Investigating effects of surrounding landscape composition and complexity on populations of two polyphagous insect pest groups in Iowa soybean

by

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DEDICATION

I wish to dedicate this work to my family; in memory of those who have gone before and paved the way, in honor of those who continue to offer guidance, in welcome to those who are new members, and in anticipation of those yet to come.

“We hope that, when the insects take over the world, they will remember with gratitude how we took them along on all our picnics.” ~Bill Vaughan
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>THESIS ABSTRACT</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW</td>
<td>1</td>
</tr>
<tr>
<td>Thesis Organization</td>
<td>1</td>
</tr>
<tr>
<td>Introduction and Literature Review</td>
<td>1</td>
</tr>
<tr>
<td>\textit{Popillia japonica} biology and ecology</td>
<td>1</td>
</tr>
<tr>
<td>\textit{Popillia japonica} pest status and management in soybean</td>
<td>3</td>
</tr>
<tr>
<td>Stink bug biology and ecology</td>
<td>4</td>
</tr>
<tr>
<td>Stink bug pest status and management in soybean</td>
<td>6</td>
</tr>
<tr>
<td>Landscape effects on insect pests</td>
<td>8</td>
</tr>
<tr>
<td>Landscape in Iowa’s agro-ecosystem</td>
<td>10</td>
</tr>
<tr>
<td>Research Objectives</td>
<td>11</td>
</tr>
<tr>
<td>References Cited</td>
<td>12</td>
</tr>
<tr>
<td>CHAPTER 2. INCREASED LANDSCAPE DIVERSITY LEADS TO</td>
<td>17</td>
</tr>
<tr>
<td>INCREASED ABUNDANCE OF A POLYPHAGOUS HERBIVORE IN SOYBEAN</td>
<td></td>
</tr>
<tr>
<td>Abstract</td>
<td>17</td>
</tr>
<tr>
<td>Introduction</td>
<td>19</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>22</td>
</tr>
<tr>
<td>Site selection</td>
<td>22</td>
</tr>
<tr>
<td>Landscape measurements</td>
<td>25</td>
</tr>
<tr>
<td>\textit{Popillia japonica} sampling</td>
<td>26</td>
</tr>
<tr>
<td>Data analysis</td>
<td>27</td>
</tr>
<tr>
<td>Results</td>
<td>28</td>
</tr>
<tr>
<td>Landscape measurements</td>
<td>28</td>
</tr>
<tr>
<td>\textit{Popillia japonica} phenology</td>
<td>29</td>
</tr>
<tr>
<td>Landscape factors and \textit{P. japonica} abundance</td>
<td>31</td>
</tr>
<tr>
<td>Discussion</td>
<td>32</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>37</td>
</tr>
<tr>
<td>References Cited</td>
<td>37</td>
</tr>
<tr>
<td>Tables</td>
<td>46</td>
</tr>
<tr>
<td>Figure Legends</td>
<td>51</td>
</tr>
<tr>
<td>Figures</td>
<td>53</td>
</tr>
</tbody>
</table>
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ABSTRACT

The composition and complexity of agro-ecosystems are important factors influencing the population dynamics of insect pests. Understanding these interactions may improve our ability to predict the spatial occurrence of pest outbreaks, thereby informing scouting and management decisions. In 2012 and 2013, two concurrent studies were conducted to examine the relationship between landscapes surrounding Iowa soybean, *Glycine max* [L.] Merrill, fields and two polyphagous pest groups; Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), and stink bugs (Hemiptera: Pentatomidae). Population densities were monitored in soybean within simple and complex agricultural landscapes to determine the response of these pests to landscape complexity. Results revealed *P. japonica* populations were significantly greater in soybean fields within complex landscapes and were positively associated with area of uncultivated land. The specific compositions of surrounding landscapes were also analyzed to determine the landscape features that explain the greatest variation in *P. japonica* and stink bug population densities. Results suggested that the area of wooded and grass habitat around fields accounted for the greatest variation in *P. japonica* populations; however, no discernable relationships were observed with stink bug populations. Sampling also sought to survey the community of stink bugs present in Iowa soybean. The community was predominantly comprised of stink bugs in the genus *Euschistus*, comprising a combined 91.04% of all captures. Additional species included the green stink bug, *Acrosternum hilare* (Say) (4.48%); spined soldier bug, *Podisus maculiventris* (Say) (2.99%); and red shouldered stink bug, *Thyanta custator accerra* (McAtee) (1.49%). Future work will be needed to determine if the landscape effects on *P.
*japonica* in soybean reported here are representative of other similar polyphagous pests of soybean and if they extend to other host plants as well. Furthermore, additional comprehensive surveys will be needed to better characterize the existing community of stink bug species present in Iowa field crops.
CHAPTER 1. GENERAL INTRODUCTION AND LITERATURE REVIEW

Thesis Organization

This thesis is organized into four chapters. The first chapter contains an introduction including research objectives and a review of pertinent literature on Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), and stink bugs (Hemiptera: Pentatomidae). Topics covered include a summary of biology, ecology, pest status on soybean, and management, as well as previous work related to landscape-scale effects on pest insects within agro-ecosystems. This information provides relevant background and addresses the significance of research presented in later chapters.

Chapter two reports observed effects on the population density of *P. japonica* within soybean relative to the composition and complexity of the landscape surrounding focal fields. Chapter three describes the composition of stink bug communities in sampled soybean fields and the relationship between the makeup and complexity of the surrounding landscape and stink bug captures. Chapter four summarizes conclusions from the previous chapters and comments on possible implications of results as well as suggestions for future related work.

Introduction and Literature Review

*Popillia japonica* Biology and Ecology. The Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), is an introduced pest in North America originating from eastern Asia. In the United States, *P. japonica* populations have successfully established in all states east of the Mississippi River with Florida as the only exception.
They have also spread westward and are now considered established in Minnesota, Iowa, Missouri, Arkansas, Oklahoma, Kansas, Nebraska, South Dakota, and Montana (NAPIS 2013). In addition, *P. japonica* have been reported in all western states (including one of the Hawaiian islands) with the exceptions of Wyoming and Alaska. However, it is currently unclear if these represent established populations (NAPIS 2013).

*Popillia japonica* completes one generation per year in the United States except for the northernmost regions of the country, where colder temperatures may extend development to two years (Potter and Held 2002). Variations in the first emergence of adults in the spring, timing of reproduction, and rates of development are mostly attributable to latitude and local climatic fluctuations between years (Fleming 1972).

After emergence, unmated females produce a volatile sex pheromone that attracts males (Ladd 1970). Females then proceed through several mating and egg-laying cycles. Female *P. japonica* typically enter the soil more than a dozen times and deposit 40-60 solitary eggs during their lifetime (Fleming 1972, Potter and Held 2002). Females prefer to lay eggs into the top few inches of soil in areas with moderate soil moisture and texture, sunlight, and short perennial grass cover (Allsopp et al. 1992, Potter et al. 1996, Potter and Held 2002). An area’s suitability for *P. japonica* oviposition may also be influenced by cultivation practices. For example, a 10-fold increase in *P. japonica* larval abundance has been recorded in weedy nursery fields compared with fields that have been cultivated (Szendrei and Isaacs 2006). It takes about 10-14 days for eggs to hatch, and larvae feed on roots for several weeks (Potter and Held 2002). Larvae move downward in the soil as temperatures cool in the fall and overwinter as third instars. As
the weather warms, larvae move upward in the soil and continue feeding until pupating in early spring. Mature adults emerge from the soil a few weeks later (Potter and Held 2002). *Popillia japonica* larvae have limited mobility and are generally restricted in movement other than their accidental relocation through movement of soil to a new location (Potter and Held 2002). Conversely, adults are able to fly up to several miles to colonize new areas, but typically make relatively short flights to feed or lay eggs (Fleming 1972, Potter et al. 2010).

The host range of *P. japonica* is quite broad. Adults can consume the leaves, flowers, petals, and fruits of more than 300 plant species in at least 79 families (Potter and Held 2002; Potter et al. 2010). Larvae feed on the roots of a wide variety of weeds and grasses as well as garden, nursery, and ornamental plants. Some of the most economically important hosts of adult *P. japonica* include soybean (*Glycine max* [L.] Merrill), corn (*Zea mays* [L.]), and grapes (Rhamnales: Vitaceae), as well as many other fruit, vegetable, and horticultural plants (Fleming 1972, Ladd 1989). Adults tend to aggregate on host plants, with the males attracted to sex pheromones released by females and both sexes attracted to volatile compounds released by injured plants (Ladd 1970, Loughrin et al. 1995). Adult aggregations incur the greatest injury to plants, skeletonizing the leaf tissue between the veins and leaving a lacy appearance (Fleming 1972).

**Popillia japonica Pest Status and Management in Soybean.** In soybean, adult *P. japonica* generally occur in greatest densities and cause the most injury during the reproductive stages of plant development (Cook and Gray 2004). Leaf feeding by *P. japonica* in soybean is usually focused in the upper canopy (Cook and Gray 2004). Turnipseed and Kogan (1976) demonstrated soybean is most susceptible to defoliation
during seed development due to the reduction in leaf area needed for photosynthesis.

Soybean fields severely infested with *P. japonica* have been documented to have feeding on over 90% of leaflets, resulting in a 20% reduction in yield (Gould 1963). Although this level of damage by *P. japonica* alone appears to be rare, even minor injury by this pest may be compounded by the concurrent feeding of other leaf defoliators as well.

As *P. japonica* are gregarious and mobile pests, economic thresholds for soybean are not usually based on beetle abundance, but rather on estimations of leaf defoliation. It is therefore necessary to sample a representative area of the entire field in order to determine the extent of injury. For soybean, foliar insecticides are recommended for *P. japonica* if scouting shows that defoliation has reached or exceeded an average of 30% before bloom or 20% between bloom and pod fill (Cook and Gray 2004). Because *P. japonica* is a member of a complex of insects that defoliate soybean, these thresholds encompass the total leaf defoliation, not only that caused by *P. japonica*. There are several commercially available foliar insecticides encompassing multiple modes of action that are currently labeled for use against *P. japonica* in soybeans (Stewart and McClure 2014).

**Stink Bug Biology and Ecology.** Stink bugs (Hemiptera: Pentatomidae) are a diverse and widespread group of pests estimated to contain nearly 5,000 species worldwide, with nearly 250 of those species occurring in North America (McPherson 1982, McPherson and McPherson 2000, Rider 2011). Most stink bugs are phytophagous; however, those in the subfamily Asopinae are predaceous and feed on a wide variety of arthropod hosts, including destructive pest species (McPherson 1982, McPherson and McPherson 2000).
Stink bugs in North America are able to complete between one and five
generations per year depending on latitude and local temperature variations (McPherson
and McPherson 2000). Adult stink bugs emerge from overwintering habitats in early
spring and disperse rapidly to various initial hosts including herbaceous plants, grasses,
trees, and shrubs to feed and reproduce (Rolston and Kendrick 1961, Panizzi 1997,
McPherson and McPherson 2000).

In addition to the long-distance attraction mediated by pheromones, many stink
bug species also utilize short range cues, including vibrational songs on substrates for
mate location and visual cues for host location (Aldrich et al. 2009, Tillman et al. 2010).
After mating, females lay clusters of cylindrical eggs directly on various plant tissues,
particularly on the surface of leaves (Triplehorn and Johnson 2005). A sticky secretion
released by the female adheres the eggs to the plant and to each other (McPherson and
McPherson 2000). First instars emerging from these eggs are generally non-feeding and
remain aggregated near the egg cluster, likely as a defensive mechanism during this
vulnerable stage (Lockwood and Story 1986). Subsequent instars begin to feed and
disperse, although some species remain gregarious through the third molt (McPherson
and McPherson 2000). Stink bugs complete a total of five instars before reaching
adulthood (McPherson and McPherson 2000). Adults continue to feed and reproduce
during the warm summer months and migrate back to overwintering habitats with
cooling temperatures in the fall. Stink bugs generally overwinter as adults in a state of
reproductive diapause beneath leaf litter, tree bark, and other debris (McPherson and
McPherson 2000).
Some species also overwinter in man-made structures, in some instances becoming nuisance pests for homeowners and businesses (Nielsen and Hamilton 2009).

Stink bugs are considered an economically important pest group of many grain, fruit, and fiber crops in the United States, particularly in the southern and coastal growing regions (Panizzi 1997, McPherson and McPherson 2000). As they prefer hosts with growing shoots and developing seeds, phytophagous stink bugs will move sequentially from one host plant to another depending on each plant’s suitability at the time (McPherson and McPherson 2000). The immigration of stink bugs into cultivated crops from wild host plants typically coincides with seed development (Rolston and Kendrick 1961, McPherson and McPherson 2000).

The range of suitable host plants for phytophagous stink bugs is quite broad, with successful feeding and development reported on over 250 plant species (McPherson and McPherson 2000). Stink bugs feed by inserting their piercing-sucking mouthparts into plant tissue (or other arthropods in the case of Asopinae), injecting saliva containing digestive enzymes, and removing the liquid contents (Panizzi 1997, McPherson and McPherson 2000).

**Stink Bug Pest Status and Management in Soybean.** Phytophagous stink bugs generally occur in greatest densities and cause the greatest injury to soybean during the reproductive stages of plant development, and are especially active during seed development (McPherson and McPherson 2000). Soybean is susceptible to the greatest economic losses from stink bug feeding during the R3 (pods beginning to develop) to R6 (seeds fully formed) stages of development (Fehr 1971, McPherson and McPherson

In soybean, phytophagous stink bugs have the ability to feed on foliage, blooms, and stems, but preferentially feed on pods (Bundy and McPherson 2000, McPherson and McPherson 2000). With the exception of the first instar (which is generally non-feeding), immatures and adults are able to utilize soybean as a host plant, potentially causing economic damage (McPherson and McPherson 2000). However, the greatest amount of injury in soybean is caused by fifth instars and adults (McPherson and McPherson 2000).

In addition to potential yield loss, feeding can open up the plant to diseases such as yeast spot disease, of which stink bugs are known to transmit the causative agent, as well as result in a condition known as green stem disorder (Boethel et al. 2000, McPherson and McPherson 2000). This delayed plant maturity is exhibited by the retention of leaves and the stems of the plant remaining green long after the pods have senesced (Boethel et al. 2000, Hobbs et al. 2006). Harvesting plants with green stem disorder is complicated as the tough and pliable stems are difficult for mechanical harvesters to cut and process efficiently, leading to additional yield losses and possible damage to harvesting equipment due to clogging (Hobbs et al. 2006).

Management practices for phytophagous stink bugs are complicated by the fact that they are highly mobile and readily vacate host plants when disturbed. Management recommendations are based on population density and vary depending on species and region. Sources from the North Central United States recommend considering foliar insecticide applications in soybean if an average of 4 or more nymphs and adults are collected per 10 sweeps or if an average of 1 or more individuals per row foot are
observed (Ritson and Hodgson 2010, Michel et al. 2013). Economic threshold recommendations are greatly reduced for food-grade soybeans or soybeans grown for seed where consistent seed quality is of greater concern (Michel et al. 2013). There are several currently commercially available foliar insecticides that are recommended for use against stink bugs in soybean (Stewart and McClure 2014).

**Landscape effects on insect pests.** Although several studies have detailed the responses of beneficial insects to the surrounding landscape, relatively little work has been done examining these relationships for insect pests. Reviews of published literature examining landscape-scale effects on insects show a varied response for insect pests with many monophagous or oligophagous pests displaying negative responses and polyphagous pests displaying more neutral or positive responses to increasing landscape complexity (Bianchi et al. 2006, Chaplin-Kramer et al. 2011). There are several possible underlying mechanisms for these observed effects. One proposed mechanism is that the increased availability of both alternative host plants and overwintering habitats within diversified habitats are conducive to the growth of certain insect populations at times when hosts in cultivated areas are unavailable (Gurr et al. 2012).

As pests with limited host ranges are often unable to fully utilize these diversified resources, it is intuitive that their responses to diversification in the landscape would be different than that of polyphagous pests. In addition, as natural enemies have often been shown to respond positively to increasing habitat diversity, susceptible pest populations within these landscapes may also suffer additional mortality (Bianchi et al. 2006, Chaplin-Kramer et al. 2011). An example of this type of landscape relationship has been shown with the soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae). A
pair of studies by Gardiner et al. (2009a, 2009b) revealed that *A. glycines* population
densities were lower in soybean fields within a diverse agricultural landscape, which was
attributed to a higher occurrence of biological control by natural enemies. Even within
Aphididae, this negative effect of landscape diversity on abundance is not a general trend,
dirhodum* Walk, and *Rhopalosiphum padi* L. (Hemiptera: Aphididae), on wheat (*Triticum
aestivum* L.) by Roschewitz et al (2005) revealed higher densities due to increased aphid
establishment in complex landscapes compared to simple landscapes. This positive
relationship with diversification of the landscape was attributed to the availability of
perennial grasses, which are utilized by these species as overwintering hosts. However,
this study observed an increase in biological control by natural enemies in these
landscapes as well, thereby likely reducing the overall size of the observed positive effect
(Roschewitz et al 2005).

Insect pests that are polyphagous and mobile (especially those that have few
natural enemies) may be able to benefit from both the alternative host plants and
overwintering habitat available in diversified landscapes while avoiding the negative
effects of increased biological control often also associated with landscape
diversification. An example of a pest displaying this type of landscape relationship is the
polyphagous western tarnished plant bug, *Lygus hesperus* Knight (Hemiptera: Miridae),
which has shown higher population densities in both upland and pima cotton (*Gossypium
hirsutum* L. and *Gossypium barbadense* L.) fields within landscapes containing greater
areas of weedy and uncultivated habitat (Carriere et al. 2006, Sivakoff et al. 2013).
Additionally, Zaller et al. (2008) studied populations of two species of polyphagous
pollen beetles, *Meligethes aeneus* Fabr. and *Meligethes viridescens* Fabr. (Coleoptera, Nitidulidae) in winter oilseed rape (*Brassica napus* L.) and found positive relationships between population densities and wooded area as well as overall diversity within the surrounding landscape. Overall, the relationships between features of the surrounding landscape and insect pest densities have been shown to be complicated and to vary widely between pest groups with different host ranges and life histories as well as between species within those groups.

**Landscape in Iowa’s Agro-ecosystem.** The landscape in Iowa has changed drastically since large-scale settlement and development in the 1800’s (Smith 1998). Prior to this landscape transformation, Iowa’s predominant land cover feature was prairie (~79.5%) followed by forest (~11.7%), savannah (~6.7%), and wetland (~1.4%) (Smith 1998). As of 2013, Iowa is dominated by two crops: corn and soybean, making up an estimated 36.6% and 25.4% of the state’s land cover, respectively, with relatively small patches remaining of more diverse uncultivated habitat (USDA NASS 2013). This intensification of agricultural production and general reduction in diversity within the overall landscape as well as the concentration of more diverse uncultivated habitats into shrinking, discontinuous patches may have unforeseen consequences on the distribution and abundance of insect populations. It is therefore necessary to study the responses of insect species to aspects of the larger landscape. This knowledge may allow us to better predict and respond to the occurrence of insect pests as well as utilize the landscape to our advantage in preserving the ecosystem services provided by beneficial species.
Research Objectives

The research presented in the following chapters sought to better understand the relationships shared between in-field populations of polyphagous insect pests and features of the surrounding landscape. Two concurrent field studies, focused respectively on populations of *P. japonica* and stink bugs, were conducted in pursuit of the objectives for this project which were:

1) to evaluate differences between populations of *P. japonica* and stink bugs in soybean within simple and complex agricultural landscapes;

2) to analyze the relationships between landscape composition and variation in *P. japonica* and stink bug populations;

3) to monitor for the presence of the invasive brown marmorated stink bug (*Halyomorpha halys* Stål) and survey the existing community of endemic stink bug species in Iowa soybean within differing landscapes; and

4) to assess the response of the existing endemic community of stink bugs in Iowa soybean to sampling methods targeting *H. halys*. 
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CHAPTER 2. INCREASED LANDSCAPE DIVERSITY LEADS TO INCREASED ABUNDANCE OF A POLYPHAGOUS HERBIVORE IN SOYBEAN

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Abstract

Many mobile, polyphagous insect pests in agro-ecosystems utilize resources in both cultivated and uncultivated habitats at different times during the growing season. Therefore, field population densities of these pests may be influenced by the composition and diversity of land cover within the surrounding landscape. Over the course of a two-year study (2012-2013), adult Japanese beetle (Popillia japonica Newman) (Coleoptera: Scarabaeidae) populations were observed in soybean (Glycine max [L.] Merrill) fields within structurally simple agricultural landscapes (i.e. containing approximately <10% uncultivated land-cover) relative to those within more complex agricultural landscapes (i.e. containing approximately >50% uncultivated land-cover). Commercial fields were selected in replicated regions across Iowa and monitored throughout the period of adult activity. More P. japonica were observed in soybean within complex landscapes compared to fields within simple landscapes when averaged across the three regions and in two of the three regions when analyzed separately. Regression analyses were used to determine how much of the variation in P. japonica abundance was explained by specific land-cover features within these landscapes. Results suggested that variation in P. japonica abundance was best explained by the percentages of wooded and grass land-
cover in the surrounding landscape. Understanding the relationship between landscape characteristics and pest abundance can inform management decisions by concentrating monitoring efforts within areas most likely to harbor large population densities. Implications of these results and possible effects on populations of other invasive pests of soybean in North America are discussed.

**Key Words**  landscape ecology, landscape complexity, population dynamics, invasive species, GIS
**Introduction**

Populations of polyphagous pest insects in agro-ecosystems are influenced by multiple factors of both cultivated and uncultivated habitat within the surrounding landscape. These factors include the availability and diversity of suitable host plant species, natural enemy habitats, and overwintering sites (Kennedy and Storer 2000, Gurr et al. 2012). This relationship between pests and the surrounding environment is a dynamic interaction between sources (habitats which these pests originate from) and sinks (habitats into which these pests immigrate) (Goodell et al. 2012). Uncultivated habitats may be especially important sources for polyphagous insect pests because they act as reservoirs for these species during periods when crop plants are unavailable or are less suitable hosts (Kennedy and Storer 2000). Within a diversified landscape the presence of uncultivated habitats directly bordering fields may also function to concentrate and retain pest populations within fields by partially restricting migration out of the area (Bach 1988).

Previous work has described the responses of several key pest and beneficial insects to factors within the agricultural landscape (Dyer and Landis 1997; Menallad et al. 1999; Roschewitz et al. 2005; Carrière et al. 2006, 2012; Zaller et al. 2008, 2009; Schmidt et al. 2011; Sivakoff et al. 2013). In general, predators and parasitoids have been shown to respond positively to increasing landscape complexity. This relationship is more varied for pests, with many monophagous and oligophagous pests displaying negative responses and polyphagous pests displaying more neutral or positive responses to increasing landscape complexity (Bianchi et al. 2006, Chaplin-Kramer et al. 2011).
Iowa is currently experiencing invasions by several exotic insect pests. These include the soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae); brown marmorated stink bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae); spotted wing drosophila, *Drosophila suzukii* Matsumura (Diptera: Drosophilidae); and Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae) (Gardiner et al. 2009a, Nutter et al. 2011, Jesse et al. 2012, Lewis and Jesse 2012). The response of these invasive insects to the Iowa landscape may affect the rate and dispersal of their colonization within the state. For this study, we focused on the response of one of these species, *P. japonica*, to varying landscape dynamics across the Iowa agro-ecosystem.

*Popillia japonica* is an invasive species from eastern Asia with the potential to be a significant pest of soybean, *Glycine max* [L.] Merrill, and other economically and aesthetically important plant species in Iowa (Fleming 1972, Potter and Held 2002). First detected in Iowa in 1994, *P. japonica* has been reported in 63 out of the 99 counties in the state as of 2013 (Nutter et al. 2011; D. R. Lewis, unpublished data). Adult *P. japonica* are capable of utilizing and moving among multiple host plants throughout a growing season (Fleming 1972, Potter et al. 2010). In the Midwest, adult emergence usually begins in early June and abundance is highest from mid-July through August (Fleming 1972). However, exceptionally hot conditions can lead to earlier than usual adult emergence (Bailey 2012, Hodgson 2012, Johnson 2012, Purdue University Extension 2012). Females oviposit into the soil, preferring areas containing short perennial grass cover (Potter and Held 2002). Therefore, the vast majority of adults found in soybean are assumed to immigrate into these fields from the surrounding landscape.
In soybean, *P. japonica* generally occur in greatest densities and cause the greatest levels of defoliation during the reproductive stages of plant development (Cook and Gray 2004). Management recommendations in soybean are not based on population density, but rather on the severity of defoliation. Insecticide applications are recommended when defoliation reaches an average of 30% before bloom or 20% between bloom and pod fill (Cook and Gray 2004). Because *P. japonica* is a member of a complex of insects that defoliate soybean, these thresholds encompass the total leaf defoliation, not only that caused by *P. japonica*.

To what extent landscape composition and complexity in a region affect the abundance of *P. japonica* in local soybean fields is currently unknown. However, studies focused on landscape effects have been conducted with other agricultural insect pests. In Iowa, *A. glycines* has been observed to respond negatively to landscape complexity. Gardiner et al. (2009a, 2009b) observed lower *A. glycines* abundance and a higher occurrence of biological control by predators in soybean fields surrounded by higher levels of landscape complexity. However, unlike *P. japonica*, *A. glycines* is monophagous during the soybean growing season and can suffer significant mortality from a variety of natural enemies in North America. Perhaps a more closely related example to *P. japonica* is the western tarnished plant bug, *Lygus hesperus* Knight (Hemiptera: Miridae). Recent studies have shown increased populations of *L. hespersus* in cotton fields within landscapes containing greater areas of weedy and uncultivated land-cover (Carriere et al. 2006, Sivakoff et al. 2013). Like *P. japonica*, *L. hespersus* is polyphagous, mobile, and utilizes both cultivated and uncultivated habitats during the growing season (Scott 1977, Goodell et al. 2000).
To determine the relationship between surrounding landscape complexity and in-field populations of *P. japonica*, a two-year study was conducted in Iowa soybean fields within simple and complex landscapes. The objectives for this study were to measure the seasonal abundance of *P. japonica* in soybean fields surrounded by landscapes with differing levels of complexity and to analyze the composition of these landscapes to determine which land-cover features explain the most variation in *P. japonica* populations. Due to its mobility, its wide host range, and its oviposition behavior, we hypothesized that the abundance of *P. japonica* would be positively associated with increasing landscape complexity and that the land-cover features that would explain the most variation in *P. japonica* population density would be uncultivated features such as wooded areas, open grass, and urban development.

**Materials and Methods**

**Site Selection.** To determine if landscape complexity influences the abundance of *P. japonica* in soybean fields, we used a modified version of a method developed by Menalled et al. (1999), in which features surrounding a crop field within a prescribed distance defined the landscape. As described in Menalled et al. (1999), pseudo-replication was avoided by selecting fields within three separate regions, in this case three Iowa counties: Story (central Iowa), Floyd (northeast Iowa), and Lucas (south-central Iowa). Over the course of this study, 26 commercial soybean fields (12 in 2012 and 14 in 2013) were selected. In 2012, four fields each were sampled in Story, Floyd, and Lucas Counties, respectively. In 2013, six fields were sampled in Story County and four fields each were sampled in Floyd and Muscatine Counties. Lucas County was replaced with
Muscatine County (southeast Iowa) in 2013 and data from Lucas County were excluded from further analysis due to the absence of *P. japonica* in traps and field samples in 2012. This left 22 total field sites for analysis.

Within each county, we began by identifying general areas representing either a complex or simple landscape. Within these general areas, unique fields were selected in both years based on preliminary estimates of the amount of habitat surrounding them within a 2 km buffer not planted to corn, *Zea mays* [L.], or soybean (i.e. uncultivated land-cover) by analyzing aerial and satellite photographs (Google 2013) and land-cover maps (USDA NASS 2012, 2013). Where possible, fields were selected from the same general areas within each county in both years. Fields were considered to be in a complex landscape if approximately >50% of the surrounding habitat within the 2 km buffer was comprised of uncultivated land-cover. Fields were considered to be in a simple landscape if the buffer contained approximately <10% uncultivated land-cover. The 2 km distance was considered appropriate for this analysis due to the reported ability of adult *P. japonica* to fly several miles to colonize new areas (Fleming 1972, Potter et al. 2010). In addition, other recent studies of landscape effects on mobile insect pests have utilized this scale of the surrounding landscape in their analyses (Zaller et al. 2008, Schmidt et al. 2011, Rusch et al. 2013, Sivakoff et al. 2013).

An initial list of possible field sites meeting the defined landscape criteria was then narrowed down by their ease of vehicle access and their proximity to each other. Fields were chosen with a minimum of 4 km between field centers to avoid overlap in the 2 km buffers. The average distance between sampled fields within each county (excluding Lucas County) in both years was 11.21 km (range: 4.01 km to 19.73 km).
Landowners were then randomly selected from the list of qualifying fields in each county and contacted for sampling permission until the required number of field sites had been secured. Contact information for landowners was obtained from plat books of each sampled county. In Story and Muscatine Counties this information was available online (Schneider Corp. 2014) and for Floyd and Lucas Counties it was available in print (FHP 2011a, 2011b). Some candidate fields had to be excluded because current plat information was unavailable, landowners could not be contacted, or sampling permission was denied.

As all fields sampled for this project were planted in a corn-soybean rotation, there was no overlap in fields sampled between 2012 and 2013. All fields were conventionally managed using standard or reduced tillage and foliar herbicides (typically glyphosate) to control weeds. Landowners were also requested to report any foliar insecticide use during both field seasons. Only one foliar insecticide application (Warrior II with Zeon Technology®, active ingredient: lambda-cyhalothrin, Syngenta Agrochemical, Basel, Switzerland) was reported during the sampling period of this study. The field receiving this application was within a complex landscape in Story County in 2012. At the time of application, this field had the highest observed \textit{P. japonica} density of all sampled fields and defoliation was nearing the economic threshold. Populations of \textit{P. japonica} were suppressed by this application for approximately two weeks and then resurged, presumably due to immigration from source habitats in the surrounding landscape. Therefore, the impact of this insecticide application on the overall sampling totals was considered to be minimal, and these data were included in the final analysis.
Landscape Measurements. In both 2012 and 2013, USDA land cover maps (USDA NASS 2012, 2013) were used to classify all major land-cover features within 2 km of each field center at a 22 m resolution. These raster land-cover maps were downloaded and converted to polygon features, which were then digitized using ArcMap 10.1 (ESRI 2012). Land-cover features from these maps were then grouped into simplified categories of cover type by summing similar features (e.g. all developed land and roads were grouped into a single cover type). Summarized cover types included corn, soybeans, alfalfa (*Medicago sativa*), wooded, grass, roads and urban development, and open water. In these landscapes, wooded cover was composed of mostly deciduous forest and wooded wetlands with a small amount of coniferous and mixed forest. Grass cover was composed of all open grass except that within heavily urbanized areas. Polygons for these summarized cover types within each field buffer were manually created and digitized in ArcMap 10.1 (ESRI 2012) using 15 m resolution aerial and satellite photographs (Google 2013) and identified using the 22 m resolution summarized land cover maps as a reference. The area in hectares of each cover type was then calculated as well as the overall percentage of each cover type within the 2 km buffer around each sampled field.

The amount of overall diversity in the landscapes within each buffer was also estimated by calculating Simpson’s Index of Diversity (1-λ) (Simpson 1949, Magurran 2004) using the equation:

$$ D = 1 - \frac{\sum n(n-1)}{N(N-1)} $$

where n was the area of each summarized land cover type and N was the total area within the 2 km buffer. Simpson’s Index values vary from zero to one, with values closer to one
representing an increased level of diversity within an area. Where possible, land cover features were also confirmed visually from adjacent roads. Overall, a low percentage of discrepancy existed between the land-cover maps, inspection of aerial and satellite imagery, and ground confirmations.

**Popillia japonica Sampling.** Funnel traps designed to capture *P. japonica* with an olfactory bait were used to determine the timing of emergence and the peak abundance of *P. japonica* in each sampled county. Tanglefoot *P. japonica* traps and lures (Contech Enterprises Inc., Victoria, B.C.) were deployed at Iowa State University research farms in each sampled county in late May in both 2012 and 2013 and were monitored weekly throughout the growing season. Lures utilized in these traps consist of a combination of food-related volatile oils (a 3:7:3 mixture of phenethyl propionate, eugenol, and geraniol) and a synthetic *P. japonica* sex pheromone (Switzer et al. 2009). Samples collected from each trap were placed into individual top-closure plastic bags and frozen for future identification at -20°C. Because these traps were baited, we did not consider them appropriate for estimating the natural occurrence and abundance of *P. japonica* in soybean fields. However, as these traps and lures are highly attractive to *P. japonica* adults, they do allow estimation of the initial emergence and phenology of adults within a general area.

To determine if landscape factors influenced the abundance of *P. japonica*, soybean fields in each county were visited once a week beginning in June and ending in September. On each sampling date the growth stage of plants in each field was recorded based on descriptions from Fehr et al. (1971). Direct observations were made of adult *P. japonica* by inspecting 10 random plants at two randomly selected locations at the field
edge (within the first five rows) and two locations at the field interior (>50 m from the field edge), for a total of 40 observations per field. Observations were made at both the edge and interior of the field to account for the possibility of edge effects, which have been previously observed for *P. japonica* in soybean (Sara et al. 2012). Initial analyses revealed no significant differences between mean totals from edge and interior samples in either the complex or simple landscapes (*P* > 0.70), thus observations were totaled from the 4 sampling locations within each field for subsequent analyses. Inspected plants were a minimum of 1 m apart to avoid counting the same individuals multiple times due to their movement during sampling. All locations from which direct observations were taken were a minimum of 50 m apart. Direct observation of adults on soybean plants was chosen to analyze *P. japonica* abundance for this study over other methods (e.g. sweep netting and drop cloth sampling) because it is can be performed across the entire field season from plant emergence to harvest, where other methods require waiting for the plant to reach a minimum growth to avoid causing damage to the plant during sampling.

**Data Analysis.** Estimates of *P. japonica* abundance from direct observations were analyzed as a randomized complete block design with county as block, landscape complexity as the treatment, and fields within each county as the experimental unit. Each field was assigned a treatment of either complex or simple based on initial estimates of surrounding landscape complexity. Both treatments were then replicated twice in each county, except Story County in 2013, in which each treatment was replicated three times to increase statistical power. Population densities of *P. japonica* observed per field on each sampling date were summed across the growing season and square root transformed to meet the assumptions of normality and equal variance. As initial analyses revealed no
significant effects of year on *P. japonica* totals (year and all interactions with year; \( P > 0.30 \)), all data were pooled across both years and year was not included as a factor in any subsequent analyses for landscape effects. The square root transformed totals from each field in both years were averaged within their surrounding landscape type (simple or complex) and statistical differences were then analyzed using a two-sample student’s *t*-test (PROC TTEST, SAS Institute 2011). To assess the uniformity of any effect of landscape complexity across the counties sampled, a two factor (county and complexity) two-way ANOVA was performed with complexity nested within county and mean totals of *P. japonica* as the dependent variable (PROC GLM, SAS Institute 2011).

The relationship between the percentage of uncultivated area surrounding each field and the total population of *P. japonica* recorded in each field for the growing season was determined using linear regression (PROC REG, SAS Institute 2011). Stepwise linear regression utilizing both forward selection and backward elimination (PROC REG with stepwise selection, SAS Institute 2011) was also used to determine the relationship between the percentage of each predominant surrounding cover type and variation in total *P. japonica* population densities across each growing season.

**Results**

**Landscape Measurements.** Our preliminary estimates of the landscape complexity around fields considered for our study resulted in two categories that did not overlap in the percentage of uncultivated land-cover that surrounded them. In 2012, fields considered to be in simple landscapes averaged 13.29% uncultivated area (range: 7.38%-17.40%) and a Simpson’s index of 0.60 (range: 0.55-0.64). Complex landscapes averaged
61.39% uncultivated area (range: 46.01%-71.93%) and a Simpson’s index of 0.77 (range: 0.76-0.80). In 2013, fields considered to be in simple landscapes averaged 9.50% uncultivated area (range: 6.35%-11.52%) and a Simpson’s index of 0.58 (range: 0.55-0.59). Complex landscapes averaged 67.01% uncultivated area (range: 51.22%-89.64%) and a Simpson’s index of 0.76 (range: 0.69-0.80). Location, area, and landscape information for each sampled field in 2012 and 2013 are summarized in Tables 1 and 2. Although the amount of uncultivated habitat did not always fall within our targeted values (i.e. <10% for the simple landscape category and >50% for the complex landscape category), the average values for fields within simple landscapes were well below the average values for fields within complex landscapes. Tables 3 and 4 list the percentages of each summarized cover type surrounding sampled fields. Although variation in landscape composition between field sites was unavoidable, as average Simpson’s index values were similar between years and among counties within each year, we suggest that fields chosen for sampling were adequate replicates of overall landscape complexity.

**Popillia japonica Phenology.** In 2012, the first adult *P. japonica* were captured in baited traps during the first week of June in Story County and the third week of June in Floyd County. No *P. japonica* were collected in baited traps in Lucas County during 2012. This absence of adult *P. japonica* in Lucas County is most likely due to this being a recently invaded area of Iowa where this pest is still in the process of becoming established. A single baited trap was also deployed in Lucas County in 2013 and again failed to catch any *P. japonica*, supporting our hypothesis that the absence of adults in traps in this county in 2012 was due to low overall populations in the area and not to
yearly variation. In 2013, baited traps caught the first adult *P. japonica* in the fourth week of June in Story County and the second week of July in Muscatine and Floyd Counties.

After catching adult *P. japonica* in baited traps in each county, adults were observed in fields within approximately one to four weeks. In 2012, we observed the first adult *P. japonica* in soybean in the second week of June and the first week of July in Story County and Floyd County, respectively. Populations of *P. japonica* were higher throughout the growing season in Story County compared to Floyd County. In 2013, we observed the first adult *P. japonica* in soybean in the first week of July in Story County, the second week of July in Muscatine County, and the first week of August in Floyd County. Floyd County, again, had lower populations throughout the growing season than Muscatine County and Story County. Peak populations of *P. japonica* in both baited traps and field samples occurred in mid July in 2012 and in late July through August in 2013, corresponding to the early to mid-reproductive growth stages of soybeans in both years.

In summary, we first observed *P. japonica* in the baited traps, but saw similar timing of peak abundance estimated with both baited traps and direct observations (Figs. 1, 2). We therefore suggest that the sampling of adults conducted in soybeans captured the phenology of *P. japonica* within Iowa for that crop. Adults likely emerged earlier than when we first observed them in soybean fields, but as expected, immigrated into fields from the surrounding landscape.

An early spring and exceptionally warm temperatures in 2012 led to earlier than usual emergence of *P. japonica* adults in several Midwestern states (Bailey 2012, Hodgson 2012, Johnson 2012, Purdue University Extension 2012). These warm
temperatures likely account for the 2-3 week earlier appearance of *P. japonica* in both baited traps and field observations in 2012 relative to 2013.

**Landscape Factors and *P. japonica* Abundance.** In both 2012 and 2013, numerically greater populations of *P. japonica* adults were observed in field samples within complex landscapes than those in simple landscapes throughout most of the growing season (Figs. 3, 4). A two-sample student’s *t*-test indicated higher mean populations of *P. japonica* in soybean fields within complex landscapes than those within simple landscapes when averaged across years and counties (*t* = 2.28; *df* = 20; *P* = 0.0337) (Fig. 5). Mean *P. japonica* totals (± SEM) for all fields across both years within each county-complexity combination are presented in Figure 6. Significant effects of county (*F* = 61.03; *df* = 2; *P* < 0.0001) and complexity (*F* = 29.92; *df* = 1; *P* < 0.0001) were shown by the ANOVA (Table 5). Due to large differences in *P. japonica* populations between counties, we also observed a significant county*complexity* interaction (*F* = 6.18; *df* = 2; *P* = 0.0103) (Table 5). Slicing this county*complexity* effect by county revealed significantly higher total *P. japonica* populations within complex landscape fields in both Story County (*F* = 43.74; *df* = 1; *P* < 0.0001) and Muscatine County (*F* = 6.27; *df* = 1; *P* = 0.0234) than in simple landscape fields. However, although *P. japonica* populations within complex landscapes were numerically higher than in simple landscapes in Floyd County, no significant difference was observed (*F* = 1.45; *df* = 1; *P* = 0.2455) (Fig 6).

Based on linear regression analysis, we observed a positive relationship between the percentage of non-crop habitat in the landscape surrounding soybean fields and the total population of *P. japonica* adults observed within them (Error df = 20, MSE = 45.61,
Based on a stepwise linear regression, the landscape features within field buffers explaining the greatest amount of variation in *P. japonica* adult abundance were the percentages of wooded (partial $R^2 = 0.37; F = 11.51; P = 0.0029$) and grass cover (partial $R^2 = 0.26; F = 13.55; P = 0.0016$) in the surrounding landscape.

**Discussion**

As was stated in our initial hypotheses, we expected that *P. japonica* abundance would be positively associated with increased complexity in the surrounding landscape (defined within this study as an increase in non-crop area) and that area of non-crop features such as wooded areas, open grass, and urban development within these landscapes would explain the greatest amount of variation in *P. japonica* abundance. Our analyses were mostly consistent with these hypotheses, showing significantly higher abundance in complex landscape fields than those in simple landscapes when averaged across the three regions studied as well as significant positive relationships between the area of wooded and grass cover in the surrounding landscape and *P. japonica* abundance.

An explanation for the higher population densities of *P. japonica* observed in soybean fields surrounded by complex landscapes is that these habitats provide a variety of host plants for adult feeding. As adults, *P. japonica* are able to consume more than 300 plant species in at least 79 families (Potter and Held 2002). Therefore alternative host plants within these complex landscape habitats may act as temporary reservoirs for emerging adults early in the growing season from which they then immigrate into local fields. They may also serve as sinks for adults late in the growing season during field
crop senescence and harvest. This explanation is supported by the positive relationship shown between field populations of *P. japonica* and the percentage of non-crop habitat (particularly the percentage of wooded habitat) in the surrounding landscape, as these habitats likely contain a diverse range of suitable host plants for this pest.

Another possible explanation for this effect is that these surrounding areas provide an increased area of high quality oviposition sites for *P. japonica*. Females oviposit into the soil, preferring areas containing short perennial grass cover (Potter and Held 2002). *Popillia japonica* larvae also have limited mobility and are generally restricted in movement other than their accidental relocation through movement of soil to a new location (Potter et al. 2010). Therefore, an increased number of eggs laid in a particular area could have a direct impact on increased abundances of emerging adults in that area in the following year. This explanation is supported by the positive relationship shown between field populations of *P. japonica* and the percentage of open grass in the surrounding landscape, as these habitats likely contain a variety of suitable oviposition sites for this pest and may be more conducive to larval survival and development.

Although applications of neonicotinoid insecticide to soybean seed (i.e. seed treatments) are commonly used in Iowa, we did not account for these applications as a potential source of mortality to *P. japonica*. Estimates of the duration of mortality provided by seed treatments vary by active ingredient and target insect. Although currently no seed treatments applied to soybeans include adult *P. japonica* on their label, some neonicotinoids are labeled for use against adult *P. japonica* when applied to foliage (Stewart and McClure 2014). Therefore, it is possible there is also a mortality effect when applied to seeds. However, the period in which adults were most active in soybean was
likely past the period during which these insecticides would be active in the plant. For example, seed treatments produce mortality against *A. glycines* up to 49 days after planting (McCornack and Ragsdale 2006). Although we began sampling during the early vegetative stages of plant development (~20-35 days after planting), the first *P. japonica* were not observed in fields until late vegetative plant stages (~35-50 days after planting) and the vast majority were observed in reproductive plant stages (~50+ days after planting) (Approximate days after planting for plant growth stages were obtained from Casteel (2011)). We therefore suggest that any possible effects of seed treatments on *P. japonica* likely had a minimal impact on field sampling as the period of possible residual effectiveness had limited overlap with the period in which we estimated their abundance.

An implication of these results is that soybean fields within areas of increased landscape complexity should be given priority for scouting for this pest, as they are the most likely to develop large, damaging populations. Also, because *P. japonica* is such a highly polyphagous pest, these results may potentially apply to other crops as well. Future work will be necessary to determine if landscape features have similar effects on the population dynamics of other polyphagous insect pests (especially newly established invasive species).

In Iowa, a timely example of this is *H. halys*, which has been confirmed to be in the process of becoming established (Jesse et al. 2012). First detected in Iowa in 2011, as of 2014, *H. halys* has been reported in 11 out of the 99 counties in the state (Lewis 2013; D. R. Lewis, unpublished data). In previously invaded regions of North America, *H. halys* populations have increased rapidly post-establishment and have become significant pests of multiple agricultural crops, including soybean (Nielsen et al. 2011). Recent work
has also shown that the general spatial distribution of *H. halys* is affected by multiple factors within the landscape. In a multi-year study of the invasion and establishment of *H. halys* in New Jersey, Wallner et al. (2014) observed a strong positive association between urban development and railroads and *H. halys* population densities during the initial establishment phase of this pest. As populations built up and *H. halys* expanded its range in the state, positive associations were also observed with forested land and wetlands (Wallner et al. 2014). This observed spatial response of *H. halys* to the general landscape as well as the polyphagous and mobile nature of this pest (similar to that of *P. japonica*) suggests that the response of their field abundance to landscape factors may follow a similar pattern to that of *P. japonica* as well. Also, because *H. halys* overwinter as adults beneath leaf litter and other debris, in crevices of dead trees, and within man-made structures, they may also naturally congregate in areas with increased availability of these overwintering habitats (McPherson and McPherson 2000, Nielsen and Hamilton 2009, Lee et al. 2014).

Another invasive pest that may become a concern to Midwestern soybean production in coming years is the kudzu bug, *Megacopta cribraria* Fabricius, (Hemiptera: Plataspidae). First discovered in North America in Georgia in 2009, *M. cribraria* has been reported in nine southeastern states (Gardner 2013, University of Georgia 2014). Like *H. halys*, *M. cribraria* overwinter as adults in natural areas beneath leaf litter as well as in man-made structures (Ruberson et al. 2012, Zhang et al. 2012). However unlike *P. japonica* and *H. halys*, *M. cribraria* is oligophagous in its U.S. range, where its primary host plants are kudzu (*Pueraria lobata* Willdenow) and soybean (Zhang et al. 2012). In soybean, *M. cribraria* feed primarily on the stems and have the
potential to cause significant yield losses (Seiter et al. 2013). Although not currently reported in the Midwest, ecological niche modeling based on its native Asian range has shown that *M. cribraria* has the potential to expand its U.S. range into northern soybean growing regions (Zhu et al. 2012). This range expansion may also include areas where kudzu is not present, as recent work has shown that *M. cribraria* can complete development solely on soybean (Zhang et al. 2012, Del Pozo-Valdivia and Reisig 2013). Although the narrow host range of *M. cribraria* would suggest a negative response to landscape complexity as has been the general trend (Bianchi et al. 2006, Chaplin-Kramer et al. 2011), the relative lack of natural enemies for this pest as well as its overwintering in natural and urban areas complicate predicting its response to landscape factors.

As populations of *H. halys*, *M. cribraria*, and other insect pests continue to expand their range, understanding their individual responses to landscape factors may grant insight into the unique patterns of their invasion and dispersal. When these pests become fully established in new areas and begin to move into agricultural production, it may be possible to apply similar methods to those outlined here in order to evaluate if their abundance within fields is related to factors in the surrounding landscape. This information, in turn, could then be used to focus monitoring and management efforts for these pests.
Acknowledgements

We thank all of the landowners and their families for graciously providing their commercial soybean fields as sampling sites. We also thank hourly employees Emily Feldkamp, Shari Sweeney, and Samuel Gire for assisting in the data collection for this project. This research was supported by the Iowa Soybean Association and the Soybean Checkoff.

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### Tables

**Table 1. Characteristics of Iowa soybean fields sampled for *P. japonica* in 2012**

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<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)</th>
<th>% Crop</th>
<th>% Non-Crop</th>
<th>Simpson’s Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story Complex 1</td>
<td>42.0907°, -93.5841°</td>
<td>9.31</td>
<td>36.16</td>
<td>63.84</td>
<td>0.77</td>
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<tr>
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<td>31.62</td>
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<td>Floyd Simple 2</td>
<td>42.9418°, -92.6584°</td>
<td>38.66</td>
<td>82.60</td>
<td>17.40</td>
<td>0.64</td>
</tr>
</tbody>
</table>

*Identification for each Iowa soybean field sampled during the 2012 field season (Story and Floyd refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)*

*GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)*

*Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)*

*Percentage of each field’s surrounding landscape (within 2km of field center) consisting of row-crop agriculture figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2012)*

*Percentage of each field’s surrounding landscape (within 2km of field center) consisting of non-crop features figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2012)*

*Simpson’s Index of Diversity (values closer to 1 correspond to increased diversity)*
Table 2. Characteristics of Iowa soybean fields sampled for *P. japonica* in 2013

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<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)</th>
<th>% Crop</th>
<th>% Non-Crop</th>
<th>Simpson’s Index</th>
</tr>
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<td>Story Complex 1</td>
<td>42.0928°, -93.5777°</td>
<td>1.82</td>
<td>37.44</td>
<td>62.56</td>
<td>0.77</td>
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<tr>
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</tr>
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<td>Floyd Simple 1</td>
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<td>0.59</td>
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<td>Muscatine Complex 1</td>
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<tr>
<td>Muscatine Complex 2</td>
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<td>0.69</td>
</tr>
<tr>
<td>Muscatine Simple 1</td>
<td>41.5417°, -91.2165°</td>
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<td>90.25</td>
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<td>0.58</td>
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<td>88.72</td>
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<td>0.59</td>
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</table>

*Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

*b GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

*c Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)

*d Percentage of each field’s surrounding landscape (within 2km of field center) consisting of row-crop agriculture figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)

*e Percentage of each field’s surrounding landscape (within 2km of field center) consisting of non-crop features figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)

*f Simpson’s Index of Diversity (values closer to 1 correspond to increased diversity)
Table 3. Surrounding landscape variables for Iowa soybean fields sampled for *P. japonica* in 2012

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Corn</th>
<th>Soybean</th>
<th>Wooded</th>
<th>Grass</th>
<th>Alfalfa</th>
<th>Developed</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story Complex 1</td>
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</table>

*Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)*

*GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)*

*Percentage of each field’s surrounding landscape (within 2km of field center) consisting of each cover type figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)*
Table 4. Surrounding landscape variables for Iowa soybean fields sampled for *P. japonica* in 2013

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Corn</th>
<th>Soybean</th>
<th>Wooded</th>
<th>Grass</th>
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<td>5.35</td>
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</table>

* Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

* GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

* Percentage of each field’s surrounding landscape (within 2km of field center) consisting of each cover type figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)
Table 5. Two-factor analysis of variance for effects of county and surrounding landscape complexity

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<th>P-value</th>
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<td>&lt;0.0001</td>
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<tr>
<td>Complexity</td>
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</tr>
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<td>County*Complexity</td>
<td>2</td>
<td>6.18</td>
<td>0.0103</td>
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Figure Captions

**Figure 1.** Mean abundance of *P. japonica* (mean ± SEM) captured per baited trap (in thousands) (solid line) and observed per soybean field (dotted line, n = 8 fields) averaged across sampled counties in 2012.

**Figure 2.** Mean abundance of *P. japonica* (mean ± SEM) captured per baited trap (in thousands) (solid line) and observed per soybean field (dotted line, n = 14 fields) averaged across sampled counties in 2013.

**Figure 3.** Mean abundance of *P. japonica* per field (mean ± SEM) in soybean fields within complex landscapes (solid line, n = 4 fields) or simple landscapes (dotted line, n = 4 fields) in 2012.

**Figure 4.** Mean abundance of *P. japonica* per field (mean ± SEM) in soybean fields within complex landscapes (solid line, n = 7 fields) or simple landscapes (dotted line, n = 7 fields) in 2013.

**Figure 5.** Mean total *P. japonica* (mean ± SEM) observed in soybean fields averaged across the 2012 and 2013 growing seasons. Fields were selected within landscapes of varying diversity (simple vs. complex; n = 11 per category). Population data were square root transformed to meet assumptions of normality and equal variance. Greater populations were observed in fields within complex landscapes than within simple
landscapes ($t = 2.28; \text{df} = 20; P = 0.0337$). Significance (*) was based on a threshold of $P < 0.05$ using a two-sample student’s $t$-test.

**Figure 6.** Mean total *P. japonica* (mean ± SEM) in soybean fields within each sampled county averaged across the 2012 and 2013 growing seasons. Fields were selected within landscapes of varying complexity (simple vs. complex; $n = 4$ per category for Floyd County, $n = 5$ per category for Story County, $n = 2$ per category for Muscatine County). Population data were square root transformed to meet assumptions of normality and equal variance. Greater populations were observed in fields within complex landscapes than within simple landscapes in both Story County ($F = 43.74; \text{df} = 1; P < 0.0001$) and Muscatine County ($F = 6.27; \text{df} = 1; P = 0.0234$) but not in Floyd County ($F = 1.45; \text{df} = 1; P = 0.2455$). Significance (*) was based on a threshold of $P < 0.05$ in the ANOVA. N.S. = not significant.

**Figure 7.** Linear regression analysis of the total *P. japonica* observed per field by the percentage of uncultivated land-cover in the landscape surrounding each field within a 2 km buffer of field center. Population data were square root transformed to meet assumptions of normality and equal variance.
Figure 1
Figure 2

Mean *P. japonica* ± SEM

- **Traps (Thousands)**
- **Direct Observation**

Month: June, July, August, September, October
Figure 3

Mean Observed Per Field ± SEM

- Complex
- Simple
Figure 4: Mean Observed Per Field ± SEM

- **Complex**
- **Simple**

June | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3
July |  |  | 1 | 2 | 3 | 4 |  |  |  |  |  |  |  | 3
August |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 2
September |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1
Figure 5

(SQRT) Mean Total Observed Per Field ± SEM

*
Figure 6

(SQRT) Mean Total Observed Per Field ± SEM

- Floyd
- Story
- Muscatine

Simple | Complex
--- | ---
Simple | Complex
N.S.

*significant difference
Figure 7

\[ y = 0.15x + 3.21 \]

\[ R^2 = 0.30 \]
CHAPTER 3. SURVEYING SPECIES COMPOSITION AND SEASONAL ABUNDANCE OF STINK BUGS (HEMIPTERA: PENTATOMIDAE) IN IOWA SOYBEAN WITHIN DIFFERING LANDSCAPES

C. D. Kuntz¹, M. E. O’Neal¹,²

¹Department of Entomology, Iowa State University, Ames, IA 50011
²Author for correspondence (email: oneal@iastate.edu)

Abstract

Phytophagous stink bugs (Hemiptera: Pentatomidae) can be an economic pest of soybean (Glycine max [L.] Merrill) in many growing regions. Historically, stink bugs in Iowa have rarely caused economic loss in field crops. However an invasive species, Halyomorpha halys Stål (Hemiptera: Pentatomidae), is currently becoming established in Iowa. Previous literature has shown that the population density and spatial distribution of H. halys is affected by multiple landscape factors. This two-year study sought to survey the community of stink bugs present in Iowa soybean within simple agricultural landscapes (i.e. containing approximately <10% uncultivated land-cover) relative to those within more complex agricultural landscapes (i.e. containing approximately >50% uncultivated land-cover). No significant differences were observed between population densities in simple landscapes compared to those in complex landscapes and no discernable relationships were observed with landscape composition by linear regression analyses. The community was comprised predominantly of stink bug species in the genus Euschistus, making up a combined 91.04% of all captures followed by the green stink
bug, *Acrosternum hilare* (Say) (4.48%); spined soldier bug, *Podisus maculiventris* (Say) (2.99%); and red shouldered stink bug, *Thyanta custator accerra* (McAtee) (1.49%). Populations recorded in soybean fields peaked when seeds were fully developed. Stink bug populations were generally low across both years and did not exceed economic thresholds. Therefore, we suggest a low risk level currently to soybean production in Iowa from the endemic community of stink bugs. However, as *H. halys* becomes further established this risk may be intensified.

**Key Words**  Species composition, landscape ecology, population dynamics, invasive species, GIS
**Introduction**

Phytophagous stink bugs (Hemiptera: Pentatomidae) represent a pest complex of multiple cultivated and uncultivated plants (Panizzi 1997, McPherson and McPherson 2000). The host range of stink bugs is quite broad and includes more than 250 plant species (McPherson and McPherson 2000). These polyphagous pests disperse readily among suitable host plants and have the potential to cause economic damage to several crops (McPherson 1982, McPherson and McPherson 2000). In many southern states, stink bugs are a significant pest group of soybean, *Glycine max* [L.] Merrill, and often require multiple insecticide applications to avoid yield loss (Bundy and McPherson 2000, Smith et al. 2009, Catchot 2013, Musser et al. 2013, Temple et al. 2013).

Several stink bug species are endemic to the soybean growing regions of the North Central U.S. The most commonly reported in soybean are the brown stink bug, *Euschistus servus* (Say), the one-spotted stink bug, *Euschistus variolarius* (Palisot de Beauvois), the dusky stink bug, *Euschistus tristigmus luridus* (Dallas), the green stink bug, *Acrosternum hilare* (Say), and the spined soldier bug, *Podisus maculiventris* (Say) (McPherson 1982, McPherson and McPherson 2000). To date, surveys specifically focused on the stink bug community in Iowa soybean have been lacking. However, data has been collected as part of surveys targeting other soybean pests in the state. For example, analysis of data collected as part of a 2011 survey targeting bean leaf beetles, *Cerotoma trifurcata* (Forster), consisting of 50 sweeps in three conventionally managed commercial soybean fields within each of Iowa’s 99 counties, revealed a stink bug community dominated by brown stink bugs in the genus *Euschistus* (not identified to species) (65.69% of captures) followed by *A. hilare* (30.77% of captures) and *P.*
maculiventris (3.54% of captures) (Jesse et al. 2013). Captures of Euschistus species and A. hilare were fairly ubiquitous across Iowa, but captures of P. maculiventris were much less frequent. Population densities captured from each individual field were relatively low with a maximum of only 14 individuals captured within a single field per 50 sweeps. However, as sampling was completed at only a single time point for each field site (generally at the R2-R3 plant growth stage; Fehr et al. 1971), and as stink bugs are most active in soybean during seed development (R5-R6 growth stages), this survey may have underestimated the overall abundance and species composition of stink bugs present in Iowa soybean throughout the growing season (McPherson and McPherson 2000).

Recently, the invasive brown marmorated stink bug (Halyomorpha halys Stål) (Hemiptera: Pentatomidae), has become a concern in North America. First identified in Allentown, Pennsylvania in 2001 (Hamilton 2009, Aldrich et al. 2009), as of 2014, H. halys has rapidly expanded its range, and has been reported in 42 states in the U.S. as well as Ontario and Québec in Canada (Palmer and Lurvey 2011, Jacobs 2011, Northeastern IPM Center 2012, Leskey 2014). After being identified in Iowa in 2012, H. halys has to date been reported in 11 out of the 99 Iowa counties (Jesse et al. 2012, Lewis 2013; D. R. Lewis, unpublished data). In previously invaded regions of North America, H. halys populations have increased rapidly post-establishment and have become significant pests of multiple agricultural crops, including soybean (Nielsen et al. 2011).

Previous work has shown that the spatial distribution and population density of H. halys in an area are associated with multiple land cover features. In a multi-year study of the invasion and establishment of H. halys in New Jersey, Wallner et al. (2014) observed a strong positive association between urban development and railroads and H. halys
population densities during the initial establishment phase of this pest. As populations increased and its range expanded, positive associations were also observed with forested land and wetlands (Wallner et al. 2014).

*Halyomorpha halys*, *E. servus*, *E. variolarius*, *E. tristigmus luridus* and *A. hilare* are all able to utilize soybean as a host plant, with the potential to cause significant reduction in yield and seed quality given a sufficient population (Nielson and Hamilton 2009, Nielsen et al. 2011, McPherson and McPherson 2000). However, it is currently unclear what risk to soybean production in Iowa the combination of *H. halys* and established endemic stink bug species may pose.

Stink bugs generally overwinter as adults beneath leaf litter and other debris (McPherson and McPherson 2000). Some species (including *H. halys*) also overwinter in man-made structures, becoming nuisance pests for homeowners and businesses (Nielsen and Hamilton 2009). Adult stink bugs emerging in the spring from these overwintering sites move to various initial hosts for feeding and reproduction including grasses and herbaceous plants as well as trees and shrubs (McPherson and McPherson 2000). From these initial hosts, they then disperse into annual crops, including soybean. To what extent the larger surrounding landscape can explain variation in field populations of stink bugs is not clear. However, habitat directly bordering a crop has been shown to affect the abundance of stink bugs along a field edge in some cases. For example, Reay-Jones et al. (2009) reported alternative hosts in adjacent woodland edges were important sources for stink bug infestation in wheat (*Triticum aestivum* [L.]). Similarly, Olson et al. (2012) found increased populations in corn (*Zea mays* [L.]) when alternative hosts were
flowering in adjacent woodland edges. However, this effect was not consistent across other crops investigated, including soybean (Olson et al. 2012).

To determine the relationship between surrounding landscape composition and complexity and in-field populations of stink bugs, a two-year field study was conducted in Iowa soybean fields within simple and complex landscapes. The objectives for this study were to measure the seasonal abundance and community composition of stink bugs in soybean fields surrounded by landscapes with differing levels of diversity, analyze the composition of the landscapes around the sampled fields to determine if landscape factors explain variation in stink bug abundance, monitor for the presence of *H. halys*, and determine how the existing community of stink bugs responds to sampling techniques recommended for *H. halys*. We hypothesized that the abundance of stink bugs would be positively associated with increasing landscape diversity and that the landscape features that would have the greatest positive relationship with stink bug abundance would be non-crop features such as wooded areas, grass, and urban development. We also hypothesized that sampling techniques targeting *H. halys* (e.g. direct observation, sweep-netting, and deploying pheromone baited traps) would also collect individuals of the existing endemic stink bug community.

**Materials and Methods**

**Site Selection.** A modified version of a method developed by Menalled et al. (1999) was used to define landscapes surrounding focal soybean fields. To avoid pseudo-replication as described in Menallad et al. (1999), fields were selected within three distinct regions during the 2012 growing season, in this case three Iowa counties: Story
(central Iowa), Floyd (northeast Iowa), and Lucas (southern Iowa). In 2013, Lucas County was replaced with Muscatine County (southeastern Iowa). Fields were selected in each county based on the area not planted to corn or soybean (i.e. non-crop) surrounding them within a 2 km buffer, centered on a target field. The 2 km distance was considered appropriate for this analysis due to the ability of adult stink bugs to migrate long distances to colonize new areas. For example, the southern green stink bug, *Nezara viridula* (Linnaeus), has been documented to move up to 1 km per day from overwintering sites to host plants for feeding and reproduction (Kiritani and Sasaba 1969). In addition, other recent studies of landscape effects on mobile insect pests have used this scale of the surrounding landscape in their analyses (Zaller et al. 2008, Schmidt et al. 2011, Rusch et al. 2013, Sivakoff et al. 2013). Fields selected for analysis were considered to be in a complex landscape if approximately >50% of the surrounding habitat was comprised of non-crop habitat within the 2 km buffer and a simple landscape if the buffer contained approximately ≤10% non-crop habitat.

General areas within each county representing either a complex or simple landscape based on our defined criteria were initially identified and unique fields were selected in both years from within these general areas based on preliminary estimates of the surrounding landscape diversity by analyzing aerial and satellite photographs (Google 2013) and land cover maps (USDA NASS 2012, 2013). Additional criteria used to narrow down this initial list of possible field sites included their ease of vehicle access and their proximity to each other. A minimum of 4 km between field centers was used to avoid overlap in the 2 km buffers. Landowners were then randomly selected from the list of qualifying fields in each county and contacted for sampling permission until the
required number of field sites had been secured. Plat books of each sampled county were
used to obtain contact information for landowners. In Story and Muscatine Counties this
information was available online (Schneider Corp. 2014) and for Floyd and Lucas
Counties it was available in print (FHP 2011a, 2011b). Unfortunately some fields that
would otherwise have been candidates for this project had to be excluded because current
plat information was unavailable, landowners could not be contacted, or sampling
permission was denied.

**Landscape Measurements.** All land cover features within 2 km of each field
center were classified based on USDA land cover maps (USDA NASS 2012, 2013). After
downloading and converting these raster land-cover maps to polygon features, they
were digitized using ArcMap 10.1 (ESRI 2012). Simplified categories of cover type were
then summarized on these maps by combining similar features. Summarized cover types
included corn (*Zea mays* [L.]), soybeans, alfalfa (*Medicago sativa*), wooded, grass, roads
and urban development, and open water. All wooded land cover features (mostly
deciduous forest and wooded wetlands with a small amount of coniferous and mixed
forest) were combined to create the summarized wooded habitat cover type. Similarly,
the grass cover type was composed of a combination of all open grass features other than
those in heavily urbanized areas. Using the summarized land cover maps as a reference
along with aerial and satellite photographs (Google 2013), polygons for all summarized
land cover features within each field buffer were then manually created and digitized in
ArcMap 10.1 (ESRI 2012). Calculations were then made of the area of each cover type in
hectares as well as the overall percentage of each cover type within the 2 km buffer
around each sampled field.
By calculating Simpson’s Index of Diversity \((1-\lambda)\) (Simpson 1949, Magurran 2004) using the equation

\[
D = 1 - \frac{\sum n(n - 1)}{N(N - 1)}
\]

the amount of overall diversity in the landscapes within each buffer was also estimated where \(n\) was the area of each summarized land cover type and \(N\) was the total area within the 2 km buffer. Values of Simpson’s Index range from zero to one, with values closer to one representing an increased level of diversity within an area. Where possible, land cover features were also confirmed visually from adjacent roads. Overall, a low percentage of discrepancy existed between the land cover maps, inspection of aerial and satellite imagery, and ground confirmations.

**Stink Bug Sampling.** Traps designed to capture stink bugs (specifically targeting *H. halys*) with a pheromone bait were deployed at Iowa State University research farms in each sampled county in late May in both 2012 and 2013 and were monitored weekly throughout the growing season. Traps consisted of the bases and funnels of plum curculio traps (Great Lakes IPM [http://www.greatlakesipm.com]) and tops constructed using methods developed by Brunner (2012). Commercial *H. halys* pheromone lures (methyl (E,E,Z)-2,4,6,-decatrienoate, (Alpha Scents [http://www.alphascents.com]) were used as bait in both 2012 and 2013. In 2013, we also utilized a novel *H. halys* pheromone lure (10,11-epoxy-1-bisabolen-3-ol) provided by Dr. Tracy Leskey and collaborators at USDA ARS (Appalachian Fruit Research Station, Kearneysville, WV), which has shown increased attraction for *H. halys* over methyl (E,E,Z)-2,4,6,-decatrienoate alone (Leskey 2012, Weber et al. 2013). Samples collected from each trap were placed into individual top-closure plastic bags and frozen at -20°C for future identification. Because these traps
were baited, we did not consider them appropriate for estimating the natural occurrence of stink bugs in soybean fields. However, they may be used to detect the presence of *H. halys* when population densities are below the detection level of other sampling methods.

To determine if landscape factors influenced the abundance of stink bugs, soybean fields in each county were sampled by direct observation and sweep-net. In both years, samples were taken weekly beginning in June and ending in September, with sweep net samples beginning in mid-July when sufficient plant growth was present. On each sampling date the growth stage of plants in each field was recorded based on descriptions from Fehr et al. (1971). Direct observations were made by inspecting ten plants at two locations at the field edge (within the first five rows) and two locations at the interior (>50 m from the field edge), for a total of 40 observations per field. Inspected plants were a minimum of 1 m apart to avoid counting the same individuals multiple times due to their movement during sampling. Sweep-net samples were taken with a 30.5 cm diameter canvas sweep-net by conducting ten pendulum sweeps back and forth across two parallel rows at two locations at the edge and two locations at the interior of each field for a total of 40 sweeps per field. Each sweep-net sample was placed into an individual top-closure plastic bag and frozen at -20°C for future identification. Samples using both methods were taken at both the edge and interior of the field to account for the possibility of edge effects, which have been previously observed for stink bugs in some crops (Reeves et al. 2010, Herbert and Toews 2011, Tillman et al. 2014). All locations from which direct observation and sweep-net samples were taken were a minimum of 50 m apart within a field. Species identifications were made in the field on live insects for direct observation samples and from frozen samples taken from sweep-net samples. For
sweep-net samples, a dissecting microscope was used when necessary to distinguish between minute features.

**Data Analysis.** A randomized complete block design with county as block, landscape diversity as treatment, and fields within each county as the experimental units was used to analyze estimates of stink bug abundance collected from sampled fields. Fields were assigned a treatment of either a complex or simple landscape. Two replicates of each treatment were sampled in each county, except Story County in 2013, in which each treatment was replicated three times. Population densities of stink bugs per field on each sampling date were summed across the field season and square root transformed to meet the assumptions of normality and equal variance. These transformed totals from each field in both years were averaged within their surrounding landscape type (simple or complex) and statistical differences were then analyzed using a two-sample student’s $t$-test (PROC TTEST, SAS Institute 2011). To assess the uniformity of any effects across the counties sampled, a two factor (county and complexity) two-way ANOVA was performed with complexity nested within county and the mean total abundance of stink bugs as the dependent variable (PROC GLM, SAS Institute 2011).

The relationship between the percentage of non-crop area surrounding each field and the total population of stink bugs in each field across the growing season was determined using linear regression (PROC REG, SAS Institute 2011). Stepwise linear regression utilizing both forward selection and backward elimination (PROC REG with stepwise selection, SAS Institute 2011) was also used to determine the relationship between each predominant surrounding cover type and the total population of stink bugs sampled in each field.
Results

**Site Selection.** Sampling was conducted in 26 commercial soybean fields (12 in 2012 and 14 in 2013) over the course of this study. In 2012, four fields were sampled in Story, Floyd, and Lucas Counties, respectively. In 2013, six fields were sampled in Story County and four fields each were sampled in Floyd and Muscatine Counties. Lucas County was replaced with Muscatine County (southeast Iowa) in 2013 due to very low captures of stink bugs and the determination after GIS analysis that the simple landscape fields chosen within this county were excessively outside our intended level of landscape diversity (i.e. approximately <10% non-crop habitat). Data from Lucas County field sites from 2012 were therefore excluded from further analysis. This left 22 total field sites for the final analysis. The average distance between sampled fields within each county (excluding Lucas county) in both years was 11.21 km (range: 4.01 km to 19.73 km).

As all fields sampled for this project were planted in a corn-soybean rotation, there was no overlap in fields sampled between 2012 and 2013. All fields were conventionally managed using standard or reduced tillage and foliar herbicides (typically glyphosate) to control weeds. Landowners were also requested to report any foliar insecticide use during both field seasons. During the sampling period of this study, a single foliar insecticide application was reported (Warrior II with Zeon Technology®, active ingredient: lambda-cyhalothrin, Syngenta Agrochemical, Basel Switzerland). This application was made to a field within a complex landscape in Story County in 2012. Prior to this application, only a single stink bug individual had been collected from this particular field. Although the population of stink bugs may have been suppressed by this application, sampling totals from subsequent weeks were similar to other fields within the
same county. Therefore, the impact of this insecticide application on the overall sampling totals was considered to be minimal, and these data were included in the final analysis.

We did not account for applications of neonicotinoid insecticide to soybean seed (i.e. seed treatments) as a potential source of mortality to stink bugs. Although seed treatments currently available for soybean are not labeled for use against stink bugs, foliar applications of some neonicotinoids are used for stink bug management (Stewart and McClure 2014). However, the period in which stink bugs were most active in soybean was likely past the period during which these insecticides would be active in the plant. Mortality effects from seed treatments on the soybean aphid, *Aphis glycines* (Matsumura), have been reported up to 49 days after planting (McCornack and Ragsdale 2006). Although we began sampling for stink bugs during the early vegetative stages of plant development (~20-35 days after planting), the first stink bugs were not observed or collected in fields until late vegetative plant stages (~35-50 days after planting) and the vast majority of stink bugs were observed and collected in reproductive plant stages (~50+ days after planting) (Approximate days after planting for plant growth stages were obtained from Casteel (2011)). We therefore suggest that if any effects of seed treatments on stink bugs occur they likely had a minimal impact on our estimate of field populations as there was limited overlap between the period of possible residual effectiveness and the period in which we estimated their abundance.

**Landscape Measurements.** Our preliminary estimates of the landscape diversity around fields considered for our study resulted in two categories that did not overlap in the percentage of non-crop habitat that surrounded them. In 2012, fields considered to be in simple landscapes averaged 13.29% non-crop habitat (range: 7.38%-17.40%) and a
Simpson’s index of 0.60 (range: 0.55-0.64). Complex landscapes averaged 61.39% non-crop habitat (range: 46.01%-71.93%) and a Simpson’s index of 0.77 (range: 0.76-0.80). In 2013, fields considered to be in simple landscapes averaged 9.50% non-crop habitat (range: 6.35%-11.52%) and a Simpson’s index of 0.58 (range: 0.55-0.59). Complex landscapes averaged 67.01% non-crop habitat (range: 51.22%-89.64%) and a Simpson’s index of 0.76 (range: 0.69-0.80). Location, area, and landscape information about each sampled field in 2012 and 2013 are summarized in tables 1 and 2. Although the amount of non-crop habitat did not always fall within our targeted values (i.e. ≤10% for the simple landscape category and >50% for the complex landscape category), the average values for fields within simple landscapes were well below the average values for fields within complex landscapes. Supplemental tables S1 and S2 in the appendix list the percentages of each summarized cover type surrounding sampled fields. Although variation in landscape composition between field sites was unavoidable, as average Simpson’s index values were similar between years and among counties within each year, we suggest that fields chosen for sampling were adequate replicates of overall landscape complexity.

**Sampling Method Evaluation.** Only two individuals were caught in pheromone traps in 2012 (both adult *A. hilare*) and no stink bugs were caught in these traps in 2013. Similarly, relatively low numbers of stink bugs occurred in direct observation samples (25 and 49 total stink bugs observed in 2012 and 2013, respectively). An additional species was also collected in sweep-net samples that did not appear in direct observation samples. As species identifications of these stink bugs were generally made in the field on living specimens without the use of any magnification, the accuracy of these
identifications for similar looking species is also likely to be less than that of sweep-net sampling. Therefore, due to fewer numbers and fewer overall species observed than caught by sweep-net sampling, these samples were excluded from further analysis of landscape effects in favor of the sweep-net sampling data. Sweep-net sampling in all analyzed fields captured a total of 402 individuals across both years (more than a five-fold increase over direct observation sampling).

**Species and Life Stage Composition.** Total captures, frequency of capture, average densities, and overall percentages of each stink bug species group captured in all fields and in the simple and complex landscapes separately are summarized in table 3. *Halyomorpha halys* specimens were not collected in any of the traps or soybean fields sampled in either year. However, analysis of sweep-net samples did reveal a community of stink bugs dominated by species in the genus *Euschistus*, followed by *A. hilare*, and *P. maculiventris*, as well as the red-shouldered stink bug (*Thyanta custator accerra* McAtee). Although all stink bug individuals were tentatively identified to species, as endemic members of the genus *Euschistus* are often difficult to distinguish (particularly in nymph stages) and as discrepancies exist between available descriptions and keys for some of these species (Kamminga et al. 2009, McPherson 1986, McPherson and McPherson 2000), these species were pooled together to avoid over representing a single species in the analysis.

Overall, a low abundance of stink bugs was revealed in this sampling across both years with a total of 402 stink bugs collected within both simple and complex landscapes. More nymphs than adults were caught in both years, especially from samples taken late in the growing season. In addition, stink bug eggs were recovered from leaves on several
occasions in both years (although these were not identified to species and were not included in overall abundance measurements).

**Landscape Factors and Stink Bug Abundance.** In 2012, no differences were observed between stink bug populations in fields within complex landscapes compared to those in simple landscapes throughout the growing season (Fig. 1). Similarly, in 2013, no differences were observed throughout much of the growing season. However, a spike in stink bug captures in a single field within a simple landscape late in the 2013 growing season resulted in a slight separation with higher mean captures in simple landscapes being observed for two sampling dates (Fig. 2). One of these sampling dates in this particular field occurred at R6 (fully developed seeds) and sampling averages exceeded the recommended economic threshold of 4 individuals per 10 sweeps. However, subsequent high densities at this location occurred during senescence of the plant (R7-R8), when damage caused by stink bug feeding is considered minimal and economic thresholds are generally increased substantially (Musser et al. 2011, Catchot 2013).

Analysis of seasonal stink bug captures averaged across both years by the soybean plant growth stages at each sampling date revealed the highest number of captures at the R6 growth stage (fully developed seed) (Fig. 3).

A two-sample student’s *t*-test revealed no significant difference between stink bug populations in soybean fields within complex landscapes compared to those within simple landscapes (*t* = 0.76; df = 20; *P* = 0.4562) (Fig. 4). The ANOVA revealed a significant effect of county (*F* = 5.90; df = 2; *P* = 0.0120), most likely due to high captures late in the growing season in a single field in Muscatine County. However, no
significant effects of diversity ($F = 2.73; df = 1; P = 0.1180$), or county*diversity ($F = 2.11; df = 2; P = 0.1535$) were detected.

Linear regression analysis showed no significant relationship between the percentages of non-crop habitat in the landscape surrounding sampled fields and the total population of stink bugs captured within those fields (Error df = 20, MSE = 4.77, $R^2 = 0.02$) (Fig. 5). Utilizing a stepwise linear regression then revealed no significant relationship with any of the surrounding landscape variables (i.e. no parameters met the requirement of $P < 0.15$ to remain in the model).

**Discussion**

Although discoveries of living *H. halys* adults in eastern Iowa were confirmed in late 2012 and several new county records were reported in 2012 and 2013, no specimens were found in any of the soybean fields sampled in this study. The lack of *H. halys* from this sampling is unsurprising considering this species is newly invasive to Iowa and has yet to be recovered from agricultural production in the state. Pheromone traps deployed in both years failed to capture any *H. halys* and largely avoided catching endemic stink bug species, although previous studies have shown these traps and lures targeting *H. halys* to be cross attractive to at least some of the species endemic to Iowa (Aldrich et al. 2009, Khrimian et al. 2008, Tillman et al. 2010). These traps and lures have been used successfully to collect *H. halys* in other invaded regions even when population densities were low. Therefore, they are considered to be well suited to use for monitoring for the presence of *H. halys* in newly invaded areas as well as to infer when populations of these pests may be migrating into local fields (Aldrich et al. 2007, Khrimian et al. 2008).
Continued deployment of these traps in conjunction with other sampling methods will be necessary to monitor the establishment of *H. halys* in Iowa in coming years.

Evaluating the field sampling methods used showed that sweep-net sampling collected more stink bugs in soybean than direct observation sampling. The most likely reason for this difference (based on observations) was that stink bugs were more likely to vacate the plant and avoid detection when plants were disturbed as direct observation sampling was being conducted. In addition, direct observation sampling for these pests is complicated by their coloring, which often allows them to blend in with the coloring of soybean plants. Also, sweep-net sampling caught an additional species, *T. custator accerra*, which was not seen in direct observation samples. Although sweep-net sampling in soybean requires waiting for the plants to reach a minimum growth to avoid causing plant damage during sampling, direct observation sampling for this project only recorded four stink bug individuals before sweep-net sampling began. Therefore, we suggest that the sweep-net sampling method captured the overall phenology of stink bugs within Iowa for soybean. Stink bugs likely emerged from overwintering earlier than when we first observed them in soybean fields and subsequently immigrated into fields from the surrounding landscape.

The species composition revealed by the sampling for this project was generally consistent with the previous survey data from 2011, with captures dominated by *Euschistus* species followed by *A. hilare* and *P. maculiventris*. It was surprising to collect *T. custator accerra* nymphs and adults in Iowa soybean fields in both 2012 and 2013, especially as far north as Story County (central Iowa). This species is commonly recovered from soybean and other crops in the southern regions of the U.S. but has not
been widely reported in the Midwest (McPherson and McPherson 2000, Michel et al. 2013). However, it has been proposed that southern stink bug species have been recently expanding their range to the North (NCSRP 2011). In addition, the collection of all life stages from egg to adult in fields suggests that populations of stink bugs within these fields are utilizing soybean in Iowa as both feeding and reproductive hosts with the possibility of complete generations occurring solely on soybean.

Peak populations of stink bugs were collected from fields during the R6 growth stage (seed fully developed). As data collection for the 2011 survey was conducted between late vegetative stages and R4 (with the majority of samples taken at R2 and R3) (Jesse et al. 2013), it is likely that this survey underestimated the total population density and species diversity of stink bugs occurring in Iowa soybean during the growing season. Therefore, additional comprehensive surveys will be needed to determine the existing species composition across the state as well as to monitor for the presence of *H. halys* as it continues to expand its range in Iowa.

The lack of any significant differences between stink bug population densities within differing levels of landscape diversity as well as the inability to discern any relationships between specific landscape factors and abundance may be simply a result of the generally low stink bug populations captured across both years. Another explanation is that the effects of landscape on stink bugs occur at different spatial scales than that which was studied here. As populations of *H. halys* have been shown to be influenced by factors within the landscape, it is possible that the methods outlined here may be utilized in future work with this pest to determine the patterns of invasion and establishment in varying landscapes.
As overall stink bug populations revealed by this sampling were generally very low, with only a single field sample showing an economically damaging level, and as these population densities were consistent with low field captures from the previous survey of Iowa soybean, we suggest that the current risk posed to soybean production in Iowa by the endemic community of stink bugs present in the state is relatively low. However the full establishment of *H. halys* in agricultural production regions of Iowa in future years in conjunction with populations of endemic stink bug species present in the state may intensify this risk. Therefore vigilant monitoring efforts in soybean and other crop production is necessary to preempt this threat.
Acknowledgements

We thank all of the landowners and their families for graciously providing their commercial soybean fields as sampling sites. We also thank Dr. Tracy Leskey’s research group at USDA ARS for providing their novel *H. halys* pheromone for use in baited traps in 2013 and Laura Jesse for providing the survey data from 2011. In addition, we thank hourly employees Emily Feldkamp, Shari Sweeney, and Samuel Gire for assisting in the data collection for this project. This research was supported by the Iowa Soybean Association and the Soybean Checkoff.

Literature Cited


Stewart, S., and A. McClure. 2014. 2014 Insect control recommendations for field crops.


### Table 1. Characteristics of Iowa soybean fields sampled for stink bugs in 2012

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)</th>
<th>% Crop</th>
<th>% Non-Crop</th>
<th>Simpson’s Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story Complex 1</td>
<td>42.0907°, -93.5841°</td>
<td>9.31</td>
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<td>38.66</td>
<td>82.60</td>
<td>17.40</td>
<td>0.64</td>
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</tbody>
</table>

*a Identification for each Iowa soybean field sampled during the 2012 field season (Story and Floyd refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

*b GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

*c Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)

*d Percentage of each field’s surrounding landscape (within 2km of field center) consisting of row-crop agriculture figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2012)

*e Percentage of each field’s surrounding landscape (within 2km of field center) consisting of non-crop features figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2012)

*f Simpson’s Index of Diversity (values closer to 1 correspond to increased diversity)
Table 2. Characteristics of Iowa soybean fields sampled for stink bugs in 2013

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)</th>
<th>% Crop</th>
<th>% Non-Crop</th>
<th>Simpson’s Index</th>
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<td>89.82</td>
<td>10.18</td>
<td>0.59</td>
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<td>88.72</td>
<td>11.28</td>
<td>0.59</td>
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</tbody>
</table>

a Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

b GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

c Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)

d Percentage of each field’s surrounding landscape (within 2km of field center) consisting of row-crop agriculture figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)

e Percentage of each field’s surrounding landscape (within 2km of field center) consisting of non-crop features figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)

f Simpson’s Index of Diversity (values closer to 1 correspond to increased diversity)
Table 3. Stink bug populations captured in Iowa soybean fields during the 2012 and 2013 field seasons

<table>
<thead>
<tr>
<th>Species</th>
<th>Total captured&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Frequency&lt;sup&gt;b&lt;/sup&gt; (≥1/field)</th>
<th>Avg. density&lt;sup&gt;c&lt;/sup&gt;</th>
<th>SEM</th>
<th>Max. density&lt;sup&gt;d&lt;/sup&gt;</th>
<th>% total&lt;sup&gt;e&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stink bugs</td>
<td>402</td>
<td>57.71%</td>
<td>2.00</td>
<td>0.34</td>
<td>50</td>
<td>100.00%</td>
</tr>
<tr>
<td>Complex</td>
<td>157</td>
<td>54.46%</td>
<td>1.55</td>
<td>0.24</td>
<td>12</td>
<td>39.05%</td>
</tr>
<tr>
<td>Simple</td>
<td>245</td>
<td>61.39%</td>
<td>2.45</td>
<td>0.64</td>
<td>50</td>
<td>60.95%</td>
</tr>
<tr>
<td>Life Stage Composition</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stink bug adults</td>
<td>161</td>
<td>40.30%</td>
<td>0.80</td>
<td>0.11</td>
<td>14</td>
<td>40.05%</td>
</tr>
<tr>
<td>Complex</td>
<td>70</td>
<td>38.61%</td>
<td>0.69</td>
<td>0.11</td>
<td>5</td>
<td>17.41%</td>
</tr>
<tr>
<td>Simple</td>
<td>91</td>
<td>42.57%</td>
<td>0.91</td>
<td>0.20</td>
<td>14</td>
<td>22.64%</td>
</tr>
<tr>
<td>Stink bug nymphs</td>
<td>241</td>
<td>37.81%</td>
<td>1.20</td>
<td>0.25</td>
<td>36</td>
<td>59.95%</td>
</tr>
<tr>
<td>Complex</td>
<td>87</td>
<td>34.65%</td>
<td>0.86</td>
<td>0.17</td>
<td>9</td>
<td>21.64%</td>
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<tr>
<td>Simple</td>
<td>154</td>
<td>41.58%</td>
<td>1.54</td>
<td>0.48</td>
<td>36</td>
<td>38.31%</td>
</tr>
<tr>
<td>Species Composition</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Euschistus spp.</td>
<td>366</td>
<td>56.22%</td>
<td>1.82</td>
<td>0.34</td>
<td>50</td>
<td>91.04 %</td>
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<tr>
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<td>1.35</td>
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<td>10</td>
<td>33.83%</td>
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<td>Simple</td>
<td>230</td>
<td>59.41%</td>
<td>2.30</td>
<td>0.64</td>
<td>50</td>
<td>57.21%</td>
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<tr>
<td>A. hilare</td>
<td>18</td>
<td>7.46%</td>
<td>0.09</td>
<td>0.02</td>
<td>2</td>
<td>4.48%</td>
</tr>
<tr>
<td>Complex</td>
<td>13</td>
<td>9.90%</td>
<td>0.13</td>
<td>0.04</td>
<td>2</td>
<td>3.23%</td>
</tr>
<tr>
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<td>5</td>
<td>5.94%</td>
<td>0.05</td>
<td>0.02</td>
<td>1</td>
<td>1.24%</td>
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<tr>
<td>P. maculiventris</td>
<td>12</td>
<td>4.48%</td>
<td>0.06</td>
<td>0.02</td>
<td>2</td>
<td>2.99%</td>
</tr>
<tr>
<td>Complex</td>
<td>3</td>
<td>2.97%</td>
<td>0.03</td>
<td>0.02</td>
<td>1</td>
<td>0.75%</td>
</tr>
<tr>
<td>Simple</td>
<td>9</td>
<td>6.93%</td>
<td>0.09</td>
<td>0.04</td>
<td>2</td>
<td>2.24%</td>
</tr>
<tr>
<td>T. custator accera</td>
<td>6</td>
<td>2.49%</td>
<td>0.03</td>
<td>0.01</td>
<td>2</td>
<td>1.49%</td>
</tr>
<tr>
<td>Complex</td>
<td>5</td>
<td>3.96%</td>
<td>0.05</td>
<td>0.03</td>
<td>2</td>
<td>1.24%</td>
</tr>
<tr>
<td>Simple</td>
<td>1</td>
<td>1.98%</td>
<td>0.01</td>
<td>0.01</td>
<td>1</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

<sup>a</sup>N = 202 field sampling dates (N = 101 for Complex fields, N=101 for Simple fields)
<sup>b</sup>Total stink bug captures in each stink bug category
<sup>c</sup>Frequency (% of total field samples) that each total field sample contained at least one stink bug within a particular category
<sup>d</sup>Average density of each stink bug category per total field sample
<sup>e</sup>Maximum number of stink bugs captured per total field sample
<sup>f</sup>Percentage of total captures represented by each stink bug category
Figure Captions

**Figure 1.** Mean abundance of stink bugs per sample (10 sweeps) (mean ± SEM) captured in sampled soybean fields within complex landscapes (solid line, n = 4 fields) or simple landscapes (dotted line, n = 4 fields) in 2012.

**Figure 2.** Mean abundance of stink bugs per sample (10 sweeps) (mean ± SEM) captured in sampled soybean fields within complex landscapes (solid line, n = 7 fields) or simple landscapes (dotted line, n = 7 fields) in 2013.

**Figure 3.** Mean total stink bug populations captured (mean ± SEM) by soybean growth stage averaged across the 2012 and 2013 field seasons. All vegetative stages were combined.

**Figure 4.** Mean total stink bugs (mean ± SEM) in soybean fields averaged across the 2012 and 2013 growing seasons. Fields were selected within landscapes of varying diversity (simple vs. complex; n = 11 per category). Data were square root transformed to meet assumptions of normality and equal variance. No significant differences in stink bug abundance were observed between fields within complex landscapes and fields within simple landscapes (t = 0.76; df = 20; P = 0.4562). Significance (*) was based on a threshold of P<0.05 using a two-sample student’s t-test. N.S. = not significant.

**Figure 5.** Linear regression analysis of the total stink bugs captured per field by the percentage of non-crop habitat in the landscape surrounding each field within a 2 km
buffer of field center. Data were square root transformed to meet assumptions of normality and equal variance.
Figure 1
Figure 2

Mean Captured Per Field ± SEM

- Complex
- Simple
Figure 3

Mean Total Captured Per Field ± SEM

Soybean Growth Stage
Figure 4

(SQRT) Mean Total Captured Per Field ± SEM

Simple | Complex

N.S.
Figure 5

\[y = -0.01x + 4.14\]

\[R^2 = 0.02\]
CHAPTER 4. GENERAL CONCLUSIONS

The two field studies outlined in the previous chapters sought to characterize the response of in-field populations of both *P. japonica* and stink bugs to features of the surrounding landscape. Based on the results from these studies, it would appear that field populations of these two pest groups respond differently to both landscape composition and complexity. Populations of *P. japonica* responded positively to increased landscape complexity and were shown to vary the most in response to the area of wooded and grassland-cover components within the surrounding landscape. These relationships are likely attributable to increased availability of alternative host plants and ovipositional habitat within these more diverse landscapes. Conversely, no significant relationships between stink bug populations and landscape variables were perceived from this sampling effort. However, stink bug population densities may have simply been too low to detect these relationships or they may occur at a different spatial scale than that used for this study.

Although field populations of stink bugs captured were generally low, the survey effort for stink bug species present in sampled fields during the course of this sampling revealed a community of multiple pest species (*Euschistus* spp., *A. hilare*, and *T. custator accerra*) and one predatory species (*P. maculiventris*). The low densities of field captures and composition of species were mostly consistent with the analysis of previous survey data collected from Iowa soybean (other than the collection of *T. custator accerra* which seems to be rarely collected in the region). Although the presence of *H. halys* has been confirmed in Iowa, no individuals were collected in any of the field or pheromone trap sampling conducted for this survey effort. In addition, evaluating the sampling methods utilized for stink bugs revealed that sweep-net sampling was more successful at analyzing
the field abundance and species composition of stink bugs than direct observation sampling. Furthermore, pheromone-baited traps specifically targeting *H. halys* deployed in each sampled county were generally ineffective at capturing any of the endemic stink bug species captured by the other sampling methods used.

Implications of these results include that soybean fields within areas of increased landscape complexity (especially those in landscapes containing increased area of wooded and grass land-cover) should be given priority for scouting for *P. japonica*, as they are the most likely to develop large populations densities that may require management. Also, low overall populations of stink bugs across both years appear to imply a relatively low level of risk currently posed to soybean production in Iowa from the endemic community of stink bugs. However, as *H. halys* becomes fully established in agricultural production regions of Iowa in future years this risk may increase.

The three sampling methods used for the stink bug survey are all recommended for sampling for *H. halys*. Comparing the captures from these different methods showed that sweep-netting caught the greatest number of individuals and species of stink bugs followed by direct observation and pheromone-baited trapping. Therefore, if it is the goal of a sampling effort to best analyze the natural population size and species composition in an area sweep-netting would seem to be the best method. However, if focusing on a single species (such as *H. halys*) and attempting to avoid non-target captures, pheromone-baited traps utilizing a species-specific pheromone should be recommended.

Based on these conclusions, we suggest the necessity of future studies to determine if the landscape effects on *P. japonica* in soybean reported here are representative of other similar polyphagous pests of soybean and if they extend to other
host plants as well. We also propose that additional studies utilizing alternative sampling methods, increased sampling effort, or different spatial scales may be able to better identify relationships between stink bug populations in agricultural production and landscape variables. Furthermore, additional comprehensive surveys will be needed to better characterize the existing community of stink bug species present in Iowa field crops and to continue to monitor the invasion of *H. halys* as it expands its range in the state.
## APPENDIX

### Table S1. Surrounding landscape variables for Iowa soybean fields sampled for stink bugs in 2012

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)</th>
<th>Corn</th>
<th>Soybean</th>
<th>Wooded</th>
<th>Grass</th>
<th>Alfalfa</th>
<th>Developed</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Story Complex 1</td>
<td>42.0907°, -93.5841°</td>
<td>9.31</td>
<td>20.80</td>
<td>15.35</td>
<td>28.99</td>
<td>28.56</td>
<td>0.00</td>
<td>3.13</td>
<td>3.15</td>
</tr>
<tr>
<td>Story Complex 2</td>
<td>42.0537°, -93.6722°</td>
<td>18.52</td>
<td>15.63</td>
<td>20.60</td>
<td>25.24</td>
<td>21.34</td>
<td>0.51</td>
<td>15.64</td>
<td>1.03</td>
</tr>
<tr>
<td>Story Simple 1</td>
<td>42.1305°, -93.6666°</td>
<td>61.12</td>
<td>56.37</td>
<td>36.25</td>
<td>0.28</td>
<td>5.55</td>
<td>0.38</td>
<td>1.17</td>
<td>0.00</td>
</tr>
<tr>
<td>Story Simple 2</td>
<td>42.0820°, -93.5091°</td>
<td>31.62</td>
<td>54.09</td>
<td>34.34</td>
<td>0.67</td>
<td>9.60</td>
<td>0.00</td>
<td>1.27</td>
<td>0.02</td>
</tr>
<tr>
<td>Floyd Complex 1</td>
<td>42.9752°, -92.5714°</td>
<td>21.20</td>
<td>35.67</td>
<td>18.32</td>
<td>12.20</td>
<td>21.47</td>
<td>1.62</td>
<td>2.35</td>
<td>8.37</td>
</tr>
<tr>
<td>Floyd Complex 2</td>
<td>43.0987°, -92.7700°</td>
<td>13.00</td>
<td>17.36</td>
<td>10.71</td>
<td>27.23</td>
<td>35.48</td>
<td>2.95</td>
<td>2.46</td>
<td>3.80</td>
</tr>
<tr>
<td>Floyd Simple 1</td>
<td>42.9399°, -92.5912°</td>
<td>67.86</td>
<td>42.04</td>
<td>41.13</td>
<td>1.62</td>
<td>11.25</td>
<td>2.51</td>
<td>1.45</td>
<td>0.00</td>
</tr>
<tr>
<td>Floyd Simple 2</td>
<td>42.9418°, -92.6584°</td>
<td>38.66</td>
<td>35.81</td>
<td>46.79</td>
<td>2.65</td>
<td>12.60</td>
<td>0.71</td>
<td>1.45</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*a Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

*b GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

*c Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)

*d Percentage of each field’s surrounding landscape (within 2km of field center) consisting of each cover type figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)
Table S2. Surrounding landscape variables for Iowa soybean fields sampled for stink bugs in 2013

<table>
<thead>
<tr>
<th>Field ID</th>
<th>GPS Coordinates</th>
<th>Area (ha)²</th>
<th>Corn²</th>
<th>Soybean²</th>
<th>Wooded²</th>
<th>Grass²</th>
<th>Alfalfa²</th>
<th>Developed²</th>
<th>Water²</th>
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</thead>
<tbody>
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<td>19.43</td>
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<td>0.00</td>
<td>3.47</td>
<td>3.24</td>
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<td>42.0546°, -93.6763°</td>
<td>10.96</td>
<td>22.87</td>
<td>18.78</td>
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<td>0.99</td>
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<td>8.33</td>
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<td>1.78</td>
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<td>29.67</td>
<td>1.78</td>
<td>2.22</td>
<td>4.36</td>
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<td>8.59</td>
<td>25.63</td>
<td>22.41</td>
<td>17.36</td>
<td>27.09</td>
<td>1.43</td>
<td>3.35</td>
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<td>35.11</td>
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<td>5.24</td>
<td>1.76</td>
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<td>48.49</td>
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<td>1.45</td>
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<td>6.26</td>
<td>3.61</td>
<td>1.40</td>
<td>0.00</td>
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</tbody>
</table>

² Identification for each Iowa soybean field sampled during the 2013 field season (Story, Floyd, and Muscatine refer to the Iowa county the commercial field was in, Complex or Simple refers to surrounding landscape diversity)

² GPS coordinates (in decimal degrees) for the centroid of each field obtained from ArcMap 10.1 (ESRI 2012)

² Area in hectares of each field figured using ArcMap 10.1 (ESRI 2012)

² Percentage of each field’s surrounding landscape (within 2km of field center) consisting of each cover type figured using ArcMap 10.1 (ESRI 2012), aerial and satellite photographs (Google 2013), and land cover maps (USDA NASS 2013)