± 0.02</td>
<td>-3.1 ± 0.28</td>
<td>0.25</td>
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<tr>
<td></td>
<td>0.8</td>
<td>0.51 ± 0.04</td>
<td>-3.1 ± 0.28</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>0.25 ± 0.03</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

\(^1\) Proportion defoliation ranging from 0 to 1
\(^2\) Proportion of maximum yield
\(^3\) Pooled standard error
\(^4\) Percent yield loss per 10,000 cumulative aphid days
Table 2. Yield regression slope for cumulative soybean aphid day exposure and intercepts at each defoliation level using the common model\(^1\)

<table>
<thead>
<tr>
<th>Year</th>
<th>Defoliation (^2)</th>
<th>Intercept (^3) ± SE (^4)</th>
<th>Slope (^5) ± SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.0</td>
<td>1.07 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>1.02 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.96 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.91 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td>2009</td>
<td>0.0</td>
<td>0.96 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.90 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.85 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.80 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td>Combined</td>
<td>0.0</td>
<td>1.01 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.96 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.90 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.84 ± 0.3</td>
<td>-4.5 ± 0.7</td>
</tr>
</tbody>
</table>

\(^1\) Common model was restricted to proportional defoliation of 0 to 0.6, and cumulative aphid day exposures of 0 to 60,000
\(^2\) Proportion of maximum yield
\(^3\) Pooled standard error
\(^4\) Percent yield loss per 10,000 cumulative aphid days
FIGURE CAPTIONS

Figure 1. Exclusion cages in the field with A) no nets, B) the layout in the field, and C) nets

Figure 2. Proportion of maximum yield verses A) cumulative aphid day exposure with no defoliation in 2008, B) defoliation with no cumulative aphid exposure in 2008, C) cumulative aphid day exposure with no defoliation in 2009, D) defoliation with no cumulative aphid exposure in 2009

Figure 3. Proportion of maximum yield response per 1,000 cumulative aphid day (CAD) exposure and both the upper and lower 95 percent confidence intervals A-F) in 2008, and E-J) and 2009, at A, F) 0 percent defoliation, B, G) 20 percent defoliation, C, H) 40 percent defoliation, D, I) 60 percent defoliation, E, J) and 80 percent defoliation. Slopes and intercepts for each defoliation level are listed in table 1.

Figure 4. Response surface model showing proportion of maximum yield (grams seed per plant) verses soybean aphid exposure (cumulative aphid day [CAD]) and proportional defoliation in 2008 presented as: A) 3-D Surface response model, and B) as contour lines showing proportion of maximum soybean yield per 10,000 cumulative aphid day (CAD) and proportion defoliation, as described by the equation \( y_{2008} = 1.1 - 0.011d - 0.0033d^2 - 0.051c \).
Figure 5. Response surface model showing proportion of maximum soybean yield (grams seed per plant) versus soybean aphid exposure (cumulative aphid day [CAD]) and proportional defoliation in 2009 presented as: A) 3-D Surface response model, and B) as contour lines showing proportion of maximum soybean yield per 10,000 cumulative aphid day and proportion defoliation, as described by the equation

\[ y_{2009} = 0.90 - 0.019d - 0.084d^2 - 0.031c. \]

Figure 6. Response surface model showing proportion of maximum soybean yield (grams seed per plant) versus soybean aphid exposure (cumulative aphid day [CAD]) and proportional defoliation for the 2008 and 2009 combined model presented as: A) 3-D Surface response model, and B) as contour lines showing proportion of maximum soybean yield per 10,000 cumulative soybean aphid day and proportion defoliation, as described by the equation \( y_{combined} = 1.0 - 0.0027d - 0.045c \).
Figure 1.
Figure 3.

Figure 4.
Figure 5.
Figure 6.
CHAPTER 6.
The goal of the first study was to evaluate the effect of insecticide application techniques on soybean aphid management. The value of managing soybean aphid with insecticides is well-supported (Ragsdale et al. 2007, Olson et al. 2008, Johnson et al. 2009, Song and Swinton 2009). While proper application of pesticides has long been understood as a critical component of pesticide use, it is sometimes overlooked. Little differences between the insecticides were observed even though they represented different chemical classes (pyrethroid and organophosphate). The lack of soybean yield differences between insecticide treatments was consistent with other insecticide evaluations (Myers et al. 2005, Johnson and O’Neal 2009, Ohnesorg et al. 2009). Our results suggested proper insecticide application would increase the efficacy of an insecticide thus increasing the value to the grower by increasing yield protection. This research has shown that efficiently applying insecticides could increase the efficacy and yield protection of a contact insecticide by 108 kg per ha (1.6 bu per A). The additional yield protection would represent a significant value ($76 to $114 per ha) to growers at the current, soybean price levels of $8.00 to $12.00 per 27.2 kg (1 bushel).

Our objectives in the next study were to compare prophylactic soybean aphid management strategies to an IPM strategy, determine which strategy resulted in the most consistent reduction in plant exposure to soybean aphids and improved soybean yield. Our results supported the current recommendations that soybean aphid management should be based on scouting and applying an insecticide only when populations exceed the ET (Ragsdale et al. 2007). Preventative applications of insecticides, either applied to the seed or
foliage, did not significantly reduce soybean exposure to soybean aphids or prevent yield loss compared to insecticides applied in an IPM approach. Our results were consistent with previous studies that show seed treatments do not provide significant protection against yield losses caused by soybean aphids (McCornack and Ragsdale 2006, Johnson et al. 2008). Although seed treatments are convenient and have limited impact to natural enemies (Ohnesorg et al. 2009), colonization by the soybean aphid usually occurs after the neonicotinoid-based residual activity has declined. Due to the variability of soybean aphid phenology within the North Central region, timing the application of a foliar insecticide with a potential outbreak is critical for effective soybean aphid management. Locations in this study did not experience injury from early-season insect pests, such as white grubs, *Phyllophaga* spp. (Coleoptera: Scarabaeidae) and bean leaf beetle, *Cerotoma trifurcata* (Förster) (Coleoptera: Chrysomeloidea), which could justify the use of seed-applied insecticides (Bradshaw et al. 2008).

The second portion of this management study was to analysis of the cost effectiveness of the management approaches. Integrated pest management approaches based on economic cost-benefit analyses are recognized for effectively dealing with insect pest populations (Stern 1973, Pedigo et al. 1986, Pedigo 1995, Ragsdale et al. 2007). This study shows that a single insecticide application can enhance soybean production profitability if used properly in an IPM-based system. In particular, the IPM treatment was most likely to provide yield protection that exceeded the gain threshold and cover the treatment cost. This finding held true even at the high scouting cost of $19.76 ha⁻¹, even though the scouting fee substantially exceeds the $5.00 ha⁻¹ rate reported by Song et al. (2006) of a typical scouting fee in Michigan that is attributable to soybean aphid scouting visits. The findings of this study are
consistent with Song and Swinton (2009), which reported that timely insecticide application resulted in soybean yield-protection that fully offset yield losses when the soybean aphid population exceeded the ET. It is important to mention that grower benefit from the $19.76 ha$–$1$ was not limited to information on aphid populations.

The objective of the third study was to investigate the applicability of the current soybean aphid management recommendations on narrow-row soybean. Many growers practice narrow-row soybean production practices (38 cm to 20 cm) (Norsworthy 2003, De Bruin and Pedersen 2008) for a variety of reasons such as increased yield (Bullock et al. 1998, De Bruin and Pedersen 2008) and improved weed management (Wax et al. 1968, Weiner et al. 2001). Average row spacing for soybean production in Iowa is 57 cm with 19 cm row spacing representing 14% of the acres, 38 cm representing 31%, or row spacing up to 76 cm representing 50%. Iowa has seen slower adopting narrow-row soybean production compared to surrounding states (De Bruin and Pedersen 2008).

The findings did not suggest any significant interactions between row spacing and soybean aphid populations, or row spacing and soybean aphid injury. We did occasionally observe difference in soybean yield due to row spacing however these differences were not caused by differences in soybean aphid exposure (CAD), and may have been due to increased disease incidence (white mold, Sclerotinia sclerotiorum) from a more humid microclimate in narrow-row soybeans. The current soybean aphid management recommendations call for weekly scouting of soybean fields and only applying insecticides when soybean aphid populations exceed the ET (Ragsdale et al. 2007, Johnson et al. 2009). Our findings tend to validate the current soybean aphid management recommendations for soybean produced using narrow row (Ragsdale et al. 2007). The consistency of our findings
in narrow-row soybean with research conducted in wide rows supports a single soybean aphid management threshold that can be across a greater range of soybean rows widths. The validation of the current soybean aphid management recommendations in narrow row soybean will allow soybean producers to confidently adopt the current recommendations for narrow row production.

The goal of our research was to characterize the soybean yield responses to two common sources of injury; defoliation and assimilate removal. We are just starting to understand the complexities of organismal interactions in agroecosystems. However, the concept of interactions has been well studied in chemistry, pesticide development, pharmacy, and toxicology (Hoffman 1953, Akobundu et al. 1975, Davis and Caseley1999, Gennings et al, 2005). By borrowing statistical and experimental design techniques from other disciplines, we may advance our understanding of organismal interactions.

The similarities between the results of this study and other field research are remarkable (Ragsdale et al. 2007, Johnson et al. 2009). Cage studies should not replace field studies when the practicality of the treatment structure is manageable. However, these similarities support the use of cage techniques in this and future injury response studies, provided researchers are aware of the limitations. As indicated by our data, strong year-by-injury interactions can limit the interpretation of the data and soybean aphid threshold development. However, when the model was restricted to CAD levels lower than 60,000 and defoliation levels below 60 percent, the year-by-injury interactions were lost and overall soybean yield was reduced by 4.5 percent per 10,000 CAD and 2.7 percent per 10 percent defoliation:

\[ y_{combined} = 1.0 - 0.0027d - 0.045c, \]
where the percentage total seed yield ($y_{combined}$) was equal to the damage caused by defoliation ($d$) and cumulative soybean aphid exposure ($c$). The lack of interactions between soybean aphid feeding and defoliation indicated that the two sources of soybean injury interact in an additive manner. This result would allow the calculation of a multi-pest EIL. It would be difficult to predict an ET from the EIL due to differences in developmental times of different insects. These findings will contribute to future soybean management in Iowa and across the Midwest.

**LITERATURE CITED**


Bradshaw, J. D., M. E. Rice, and J. H. Hill. 2008. Evaluation of management strategies for bean leaf beetles (Coleoptera: Chrysomelidae) and bean pod mottle virus (Comoviridae) in soybean. J. Econ. Entomol. 101: 1211-1227.


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