SAMPLING THE SPATIAL DISTRIBUTION OF JAPANESE BEETLES IN ILLINOIS SOYBEAN FIELDS AND THEIR IMPACT ON PRODUCTION

BY

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THESIS

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ABSTRACT

A 2-year research study was conducted in Illinois soybean, *Glycine max* (L.) Merr., fields to determine the spatial trends of Japanese beetles, *Popillia japonica* Newman, and to measure their impact on soybean production. Commercial soybean fields were sampled intensively or extensively. Densities and distributions of Japanese beetles within fields were measured with two different sampling methods (sweep-net samples and visual counts) in both intensively and extensively sampled fields, and the influence of field border type (i.e., corn, grass, soybean, road) was analyzed. Additionally, the relationship between densities of Japanese beetles and corresponding percentage defoliation over time was analyzed in intensively sampled fields. Japanese beetle densities were considerably larger in 2009 than in 2010, although corresponding percentage defoliation in both years was well below the widely accepted economic threshold of 15 to 20% defoliation between bloom and pod fill. Densities of Japanese beetles were larger in field edges than in field interiors in both 2009 and 2010, but the difference in densities between field edges and field interiors was statistically significant only in 2009. In both 2009 and 2010, significantly greater densities of Japanese beetles were found in field edges that bordered cornfields than in field edges that bordered grass, soybean, or roads. Growers who wish to manage Japanese beetle populations in soybean must recognize that field edges, where Japanese beetle densities can be highly concentrated, may not be indicative of the overall densities in their fields. Furthermore, although larger densities of Japanese beetles were observed in field edges than in field interiors, percentage defoliation and yield were not significantly different between field edges and field interiors. Under the modest Japanese beetle population densities

measured during this study, the defoliation in soybean field edges never reached a level where the yield differential would have justified the cost of managing Japanese beetles even in field edges. Sweep-net samples and visual counts to estimate Japanese beetle population densities were strongly correlated. Most soybean growers in the Midwest do not use sweep nets to sample insects, but they might be inclined to count Japanese beetles by visual observation to determine the need for insecticide application. Future economic thresholds based on numbers of Japanese beetles per meter of row likely would be more useful than the current, more subjective percentage defoliation thresholds.

DEDICATION

I dedicate this thesis to my friends and family for their support and encouragement during the research process. I especially dedicate this thesis to a friend of both mine and agriculture, Joshua Heeren. Josh was tragically killed in a farming accident in November 2010, but provided me with valuable advice, guidance, and instruction when I had the opportunity to work alongside him in the University of Illinois Insect Management and Insecticide Evaluation Program from 2008–2009.

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EXPLANATION OF THESIS FORMAT

This thesis is composed of two chapters that offer an overview of the economic importance of Japanese beetles, *Popillia japonica* Newman (Coleoptera: Scarabaeidae) in the United States and Illinois and an investigation of the effects the pest has on the United States' and Illinois' primary oilseed crop, soybean, *Glycine max* (L). Merr. The first chapter is a literature review of articles published by North American authors since the introduction of the Japanese beetle in the United States in the early 1900s. The second chapter describes an experiment conducted to measure the spatial trends of Japanese beetles in Illinois soybean fields and the corresponding effects on the crop. Japanese beetle densities are discussed in relation to location within fields, the effects of different field borders (e.g., crops, roads), and the corresponding defoliation caused by Japanese beetles. Estimates of soybean yield also were determined and are discussed in relation to densities of Japanese beetles. The experiment was conducted in soybean fields throughout Illinois. In 2009, fields in Bureau, Champaign, Hancock, Henderson, Kendall, McLean, Montgomery, Tazewell, and Vermilion counties were sampled. In 2010, fields in Champaign, Macon, McLean, and Ogle counties were sampled. The second chapter will be prepared for publication in a peer-reviewed journal.

CHAPTER ONE

LITERATURE REVIEW

Introduction

The Japanese beetle, *Popillia japonica* Newman, is an insect pest native to the Japanese Archipelago (Fleming 1976). Its spread throughout the world has been reported in Canada (NAPIS 1998), northern Japan (Ando 1986), Portugal (Lacey et al. 1994), and the United States (Edwards 1999).

The Japanese beetle was first discovered in the United States in 1916 during an inspection of nursery stock near Riverton, New Jersey (Fleming 1976). However, Dickerson and Weiss (1918) suggested that the Japanese beetle arrived in the United States on the roots of Japanese iris (*Iris sanguinea* Hornem × Donn) as early as 1911. Its establishment in the United States has been successful. The National Agricultural Pest Information Service (1998) reported U.S. infestations of the Japanese beetle in all states east of the Mississippi River (except Florida), as well as Minnesota, Iowa, and Nebraska, and in the Canadian provinces of Ontario and Quebec. Although infestations have been observed in California, eradication attempts in that state are believed to have been successful (Hammond 1994).

The Japanese beetle is the most recognizable and destructive insect pest of turf and landscape plants in the eastern United States (Potter 1998, Vittum et al. 1999). The large number of grasses on which Japanese beetle larvae feed, the many plant species on which the adults feed, and a lack of natural enemies make the eastern United States a successful host-range for Japanese beetles (Fleming 1968, 1976). Fleming (1963) and Allsopp (1996) suggested that the 100th meridian of longitude will be the western limit

for spread of the Japanese beetle because the arid climate beyond this meridian is unsuitable for Japanese beetles. In Illinois, the Japanese beetle was detected in the early 1930s near Chicago and East St. Louis (Luckmann 1964, Matzenbacher 1966).

Life History

The Japanese beetle has a univoltine life cycle. Females lay eggs in the soil from mid-June through August (Edwards 1999). Eggs are found in the upper 7.5 cm of the soil and are aggregated in areas where adults are feeding (Fleming 1972, Dalthorp et al. 2000). Females prefer moderately textured soils (characterized by good drainage) and moist soil conditions for oviposition (Régnière et al. 1979, Allsopp et al. 1992). Both corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr) fields are suitable oviposition sites; soybean fields are preferred (Luckmann 1964). Hot, dry conditions during summers reduce egg survival (Hawley 1949). However, Fox (1939) noted that females instinctively oviposit in low-lying, moist areas during dry periods. After hatching, larvae complete three instars by feeding on the roots of grasses or decaying plant material (Edwards 1999). Larvae continue feeding throughout October, move slightly deeper in the soil profile (5–15 cm) to avoid excessively cold temperatures (Hoshikawa et al. 1988), and overwinter. In the spring, the larvae move closer to the soil surface and form an earthen cell for pupation (Fleming 1972, Vittum 1986). The pupal stage lasts from 7 to 17 days (Fleming 1972). Edwards (1999) noted that adults emerge from the soil in early to late June, and males are usually observed a few days earlier than females (Fleming 1972, Régnière et al. 1981).

Edwards (1999) described the physical features of both larvae and adults. Larvae are 25 mm long when fully grown and are characterized by a creamy white body, brown

head-capsule, and, most importantly, a V-shaped pattern of bristles located on the raster (the terminal abdominal segment). Fleming (1972) indicated that larvae have three thoracic and ten abdominal segments; each thoracic segment bears a pair of segmented legs. Adults are approximately 13 mm long and have metallic green-bronze elytra and six tufts of white hair located on each side of the abdomen (Edwards 1999).

Although males emerge from the soil first, the male:female ratio in the field is approximately 1:1 (Régnière et al. 1981). Females mate immediately after emergence (Ladd 1970). Fleming (1972) suggested that virgin females discharge a sex pheromone after initial emergence but do not elicit long-range attraction of males. Immediately after they mate but before they feed, females lay approximately 20 mature eggs in the soil (Régnière et al. 1979).

Males engage in post-copulatory mate-guarding behavior. Mate-guarding can last from a few minutes to several hours, but the female can feed during this process. The male, on the other hand, cannot feed while mate-guarding because of its sexual mating position on top of the female (Fleming 1972, Barrows and Gordh 1978, Potter and Held 2002). Mate-guarding is thought to be a response to sperm competition (Barrows and Gordh 1978). Males increase mate-guarding behavior in environments where females are likely to be encountered by additional males (Saeki et al. 2005). Japanese beetles engage in both polygyny (males with numerous mating partners) and polyandry (females with numerous mating partners) (Fleming 1972, Barrows and Gordh 1978).

Flight activity of Japanese beetles is greatest when temperatures are between 29 and 35°C, relative humidity is greater than 60%, wind speed is less than 20 km/hr, and solar radiation is greater than 0.42 kW/m^2 (Fleming 1972, Lacey et al. 1994). Overcast,

rainy, or windy conditions reduce flight activity (Fleming 1972, Vittum 1986, Lacey et al. 1994). Hamilton (2003) demonstrated in a mark-release study that Japanese beetles can fly 500 m and beyond per day in favorable weather. Japanese beetles are capable of physiological thermoregulation, i.e., they can increase body temperature by muscle-shivering or allowing sunlight to increase their metabolic heat production (thermogenesis) at pre-flight or takeoff. Japanese beetles also can decrease their body temperature through evaporative cooling. Thermoregulation is jeopardized at excessively high temperatures with low humidity levels due to a loss of body water (Oertli and Oertli 1990).

Large populations of Japanese beetles occur in environments where the average summer soil temperature is between 17.5 and 27.5°C, the average winter soil temperature is above -9.4°C, and precipitation is uniformly distributed throughout the year. Adequate rainfall is required throughout the summer months to ensure survival of eggs in the soil. Snow cover in more extreme winter climates increases the survival of overwintering grubs by insulating the soil, keeping temperatures warmer throughout the soil profile (Ludwig 1928, Fox 1939). The spread and establishment of the Japanese beetle has proven to be successful in areas with adequate soil moisture and a moderate climate (Fleming 1972).

Sampling

Sampling for larvae and sampling for adults require different techniques because of the different habitats in which they live. Larval populations must be sampled in the soil and on roots. Such sampling requires a spade, golf cup-cutter, or motorized sod-cutter to cut into the sample area and to characterize densities (Potter 1998). Because of female

ovipositional preferences, larvae usually are found in loose soil (Gould 1963). Traps are effective for monitoring populations of adults, identifying new infestations, and collecting beetles for research (Potter and Held 2002). However, traps are ineffective for managing populations of Japanese beetles (Kuhlman and Briggs 1983). Alm and Dawson (2003) demonstrated that the standard trap manufactured by Trécé (Palo Alto, CA) consistently caught more adult Japanese beetles than other traps tested. Traps that utilized bags for capturing beetles were less effective because beetles used the drainage holes to escape. Hammond et al. (2001) demonstrated that sweep-net sampling was an effective approach for collecting Japanese beetle adults and other defoliating insects in soybean.

Host Plant Interactions

Japanese beetles are polyphagous, feeding on more than 300 species of plants in 79 families (Fleming 1972, Ladd 1987, 1989). An estimated $460 million is spent annually to manage Japanese beetles because of their ability to feed on and damage many economically important crops and ornamental plants (USDA 2004). Fruit crops, soybean, corn, and many species of ornamental plants are potential hosts (Fleming 1976). Plants emitting oils or with a floral- or fruit-like appearance are attractive to Japanese beetles (Fleming 1969, Potter et al. 1992, Loughrin et al. 1998). Ladd (1986) explained that their wide range of hosts is due to stimuli on the surface of leaves. Examples of these phagostimulants include sucrose, maltose, fructose, and glucose. Japanese beetles also are attracted to plants on which other Japanese beetles are feeding. Large densities of beetles will gather on plants due to the strong volatile compounds that are emitted from chewed leaves (Ladd 1966, Fleming 1972, Potter and Held 2002). As a result of these adult aggregations and subsequent oviposition nearby, larval populations also are aggregated

(Dalthorp et al. 1999). In a subsequent study, Dalthorp et al. (2000) demonstrated that densities of Japanese beetle larvae were highly correlated with aggregations of adults on susceptible plants.

Soybeans, a major host crop for Japanese beetle adults, were harvested from a record 76.4 million acres in 2009 and 76.6 million acres in 2010 (NASS 2010, 2011); the largest production (3.36 billion bushels) of soybeans ever in the United States was recorded in 2009 (NASS 2010). Because the geographic range of Japanese beetles includes states with large acreages of soybeans, Japanese beetles pose a significant threat to soybean production annually.

Japanese beetles injure soybean plants by eating leaf tissue. Adults consume tissue between the veins of soybean leaves, resulting in a lacelike skeleton (Kuhlman and Briggs 1983). Adults begin feeding at the top of the canopy (Fleming 1972), and they prefer foliage in direct sunlight (Kuhlman and Briggs 1983). Extensive feeding can be observed from mid-morning through late evening, with sporadic feeding during the night when temperatures remain greater than 15°C (Kreuger and Potter 2001). Much of this feeding occurs during the reproductive stages of soybean development (Hammond 1994).

Soybeans in reproductive stages R2 (full bloom) through R5 (beginning seed) are the most susceptible to economic damage caused by defoliating insects such as Japanese beetles (Fehr et al. 1977, Pedersen 2004). Soybeans in vegetative stages of growth are much less susceptible to economic damage caused by defoliation because of the plants' ability to compensate for tissue loss (Hunt et al. 1994). Gould (1960) demonstrated that soybean plants can lose considerable amounts of foliage by Japanese beetle feeding without experiencing yield-loss. Removing 10 or 25% of foliage from soybeans in early

to mid-July had little effect on final yield, but removing 10% of foliage in early August reduced final yield. Pod-fill coinciding with a peak in feeding by Japanese beetles accounted for the yield loss. Zavala et al. (2008) noted that heightened levels of CO_2 reduced the ability of soybeans to express defense genes, resulting in increased fitness (longer lifespan and greater fecundity) for Japanese beetles.

Government-Regulated Control Methods

Governmental agencies in North America have attempted to control the establishment of Japanese beetles. Because limited control information was available when Japanese beetles arrived in the United States, the former United States Bureau of Entomology established the Japanese Beetle Laboratory in 1917 in Riverton, New Jersey. The objectives of the laboratory were to study the life history, characteristics, and potential control methods for this insect (Fleming 1976). In 1920, the Bureau began searching for predaceous and parasitic insects that potentially could control Japanese beetles (Fleming 1976). Consequently, 49 species of natural enemies were released in the northeastern United States between 1920 and 1933 (Fleming 1968).

Cooperative Japanese beetle control efforts between the United States Department of Agriculture and Illinois Department of Agriculture were initiated in the 1930s. Illinois established a Japanese beetle quarantine in 1936 with the help of the United States Department of Agriculture (Matzenbacher 1966). The two agencies tried to eradicate the Japanese beetle in east-central Illinois with repeated insecticidal applications from 1954 to 1958 (Luckmann 1959). Results from 1958 indicated that Japanese beetles were still prevalent on almost 50,000 acres of corn and soybeans, even with dieldrin applied on nearly 18,000 acres (Luckmann 1959). Luckmann (1964) reported that Japanese beetles

were found continuously on insecticide-treated acres between 1958 and 1963. Overall, 180,000 acres in Illinois had been chemically treated for Japanese beetles by 1965 with less than adequate results; many counties in Illinois still experienced large infestations of Japanese beetles (Matzenbacher 1966).

The federal quarantine of Japanese beetles was canceled in 1978, but seven western states and British Colombia continue to regulate imports of commodities from Japanese beetle-infested areas (CDFA 1998, NPB 1998, APHIS 2000). Examples of quarantined material include soil, humus, compost, manure (except when commercially packaged), grass sod, and nursery plants in soil (NPB 1998). Additionally, the Animal and Plant Health Inspection Service regulates airport facilities that could transport Japanese beetles to quarantined states during peak flight season (APHIS 2000). Hamilton et al. (2007) suggested that corn and soybean production on airport-owned agricultural land near cargo terminals should be discontinued to reduce transport of Japanese beetles to quarantined areas. Internationally, the European and Mediterranean Plant Protection Organization classifies the Japanese beetle as a quarantined pest (Smith et al. 1996).

Host Plant Resistance

Coon (1946) surveyed 26 soybean varieties for resistance to Japanese beetles. Although no variety was identified as highly resistant, four varieties (Chief, Viking, Illini, and Wilson) were considered moderately resistant. A study with soybean lines HC95-15MB and HC95-24MB demonstrated that these Mexican bean beetle (*Epilachna varivestis* Mulsant)-resistant soybean lines were unable to reduce populations of Japanese beetle adults, but were able to protect against defoliation (Hammond et al. 2001). Nevertheless, host plant resistance still offers promise for managing populations of

Japanese beetles in the future. Development of resistant soybeans through conventional breeding or genetic engineering is critical for low-input, sustainable management of this insect (Potter and Held 2002).

Biological Control

Biological control was first used to suppress populations of Japanese beetles on a large number of acres in 1965. Milky disease spores, *Paeniacillus popilliae* (Dutky), were applied on more than 20 acres near East St. Louis, Illinois (Matzenbacher 1966). Economically, *P. popilliae* is not feasible for corn and soybean production because costs range from $200–300 per acre (Kuhlman and Briggs 1983).

Work toward establishing this bacterium in the eastern United States was initiated in 1939 (Fleming 1968). *P. popilliae* spores target Japanese beetle larvae. After spores are ingested by larvae, the spores germinate to cause fat-body depletion and death (Sharpe and Detroy 1979). However, mass production of the spores is inefficient (Klein 1986, 1992). Some spore powders were marketed during the 1980s, but were recalled because they contained spores from another, non-entomopathogenic bacterium (Stahly and Klein 1992). Genetic engineering may provide a new strain of *P. popilliae* with better virulence and a wider host range (Redmond and Potter 1995). Spores from another biological control agent, the fungus *Beauveria bassiana* (Bals.) Vuill., can be produced efficiently on a large scale and can reduce populations of Japanese beetle adults (Rex 1940).

Populations of Japanese beetle larvae can be suppressed by two species of parasitic wasps, *Tiphia vernalis* Rohwer and *T. popilliavora* Rohwer (family Tiphiidae) (Fleming 1976). *Tiphia vernalis* parasitizes overwintering larvae in the spring, whereas *T.*

popilliavora attacks young larvae in late summer (Fleming 1976). Smith and Hadley (1926) noted that entomogenous pathogens in the soil were the most effective native biological agents for suppressing populations of Japanese beetle larvae. A parasitic fly, *Istocheta aldrichi* (Mesnil) (family Tachinidae), can suppress populations of Japanese beetle adults (Fleming 1976). However, these parasitoids occur only periodically and should not be relied upon for site-specific or large-scale management efforts (Potter and Held 2002). Vertebrate predators include European starlings (*Sturnus vulgaris* L.), crows (*Corvus* spp.), grackles (*Quiscalus* spp.), gulls (family Laridae), and other birds (Fleming 1968).

Management

Although many different methods and approaches have been used for managing populations of Japanese beetles, landscape managers, crop producers, and homeowners rely primarily on insecticides (Potter and Held 2002). In soybeans, an insecticide treatment is warranted when defoliation reaches 40 to 50% before bloom, 15 to 20% between bloom and pod-fill, and more than 25% from pod-fill to harvest (Steffey and Gray 2009). Marcos Kogan, formerly a research entomologist with the Illinois Natural History Survey, suggested a spray treatment when there are more than 18 beetles per foot of row or greater than 20% defoliation with more than 12 beetles per foot of row (Kuhlman and Briggs 1983). Scouting fields is necessary to determine how much injury is occurring. Kuhlman and Briggs (1983) suggested that the best option for managing outbreaks of Japanese beetles begins with scouting fields in July.

In the 1970s and 1980s, organophosphate and carbamate insecticides were used to control Japanese beetle larvae after they hatched and began to feed on roots (Potter and

Held 2002). However, predators of Japanese beetles, such as ants and some beetles in the families Carabidae and Staphylinidae also are susceptible to these insecticides (Terry et al. 1993, Lopez and Potter 2000, Zenger and Gibb 2001a, 2001b). Insecticidal soaps, used due to their low risk against nontarget organisms, are ineffective because of their lack of residual activity (Nielsen 1990). Currently, many populations of Japanese beetle adults feeding on foliage or flowers of susceptible plants are treated with short-residual insecticides, such as carbaryl (Potter 1998).

Other agronomic practices that affect populations of Japanese beetles include weed management, intercropping, and tillage. Keeping fields free of weeds, especially Pennsylvania smartweed, *Polygonum pennsylvanicum* L., may benefit management of Japanese beetles. Pennsylvania smartweed is a preferred host for Japanese beetles, and crop injury can be greatest when this weed, soybean, and corn are located relatively close together (Gould 1963). Holmes and Barrett (1997) observed smaller numbers of Japanese beetles in soybeans that were intercropped with sorghum than in soybean monocultures. The authors suggested that intervening strips of non-host vegetation impair movement and restrict adult dispersal (Bohlen and Barrett 1990, Holmes and Barrett 1997). Athayde (2003) demonstrated that Japanese beetles were more prevalent in a no-till field than in conventionally tilled fields in one year of a three-year experiment, although the significant differences in numbers of Japanese beetles among plots with different tillage treatments were probably due to other random effects not controlled within the experiment. Athayde (2003) indicated that current year tillage may reduce populations of Japanese beetles in the following year.

Since Japanese beetles were first discovered in the United States, their management has been challenging. Because of their voracious feeding behavior and their occurrence in large numbers during some years, economic losses caused by Japanese beetles in soybean are possible. Although insecticide application is the most effective control tactic, host-plant resistance and cultural control methods could aid in bolstering an integrated pest management approach for this insect. Understanding the behavior of Japanese beetles in soybean fields and gaining more knowledge about the relationship between defoliation and yield loss will enhance management efforts for Japanese beetles.

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CHAPTER TWO

Sampling the Spatial Distribution of Japanese Beetles in Illinois Soybean Fields and Their Impact on Production

INTRODUCTION

Soybean, *Glycine max* (L.) Merr., is the most important oilseed crop grown in the United States. In 2009 and 2010, record numbers of soybean acres were planted and harvested in the United States—76.4 million acres (30.7 million hectares) harvested in 2009 (NASS 2010) and 76.6 million acres (31.0 million hectares) harvested in 2010 (NASS 2011a). Because of the increase in acreage planted and harvested, soybean production has increased dramatically, with 3.36 billion bushels (91.4 million metric tons) (NASS 2010) and 3.33 billion bushels (89.8 million metric tons) (NASS 2011a) produced in 2009 and 2010, respectively.

Soybean is consistently one of the top cash crops in Illinois' agriculture industry. Illinois farmers harvested 9.4 million acres (~3.8 million hectares) and 9.1 million acres (~3.7 million hectares) of soybean in 2009 and 2010, respectively. Although not a soybean production record, the state average yield of 52 bushels per acre in 2010 was the best on record in Illinois, enabling Illinois farmers to produce almost 471 million bushels (10.3 million metric tons) of soybeans. In 2009, farmers in Illinois produced 430 million bushels (9.4 million metric tons) of soybeans, with an average yield of 46 bushels per acre (NASS 2011b).

An economically threatening pest of soybean, the Japanese beetle, *Popillia japonica* Newman, is an invasive species native to the Japanese Archipelago (Fleming 1976). Its spread throughout the world has been reported in Canada (NAPIS 1998), northern Japan (Ando 1986), Portugal (Lacey et al. 1994), and the United States

(Edwards 1999). The Japanese beetle was first discovered in the United States in 1916 (Fleming 1976).

The Japanese beetle was first identified in Illinois in the early 1930s near Chicago and East St. Louis (Luckmann 1964, Matzenbacher 1966). The 100th meridian of longitude is most likely the western limit for spread of the Japanese beetle because the arid climate beyond this point is unsuitable for their development (Fleming 1963, Allsopp 1996).

The Japanese beetle has a univoltine life cycle, i.e., one generation per year. Females lay eggs in the soil from mid-June through August (Edwards 1999). After hatching, larvae complete three instars by feeding on the roots of grasses or decaying plant material (Edwards 1999). Larvae move slightly deeper in the soil profile (5–15 cm) to avoid excessively low winter temperatures (Hoshikawa et al. 1988) and overwinter. In the spring, the larvae move closer to the soil surface and form an earthen cell for pupation (Fleming 1972, Vittum 1986). Adults emerge from the soil from early to late June, and male emergence precedes that of females by a few days (Fleming 1972, Régnière et al. 1981, Edwards 1999).

Japanese beetles injure soybean plants by eating leaf tissue. Adults consume tissue between the veins of soybean leaves, resulting in a lacelike skeleton (Kuhlman and Briggs 1983). Adults begin feeding at the top of the canopy (Fleming 1972), and they prefer feeding on foliage in direct sunlight (Kuhlman and Briggs 1983). Extensive feeding can be observed from mid-morning through late evening, with sporadic feeding during the night when temperatures remain greater than 15°C (Kreuger and Potter 2001). Much of this feeding occurs during the reproductive stages of soybean development

(Hammond 1994). Soybeans in reproductive stages R2 (full-bloom) through R5 (beginning seed) are the most susceptible to economic damage caused by defoliating insects such as Japanese beetles (Fehr et al. 1977, Pedersen 2004). Soybeans in vegetative stages of growth are much less susceptible to economic damage caused by defoliation because of the plants' ability to compensate for tissue loss (Hunt et al. 1994).

Although many different methods have been used for managing populations of Japanese beetles, landscape managers, crop producers, and homeowners rely primarily on insecticides (Potter and Held 2002). In soybean fields, an insecticide application is warranted when defoliation reaches 40 to 50% before bloom, 15 to 20% between bloom and pod-fill, and more than 25% from pod fill to harvest (Steffey and Gray 2009). Another guideline for control of Japanese beetles in soybean suggests that an insecticide application is warranted when there are more than 18 beetles per foot of row or greater than 20% defoliation with more than 12 beetles per foot of row (Kuhlman and Briggs 1983). Scouting fields is necessary to determine the extent of injury to soybeans. Sampling with sweep nets is effective for collecting Japanese beetle adults, as well as other defoliating insects in soybean (Hammond et al. 2001).

Weed management is another agronomic practice that affects populations of Japanese beetles. Keeping fields free from weeds, especially Pennsylvania smartweed (*Polygonum pennsylvanicum* L.), a preferred host for Japanese beetles, is important. Crop injury by Japanese beetles can be greatest when smartweed, soybean, and corn are located relatively close together (Gould 1963).

Soybean growers in Illinois are faced with the potential for Japanese beetle outbreaks each summer. In recent years, outbreaks have occurred in Illinois soybean

fields in 2002, 2006, and 2008 (Steffey 2002, Gray and Steffey 2006, Gray and Steffey 2008). However, predicting the occurrence of outbreaks and estimating densities of Japanese beetles can be difficult (Gray et al. 2003). A better understanding of Japanese beetle densities within a soybean field would enable a grower to make more informed decisions about their management. Furthermore, greater knowledge of insect densities and corresponding yield-loss relationships would enable development of economic injury levels, which also can lead to more efficient pest management (Funderburk and Higley 1994).

The first objective of my experiment was to measure the spatial trends of Japanese beetles in soybean fields. Japanese beetle adults are attracted to areas where other Japanese beetles are feeding because of the volatile compounds emitted from chewed leaves (Ladd 1966, Fleming 1972, Potter and Held 2002). Understanding how densities of Japanese beetles differ between field edges and field interiors may improve our ability to make decisions about their management. Additionally, understanding the influence of field borders (e.g., corn, soybean, grass, roads) on sampling and densities of Japanese beetles might allow for population differences to be studied in greater detail.

The second objective of this experiment was to correlate densities of Japanese beetles and percentage defoliation with soybean yields. A current, widely recommended threshold for defoliating insects in soybean is 15 to 20% defoliation between bloom and pod-fill (Steffey and Gray 2009). Another management guideline was proposed by Marcos Kogan (Kuhlman and Briggs 1983). However, thresholds and guidelines for soybean defoliators were developed a number of years ago when soybean production, yield, and prices were substantially lower. Therefore, it is important to understand

whether the relationship between densities of Japanese beetles and soybean defoliation is still relevant. Yields were estimated in fields in my study to determine whether the relationship between densities of Japanese beetles and soybean defoliation was economically important in modern soybean production systems.

MATERIALS AND METHODS

Experimental Design

The experiment was conducted as a completely randomized design and included systematically sampled soybean fields throughout Illinois. The fields were procured mainly by contacting members of the Illinois Soybean Association and soybean growers who had participated previously in cooperative research efforts. Soybean fields in 11 Illinois counties were sampled in this study. In 2009, soybean fields in Bureau, Champaign, Hancock, Henderson, Kendall, McLean, Montgomery, Tazewell, and Vermilion counties were sampled. In 2010, soybean fields in Champaign, Macon, McLean, and Ogle counties were sampled. Although the fields sampled in 2010 were selected arbitrarily, regular communication with the growers increased the likelihood that Japanese beetles would be present at the time of sampling.

Both intensive and extensive sampling schemes (Southwood 1978) were developed for this study. Intensively sampled fields required weekly observation of Japanese beetles in soybean and assessment of the relationship between percentage defoliation and densities of Japanese beetles observed. Some fields were sampled only once during the growing season (extensive sampling) to understand the distribution of Japanese beetles in soybean fields and to identify patterns in their population levels.

Agronomic Information

Soybean fields sampled for this experiment were planted on many different dates in both 2009 and 2010, and agronomic practices were the responsibility of the respective growers. In 2009, planting dates ranged from 3 May to 9 June. In contrast, soybean fields in 2010 were planted earlier, from 29 April to 23 May. Agronomic practices varied among the cooperating growers. Some soybean fields were grown in reduced-tillage systems, whereas others were planted after cultivation in the spring. Some growers chose to use a pre- and post-emergence herbicide program, whereas others applied only postemergence herbicides. Additionally, soybean fields were planted in row widths of 0.19 (drilled), 0.38 (split), or 0.76 m, depending on the grower's preference and equipment.

Intensive Sampling

Intensively sampled soybean fields were visited more than once to sample populations of Japanese beetles and to estimate corresponding defoliation. Visiting a soybean field multiple times would potentially reveal changes in densities of Japanese beetle over time. In 2009, three soybean fields in McLean County were sampled intensively for the first time on 14 or 16 July; one other soybean field in Champaign County was sampled intensively for the first time on 23 July. In 2010, three soybean fields in McLean County were sampled for the first time on 7 July, and one soybean field in Champaign County was sampled for the first time on 13 July.

Samples for Japanese beetles and percentage defoliation were collected at 18 different locations in each field. Nine samples were taken from the field edge, and nine samples were taken from the field interior. An "edge sample" was taken between 0 and

7.6 m from the outermost row of the soybean field. Specifically, in soybean fields planted in 0.76 m rows, samples were taken within the first 10 rows of the field. In soybean fields planted in 0.38 m rows, samples were taken within the first 20 rows of the field.

A diagram of the field was developed and shared with samplers so that they would understand the layout of each field. Samplers were trained to make systematic stops along designated transects to be sampled in each field. The borders of each field (e.g., corn, soybean, grass, road) were indicated on these diagrams.

At each sample location, the sampler placed an orange property marker (Model 125716, Hy-Ko Products, Northfield, OH), and a wire flag (Model 30FV2, Gempler's, Madison, WI) was secured with duct tape to the top of each marker so that the sample locations would be easy to find on successive sampling trips. The sample number was written on each flag with a black permanent marker. After placing the orange property marker and taping the flag, the sampler recorded the location of the orange marker with a handheld global positioning system (GPS) unit (Model 145262, Garmin, Olathe, KS). Knowing the exact location of each sample permitted later comparisons of sample data with GPS-referenced yield data provided by growers. The GPS coordinates were written on white Tyvek labels (Model S38-35, DuPont, Wilmington, DE) with black permanent marker. At each sample location, the sampler used a sweep net (Model 315HS, Great Lakes IPM, Vestaburg, MI) that had been modified with tear-away sweep net sample bags. The cotton sample bags measured 22.9 cm long x15.2 cm wide. Velcro (Model 91134, Velcro Industries, Manchester, NH) was used to attach the sample bag to the end of the modified sweep net. The sample bags also had shoe strings sewed on the outside for rapid closure.

In 2009, 50 sweeps along a transect of approximately 150 m were taken at each sample location. In 2010, the number of sweeps taken at each location was reduced to 25 along a transect of approximately 75 m. After completing the sweep samples, the sampler walked ca. 10 m beyond the last sample and conducted a visual count of the number of Japanese beetles present in 1 m of row. The numbers of Japanese beetles counted were recorded on Tyvek labels.

After completing the sweep sample and visual count at each location, the sampler removed the tearaway sample bag on the sweep net and placed the white Tyvek label used to record the GPS coordinate and visual count of Japanese beetles per meter of soybean row inside the sample bag. The sample bag was tied closed and placed in a cooler (Model 1-97090-00-05, California Innovations, Toronto, ON). In 2009, the sampler walked back through the sampled area and collected three center leaflets from three randomly selected soybean plants. In 2010, three leaflets were picked randomly in the sweep-sampled location. Leaves were placed in plastic bags (Model S1309, U-Line, Pleasant Prairie, WI) and marked with the sample number written on the outside of the bag. Leaves also were placed in the cooler. The combination of sweeps, visual counts, and leaflets sampled comprised one sample location in each field.

After completing the sampling regimen at a location, the sampler walked to the next sample location and repeated all steps. Three samplers worked in each field; each sampler was responsible for six of the 18 sample locations in each field. After all samples were taken in a field, the samplers placed their six sample bags in a cooler (Model 7980, Thermos, Rolling Meadows, IL) with dry ice to freeze the collected insects. The sampled leaflets were placed in a different cooler (Model 00043582, Igloo, Katy, TX) with

conventional ice because dry ice would have caused the leaves to become too brittle and easily broken. All samples were returned to the Agricultural Engineering Farm in Urbana, IL, after sampling was complete.

On 23 July, 2009, the three McLean County fields were sampled for the second time. The Champaign County field was sampled for the second time on 30 July, 2009. The three McLean County fields were sampled for the third time on 30 July, 2009. It was apparent that densities of Japanese beetles had declined dramatically in one of these fields, and we learned subsequently that an insecticide had been applied on 28 July. As a result, this field was not sampled further. The remaining two McLean County fields were sampled for the fourth and final time on 6 August, 2009. The Champaign County field was sampled for the third and fourth times on 6 and 11 August, 2009, respectively.

In 2010, four fields were sampled over the course of four weeks. Three fields in McLean County were sampled on 7, 15, 22, and 29 July, 2010. One field in Champaign County was sampled on 13, 19, and 27 July, and on 2 August, 2010. The sampling protocol in 2010 was the same as the sampling protocol in 2009, except for the reduced number of sweeps taken at each sample location (50 sweeps per location in 2009, 25 sweeps per location in 2010).

Extensive Sampling

Soybean fields designated for extensive sampling were sampled only once in either 2009 or 2010. The objective was to assess densities of Japanese beetles with both sweep-net samples and visual counts so that we could determine a potential relationship between the two types of samples over a large number of fields. Additionally, densities of

Japanese beetles estimated from sweep-net sampling and visual counts would be correlated with soybean yield data to estimate a yield-loss relationship.

In 2009, fields were sampled between 9 July and 6 August. In 2010, fields were sampled between 13 July and 5 August. In each field, 18 locations were sampled—nine in field edges and nine in the field interior. The insect sampling methods were the same methods used for intensive sampling; however, no leaf samples were taken from extensively sampled fields. Twenty-nine fields were sampled in this manner in 2009; 20 fields were sampled in this manner in 2010.

Sample bags were placed in a freezer (Model HCM05LA, Haier America, New York, NY) overnight so that the insects could be counted the next day. The numbers of Japanese beetles; bean leaf beetles, *Cerotoma trifurcata* (F.); grasshoppers (more than one species, family Acrididae) larger than 19.05 mm; and soybean loopers, *Pseudoplusia includens* (Walker) were counted and recorded. These insects were counted because of their potential for defoliating soybeans and to gain a better understanding of where and in what densities these insects were found in Illinois soybean fields.

Estimation of Percentage Defoliation

All sampled leaflets were imaged with a scanner (Xerox DocuMate 515, Xerox Corporation, Wilsonville, OR) so that each leaflet could be saved as an individual image. Images of leaflets were imported into a computer program, and the amount of defoliation was estimated (GNU Image Manipulation Program 2.6) by the procedure described by O'Neal et al. (2002). Each leaflet image was coded by field number, the date the sample was taken, and the sample number. After completing estimates of percentage defoliation of all three leaflets for the sample, the three percentages were averaged to obtain an

estimate of percentage defoliation for the total sample. This procedure was repeated for all leaflet samples.

Estimates of Soybean Yield

Soybean yields were estimated in fields in which cooperating farmers had the capability of using GPS coordinates during harvest to pinpoint yields in specific sample areas. The yields were estimated for each location that was sampled.

Response Variables and Statistics

Japanese beetles, bean leaf beetles, grasshoppers, and soybean loopers from each sample location were counted by hand in the laboratory. Densities from sweep-net samples and visual counts were calculated and analyzed with SAS version 9.2 (SAS Institute 2008). Densities of Japanese beetles, bean leaf beetles, grasshoppers, and soybean loopers were also analyzed in relation to field border using SAS version 9.2 (SAS Institute 2008). In intensively sampled fields, percentage defoliation was estimated by the GNU Image Manipulation Program. Three leaflets per sample were averaged so that each sample location had one estimate of percentage defoliation. The data were analyzed with SAS version 9.2 (SAS Institute 2008). For variables of insect densities and percentage defoliation, variance for random effects and significance level (*P*) for fixed effects were determined using the mixed procedure (PROC MIXED). Data were log transformed to stabilize variances, and means were compared by the LSMEANS procedure.

Soybean yields adjusted to 13% moisture were analyzed with SAS version 9.2 (SAS Institute 2008). Variance for random effects and significance level (*P*) for fixed

effects were determined using the mixed procedure (PROC MIXED). Data were not transformed, and means were compared by the LSMEANS procedure.

For all sampled fields, densities of Japanese beetles estimated from sweep-net samples and from visual counts were analyzed to establish their potential relationship. For intensively sampled fields, the potential relationship between percentage defoliation and Japanese beetle density estimated from (1) sweep-net samples and (2) visual counts also were analyzed. For these relationships, data were log transformed to stabilize variances, and their relationship was evaluated using the regression procedure (PROC REG). Data were plotted to observe trends.

For fields with yield data, densities of Japanese beetles and yield were analyzed to determine their potential relationship. Densities of Japanese beetles were transformed to stabilize variances; however, yield data were not transformed. Regression was determined using the regression procedure (PROC REG). Data were plotted to observe trends.

RESULTS

The results presented are subdivided into fields that were sampled intensively or extensively. All results are based on a $P \leq 0.10$ significance level. Tables containing the following results are found in the appendix.

Intensive Sampling

Densities of Japanese Beetles Sampled in Field Edges and Field Interiors, 2009 and 2010

In 2009, there was only a slight significant effect of sample location observed in intensively sampled fields ($F = 2.51$, $df_N = 1$, $df_D = 231$, $P = 0.1148$) (Table 1). Densities of Japanese beetles estimated by sweep-net samples in field edges and field interiors

averaged 1.09 and 0.28 Japanese beetles per sweep, respectively. Although the *P*-value is greater than 0.10, I chose to accept a significant effect of sample location because the *P*-value was only slightly above 0.10. However, there was no significant effect of sample location on densities of Japanese beetles estimated from visual counts ($F = 0.50$, $df_N = 1$, $df_D = 228$, $P = 0.4797$) (Table 1). Visual counts in field edges and field interiors averaged 6.19 and 2.06 Japanese beetles per meter of row, respectively.

Densities of Japanese beetles were significantly smaller in 2010 than in 2009. There was no significant effect of sample location on densities of Japanese beetles estimated from sweep-net samples in 2010 ($F = 0.25$, $df_N = 1$, $df_D = 278$, $P = 0.6161$) (Table 1). Densities of Japanese beetles in field edges and field interiors averaged 0.27 and 0.09 Japanese beetle per sweep, respectively. Densities of Japanese beetles estimated from visual counts were not significantly affected by sample location, either ($F = 0.04$, $df_N = 1$, $df_D = 91.4$, $P = 0.8355$) (Table 1). Densities in field edges and field interiors averaged 0.72 and 0.5 Japanese beetle per meter of row, respectively.

Densities of Other Soybean Defoliators Sampled in Field Edges and Field Interiors, 2009 and 2010

There were low densities of other soybean defoliators during both years of my study. In 2009, there was no significant effect of sample location on densities of bean leaf beetles ($F = 1.61$, $df_N = 1$, $df_D = 237$, $P = 0.2064$), grasshoppers ($F = 0.06$, $df_N = 1$, $df_D = 24.9$, $P = 0.8024$), or soybean loopers ($F = 0.01$, $df_N = 1$, $df_D = 54.6$, $P = 0.9255$) (Table 2). Densities of bean leaf beetles, grasshoppers, and soybean loopers in field edges averaged 0.02, 0.01, and 0.01 insect per sweep, respectively. Densities in field interiors were similar, with densities of bean leaf beetles, grasshoppers, and soybean loopers averaging 0.03, 0.00, and 0.01 insect per sweep, respectively.

Similar to results from 2009, no significant effect of sample location was observed on densities of grasshoppers ($F = 0.03$, $df_N = 1$, $df_D = 266$, $P = 0.8635$) or soybean loopers ($F = 0.03$, $df_N = 1$, $df_D = 275$, $P = 0.8517$) (Table 2) in 2010. Densities of grasshoppers averaged 0.01 per sweep in field edges and 0.00 per sweep in field interiors. Densities of soybean loopers averaged 0.03 per sweep in field edges and 0.04 per sweep in field interiors. Densities of bean leaf beetles, although very small, were significantly affected by sample location ($F = 3.53$, $df_N = 1$, $df_D = 283$, $P = 0.0612$) (Table 2). Densities of bean leaf beetles averaged 0.03 per sweep in field edges and 0.02 per sweep in field interiors. The variance for this effect was small enough to contribute to the significant effect for these small densities of bean leaf beetles. However, these low numbers were not economically relevant.

Densities of Japanese Beetles Relative to Field Border, 2009 and 2010

A significant effect of field border on densities of Japanese beetles was observed ($F = 4.80$, $df_N = 3$, $df_D = 231$, $P = 0.0029$) (Table 3). Densities of Japanese beetles estimated from sweep-net samples were greatest in samples next to corn (1.48 Japanese beetles per sweep). Densities next to grass (1.24 Japanese beetles per sweep) were significantly smaller than densities next to corn but were significantly greater than densities next to roads or soybean (0.28 and 0.29 Japanese beetle per sweep, respectively). Densities of Japanese beetles next to roads and soybean were not statistically different from each other. A similar effect of field border was observed for densities of Japanese beetles estimated from visual counts ($F = 5.60$, $df_N = 3$, $df_D = 230$, $P = 0.0010$) (Table 3). Counts next to corn (8.69 Japanese beetles per meter of row) were

significantly greater than counts next to grass, roads, and soybean (5.69, 2.29, and 2.17 Japanese beetles per meter of row, respectively).

As previously indicated, densities of Japanese beetles were much smaller in 2010 than they were in 2009. However, a significant effect of field border on densities of Japanese beetles estimated from sweep-net samples was observed ($F = 4.56$, $df_N = 2$, $df_D = 116$, $P = 0.0124$) (Table 3). Significantly more Japanese beetles were found next to corn (0.34 per sweep) and roads (0.22 per sweep) than in samples next to soybean (0.08 Japanese beetle per sweep). Densities of Japanese beetles estimated from visual counts were not significantly affected by field border ($F = 1.27$, $df_N = 2$, $df_D = 4.19$, $P = 0.3695$) (Table 3). Densities next to corn, roads, and soybean averaged 0.82, 0.73, and 0.46 Japanese beetle per meter of row, respectively.

Densities of Other Soybean Defoliators Relative to Field Border, 2009 and 2010

Only densities of grasshoppers were significantly affected by field border ($F = 5.24$, $df_N = 3$, $df_D = 8.05$, $P = 0.0269$) (Table 4). More grasshoppers were present in samples next to corn, roads, and grass (0.02, 0.01, and 0.01 grasshopper per sweep) than in samples next to soybean (0.00 grasshopper per sweep). Densities of grasshoppers next to corn, roads, and grass were not statistically different from one another. Densities of bean leaf beetles ($F = 1.98$, $df_N = 3$, $df_D = 237$, $P = 0.1183$) and soybean loopers ($F = 1.09$, $df_N = 3$, $df_D = 38.9$, $P = 0.3640$) (Table 4) were not significantly affected by field border. For all field borders, densities of bean leaf beetles and soybean loopers averaged no more than 0.05 and 0.01 insect per sweep, respectively.

In 2010, there was no significant effect of field border on densities of bean leaf beetles ($F = 0.71$, $df_N = 2$, $df_D = 283$, $P = 0.4911$), grasshoppers ($F = 0.92$, $df_N = 2$, $df_D =$

236, $P = 0.4014$), or soybean loopers ($F = 1.40$, $df_N = 2$, $df_D = 276$, $P = 0.2491$) (Table 4). Densities of bean leaf beetles averaged 0.02 per sweep next to corn, roads, and soybean. Densities of grasshoppers averaged 0.01 per sweep next to corn and roads and 0.00 per sweep next to soybean. Densities of soybean loopers averaged 0.02 per sweep next to corn, 0.03 per sweep next to roads, and 0.04 per sweep next to soybean.

Percentage Defoliation in Field Edges and Field Interiors, 2009 and 2010

In 2009, there was no significant effect of sample location on percentage defoliation ($F = 0.09$, $df_N = 1$, $df_D = 214$, $P = 0.7647$) (Table 5). Defoliation in field edges and field interiors averaged 5.06 and 3.1% respectively. However, in 2010, there was a significant effect of sample location on percentage defoliation ($F = 13.15$, $df_N = 1$, $df_D = 280$, $P = 0.0003$) (Table 5). Field edges had significantly greater percentage defoliation (4.07%) than field interiors (2.38%).

Percentage Defoliation Relative to Field Border, 2009 and 2010

A significant effect of field border on percentage defoliation was observed in 2009 ($F = 2.62$, $df_N = 1$, $df_D = 216$, $P = 0.0517$) (Table 6). Defoliation next to corn (5.89%) was significantly greater than defoliation next to grass, roads, and soybean (5.10, 3.71, and 3.15%, respectively). However, there was no significant effect of field border on defoliation in 2010 ($F = 1.05$, $df_N = 2$, $df_D = 146$, $P = 0.3541$) (Table 6). Defoliation next to corn averaged 3.88% and defoliation next to roads and soybean averaged 3.89 and 2.67%, respectively.

Yield in Field Edges and Field Interiors, 2009 and 2010

Results from both years of this study suggested that yields from field interiors were larger than yields from field edges. Although not statistically significant ($F = 0.99$,

$df_N = 1$, $df_D = 64.3$, $P = 0.3236$) (Table 5), yield from field interiors averaged 60.76 bu/acre and yield from field edges averaged 58.46 bu/acre in 2009. There was no significant effect of sample location on yield in 2010 ($F = 0.23$, $df_N = 1$, $df_D = 53.4$, $P = 0.6328$) (Table 5), although yield from field interiors were larger than yields from field edges by 2.76 bu/acre (71.46 and 68.70 bu/acre, respectively).

Yield in Field Edges Influenced by Field Border, 2009 and 2010

In 2009, a significant effect of field border on yield was observed ($F = 2.94$, $df_N = 3$, $df_D = 64$, $P = 0.0396$) (Table 6). Yield next to grass was significantly less (55.48 bu/ac) than yields next to corn and roads (59.86 and 61.07 bu/acre, respectively). However, in 2010, no significant effect of field border on yield was observed ($F = 0.18$, $df_N = 2$, $df_D = 54.6$, $P = 0.8390$) (Table 6). Yields next to corn, roads, and soybean averaged 69.16, 68.01, and 71.46 bu/acre, respectively.

Densities of Japanese Beetles by Week, 2009 and 2010

There was no significant effect of sampling week on densities of Japanese beetles ($F = 1.43$, $df_N = 3$, $df_D = 169$, $P = 0.2349$) (Table 7). Densities of Japanese beetles estimated from sweep-net samples during week one (1.51 Japanese beetles per sweep) were statistically similar to densities from weeks two through four (0.45, 0.38, and 0.20 Japanese beetle per sweep, respectively). Densities of Japanese beetles estimated from visual counts in 2009 also were not significantly affected by week ($F = 1.25$, $df_N = 3$, $df_D = 196$, $P = 0.2912$) (Table 7).

In 2010, there was no significant effect of week on densities of Japanese beetles estimated by sweep-net samples ($F = 1.08$, $df_N = 3$, $df_D = 15$, $P = 0.3861$) or visual counts ($F = 1.48$, $df_N = 1$, $df_D = 11.8$, $P = 0.2705$) (Table 8). Densities of Japanese beetles in

2010 increased gradually from 0.07 per sweep in week one to 0.14 per sweep in week two, 0.24 per sweep in week three, and 0.27 per sweep in week four. This gradual increase in densities over time was not observed for densities of Japanese beetles estimated by visual counts (0.31, 0.33, 1.53, and 0.26 Japanese beetles per meter of row for weeks one through four, respectively).

Extensive Sampling

Densities of Japanese Beetles Sampled in Field Edges and Field Interiors, 2009 and 2010

Compared with densities of Japanese beetles in field edges and field interiors in intensively sampled fields, there was a considerable significant effect of sample location on densities of Japanese beetles sampled with sweep nets in extensively sampled fields in 2009 (F = 8.37, df_N = 1, df_D = 734, P = 0.0039) (Table 9). Densities were greater in samples taken from field edges (1.06 Japanese beetles per sweep) than samples taken from field interiors (0.30 Japanese beetle per sweep). A significant effect of sample location on densities of Japanese beetles sampled by visual counts also was observed (F = 4.23, df_N = 1, df_D = 746, P = 0.0400) (Table 9). Numbers of Japanese beetles were greater in samples taken from field edges (5.59 Japanese beetles per meter of row) than in samples taken from field interiors (1.95 Japanese beetles per meter of row).

Densities of Japanese beetles in 2010 were almost three times less than they were in 2009. No significant effect of sample location on densities of Japanese beetles estimated from sweep-net samples was observed (F = 1.37, df_N = 1, df_D = 594, P = 0.2415) (Table 9). Densities of beetles from samples taken from field edges and field interiors averaged 0.35 and 0.11 Japanese beetle per sweep, respectively, There also was no significant effect of sample location on densities of Japanese beetles estimated with

visual counts ($F = 0.40$, $df_N = 1$, $df_D = 601$, $P = 0.5291$) (Table 9). Visual counts in field edges and in field interiors averaged 0.99 and 0.46 Japanese beetle per meter of row, respectively.

Densities of Other Soybean Defoliators Sampled in Field Edges and Field Interiors, 2009 and 2010

The densities of other defoliators in Illinois soybean fields were very small in 2009 and 2010. In 2009, no significant effect of sample location was observed on densities of bean leaf beetles ($F = 1.50$, $df_N = 1$, $df_D = 737$, $P = 0.2211$), grasshoppers ($F = 0.02$, $df_N = 1$, $df_D = 728$, $P = 0.8931$), or soybean loopers ($F = 0.24$, $df_N = 1$, $df_D = 759$, $P = 0.6245$) (Table 10). Nor was there a significant effect of sample location on densities of bean leaf beetles ($F = 1.50$, $df_N = 1$, $df_D = 584$, $P = 0.2214$), grasshoppers ($F = 0.11$, $df_N = 1$, $df_D = 566$, $P = 0.7422$), or soybean loopers ($F = 0.09$, $df_N = 1$, $df_D = 596$, $P = 0.7669$) (Table 10) observed in 2010.

Densities of Japanese Beetles Relative to Field Border, 2009 and 2010

There was a significant effect of field border on densities of Japanese beetles estimated from sweep-net samples ($F = 28.93$, $df_N = 3$, $df_D = 733$, $P < 0.0001$) (Table 11). Densities were greatest in samples next to corn (1.71 Japanese beetles per sweep). Densities estimated from samples next to grass, roads, and soybean (0.78, 0.51, and 0.33 Japanese beetle per sweep, respectively) were significantly smaller than densities estimated from samples next to corn and were not statistically different from one another. There was also a significant effect of field border on densities of Japanese beetles estimated from visual counts ($F = 14.02$, $df_N = 3$, $df_D = 744$, $P < 0.0001$) (Table 11). Counts of Japanese beetles were greatest in samples next to corn (8.40 Japanese beetles

per meter of row) than in samples next to grass, roads, and soybean (4.31, 2.96, and 2.13 Japanese beetles per meter of row, respectively).

A significant effect of field border on densities of Japanese beetles estimated from sweep-net samples was observed in 2010 ($F = 11.56$, $df_N = 3$, $df_D = 595$, $P < 0.0001$) (Table 11). Densities were greatest in samples next to corn (0.43 Japanese beetle per sweep). However, densities estimated from samples next to roads (0.38 Japanese beetle per sweep) were not statistically different from densities estimated from samples next to corn or grass (0.31 Japanese beetle per sweep). Samples next to soybean had the smallest densities of Japanese beetles (0.10 Japanese beetle per sweep). There was also a significant effect of field border on densities of Japanese beetles estimated from visual counts ($F = 3.51$, $df_N = 3$, $df_D = 603$, $P = 0.0152$) (Table 11). Visual counts next to corn and grass (1.27 and 0.98 Japanese beetles per meter of row, respectively) were greater than counts next to soybean (0.41 Japanese beetle per meter of row). However, counts next to soybean were not statistically different from counts next to roads (0.97 Japanese beetle per meter of row).

Densities of Other Soybean Defoliators Relative to Field Border, 2009 and 2010

In 2009, a significant effect of field border on densities of grasshoppers was observed ($F = 7.10$, $df_N = 3$, $df_D = 735$, $P = 0.0001$) (Table 12). There were 0.02 grasshopper per sweep in samples next to corn. Densities of grasshoppers in samples next to grass, roads, and soybean (0.00, 0.01, and 0.00 per sweep, respectively) were significantly smaller than densities in samples next to corn and were not statistically different from one another. Although a significant effect was observed, densities were extremely small and were not economically important. Additionally, no significant effect

of field border was observed on densities of bean leaf beetles (F = 1.78, df_N = 3, df_D = 736, P = 0.1503) or soybean loopers (F = 1.47, df_N = 3, df_D = 757, P = 0.2209) (Table 12).

In 2010, there was a significant effect of field border on densities of bean leaf beetles (F = 2.12, df_N = 3, df_D = 585, P = 0.0960) (Table 12). Densities next to corn or roads (0.02 and 0.03 bean leaf beetle per sweep, respectively) were significantly smaller than densities next to grass (0.04 bean leaf beetle per sweep). Densities of bean leaf beetles next to soybean (0.04 bean leaf beetle per sweep) were not statistically different from densities next to corn, grass, and roads. A significant effect of field border on densities of soybean loopers also was observed (F = 3.49, df_N = 3, df_D = 598, P = 0.0155) (Table 12). Densities next to grass (0.02 soybean looper per sweep) were significantly less than densities next to corn and soybean (0.03 and 0.04 soybean looper per sweep, respectively). Samples bordering grass and roads had statistically similar densities of soybean loopers and averaged 0.02 soybean looper per sweep. No significant effect of field border on densities of grasshoppers was observed (F = 1.61, df_N = 3, df_D = 538, P = 0.1851) (Table 12).

Yield in Field Edges and Field Interiors, 2009 and 2010

In 2009, no significant effect of sample location on yield was observed (F = 0.17, df_N = 1, df_D = 328, P = 0.6804) (Table 13). Yield in field edges and field interiors averaged 58.65 and 59.48 bu/acre, respectively. However, a significant effect of sample location on yield was observed in 2010 (F = 3.81, df_N = 1, df_D = 251, P = 0.0520) (Table 13). Yield in field interiors was significantly greater (68.13 bu/acre) than yield in field edges (65.22 bu/acre), a 2.91 bu/acre difference.

Yield in Field Edges and Field Interiors Relative to Field Border, 2009 and 2010

In both 2009 and 2010, there was a significant effect of field border on yield. In 2009, yield next to roads (60.72 bu/acre) and soybean (59.66 bu/acre) were not significantly different ($F = 4.66$, $df_N = 3$, $df_D = 328$, $P = 0.0033$) (Table 14). Yield next to corn was significantly less (58.12 bu/acre) than yield next to roads. Yield next to grass was significantly less (57.13 bu/acre) than yields next to corn, roads, and soybean. There also was a significant effect of field border on yield in 2010 ($F = 5.81$, $df_N = 3$, $df_D = 252$, $P = 0.0007$) (Table 14). Yield next to grass was significantly less (60.06 bu/acre) than yield next to corn, roads, and soybean (67.06, 66.71, and 67.76 bu/acre, respectively), which were not statistically different from one another.

Regression between Densities of Japanese Beetles Estimated by Sweep-net Samples and by Visual Counts, 2009 and 2010

In both years of this study, linear regression between densities of Japanese beetles estimated by sweep-net samples and by visual counts was significant. In 2009, the regression relationship was highly significant ($F = 1244.05$, $df_N = 1$, $df_D = 770$, $P < 0.0001$) (Figure 1). The coefficient of determination ($R^2 = 0.6180$) indicated that 62% of the variance for densities of Japanese beetles estimated by sweep-net samples was explained by the variance for densities estimated by visual counts. Data were highly correlated ($r = 0.79$). In 2010, the linear regression between densities of Japanese beetles estimated by sweep-net samples and by visual counts was significant ($F = 176.61$, $df_N = 1$, $df_D = 620$, $P < 0.0001$) (Figure 2). The coefficient of determination ($R^2 = 0.2220$) indicated that 22% of the variance for densities of Japanese beetles estimated by sweep-net samples was explained by the variance for densities estimated by visual counts. Data were moderately correlated ($r = 0.47$).

Regression between Densities of Japanese Beetles Estimated by Sweep-net Samples and Percentage Defoliation, 2009 and 2010

In 2009, linear regression between densities of Japanese beetles estimated by sweep-net samples and percentage defoliation was significant ($F = 151.47$, $df_N = 1$, $df_D = 250$, $P < 0.0001$) (Figure 3). The coefficient of determination ($R^2 = 0.3782$) indicated that 38% of the variance for percentage defoliation was explained by the variance for densities of Japanese beetles. Data were moderately correlated ($r = 0.62$). The same pattern was observed in 2010 ($F = 15.02$, $df_N = 1$, $df_D = 286$, $P = 0.0001$). However, the coefficient of determination ($R^2 = 0.0501$) indicated that only 5% of the variance for percentage defoliation was explained by the variance for densities of Japanese beetles. Data were not highly correlated ($r = 0.22$).

Regression Between Densities of Japanese Beetles Estimated by Visual Counts and Percentage Defoliation, 2009 and 2010

In 2009, linear regression between densities of Japanese beetles estimated by visual counts and percentage defoliation was significant ($F = 173.21$, $df_N = 1$, $df_D = 250$, $P < 0.0001$) (Figure 5). The coefficient of determination ($R^2 = 0.4102$) indicated that 41% of the variance for percentage defoliation was explained by the variance for visual counts. Data were moderately correlated ($r = 0.64$). In 2010, linear regression between visual counts and percentage defoliation also was significant ($F = 3.03$, $df_N = 1$, $df_D = 286$, $P = 0.0827$) (Figure 6). However, the coefficient of determination ($R^2 = 0.0105$) was smaller than in 2009 and indicated that only 1% of the variance for percentage defoliation was explained by the variance for visual counts. Data were not highly correlated ($r = 0.10$).

Regression between Densities of Japanese Beetles and Yield, 2009 and 2010

In 2009, linear regression between densities of Japanese beetles and yield was significant (F = 3.96, df_N = 1, df_D = 337, P = 0.0474) (Figure 7). However, the coefficient of determination (R^2 = 0.0117) indicated that only 1% of the variance for yield was explained by variance for densities of Japanese beetles. Data were not highly correlated (r = –0.11). The linear regression between these two variables was not significant in 2010 (F = 1.75, df_N = 1, df_D = 265, P = 0.1867) (Figure 8). Data were not highly correlated (r = –0.08).

DISCUSSION

During the two years of my study, I learned that population densities of Japanese beetles varied significantly over time and by sample location in soybean. In 2009, densities of Japanese beetles were three to four times larger at the edges of soybean fields than in field interiors. Although densities of Japanese beetles in 2010 were much smaller than they were in 2009, greater densities again were observed at field edges. Based on the scientific literature (Gould 1963) and my observations, Japanese beetle densities likely were greater at soybean field edges because we sampled for them after they had moved into soybean fields from a previous food source, most notably corn. Weeds, especially Pennsylvania smartweed (a preferred host for Japanese beetles), on the edges of soybean fields also may influence densities of Japanese beetles along field edges. After depleting the weeds as food sources, the beetles may move into the edges of soybean fields (Gould 1963).

Males begin to emerge a few days earlier than females so males concentrate on feeding until females emerge (Fleming 1972, Régnière et al. 1981). Females emerge

looking for a food source while engaging in mate-seeking activities. Fleming (1972) suggested that females prefer flowers as food sources because they must engage in energy-expensive behaviors, including flying to oviposition sites, laying eggs, exiting the soil, and returning to host plants to feed again. Soybean field edges would be a desired location for females that emerged outside of soybean fields because of availability of soybean blooms. Because their feeding releases volatile attractive compounds, Japanese beetle adults are drawn to areas with existing populations of feeding adults (Ladd 1966, Fleming 1972, Potter and Held 2002). Orientation to feeding volatiles by mate-seeking males may be an effective way to locate potential mates. Although Japanese beetles are present in field interiors at smaller densities, edges of soybean fields have the most significant amount of aggregation.

Sweep samples and visual counts generated similar patterns of Japanese beetle densities in both soybean field edges and field interiors, and the trend for greater densities in field edges did not seem to be density-dependent. Numbers of Japanese beetles were considerably smaller in 2010 than in 2009, but densities of Japanese beetles were larger in field edges than in field interiors during both years. Understanding the economic impact of this differential in densities of Japanese beetles between field edges and field interiors would be beneficial when scouting for Japanese beetles. Densities of Japanese beetles would most likely threaten soybean yield first in field edges, so an insecticide application only in field edges might be sufficient to protect yield. Targeted insecticide application would reduce the cost of control, although continued scouting would be recommended.

Finding a relationship between visual counts of Japanese beetles per meter of soybean row and corresponding defoliation would also be beneficial. A visual count of Japanese beetles is a more convenient scouting technique than sweep-net samples for soybean producers. Estimating percentage defoliation of soybean plants is subjective because different producers likely estimate percentage defoliation differently. An economic threshold based on numbers of Japanese beetles rather than on percentage defoliation would be more objective. Counting Japanese beetles per meter of soybean row would enable producers to comprehend Japanese beetle abundance and to use this information to understand how abundance influences decision making. Overall, a combination of counts of Japanese beetles per meter of soybean row and estimates of percentage defoliation would provide a more complete assessment for potential yield loss caused by Japanese beetles.

In 2009, a regression between densities of Japanese beetles estimated by sweep-net samples and densities estimated by visual counts showed that one or fewer Japanese beetle per sweep signified about five or fewer visually observed Japanese beetles per meter of row. This relationship can be compared with the thresholds developed by Marcos Kogan, who suggested that insecticide application was warranted when there were more than 18 Japanese beetles per foot of row (~59 per meter of row) or 12 Japanese beetles per foot of row (~39 per meter of row) and 20% defoliation between bloom and pod fill (Kuhlman and Briggs 1983). In my study, 10 Japanese beetles per sweep corresponded to 36 Japanese beetles per meter of soybean row (Figure 1, 2009). Thirty-six Japanese beetles per meter of soybean row corresponds with 15% defoliation (Figure 5, 2009). From Figure 5, the economic threshold of 20% defoliation between

bloom and pod fill is reached when there are 50 Japanese beetles per meter of soybean row (2009). This compares favorably within the range of Japanese beetle densities defined by Kogan to represent economic thresholds. The regression between densities of Japanese beetles estimated with sweep-net samples and densities estimated by visual counts in 2010 was inconclusive because densities were extremely low.

Population densities of other soybean defoliators (bean leaf beetles, grasshoppers, and soybean loopers) did not differ significantly between field edges and field interiors in 2009. With the exception of bean leaf beetles, the pattern was the same in 2010. In intensively sampled fields in 2010, densities of bean leaf beetles were significantly larger in field edges than in field interiors. However, densities of this insect were never greater than 0.04 per sweep, and it is unlikely that they contributed to economically significant defoliation in the soybean fields sampled.

Densities of Japanese beetles estimated by both sweep samples and visual counts in soybean field edges next to corn were significantly greater than in soybean field edges next to other types of field borders (grass, road, soybean). This result suggests that Japanese beetles feeding in corn eventually move into soybean. Japanese beetles from cornfields are the likely source of significantly larger Japanese beetle densities at soybean field edges. Measuring the contribution of mate-finding activity to aggregation was not part of this study; however, some portion of significant edge abundance may be due to male orientation of females in soybean. Japanese beetles feed on a wide variety of plant hosts, so the nearness of corn and soybean fields throughout most of Illinois provides an ideal environment for their survival. The ubiquity of two Japanese beetle hosts in close proximity throughout much of Illinois provides an ideal setting for this pest to move

between and exploit both crops easily. Studying the movement and the sex of the movers would shed light on the contribution of reproductive behavior to edge abundance.

The observation that significantly fewer Japanese beetles were found in soybean field edges bordered by soybean is revealing. In a sense, the borders of adjacent soybean fields resemble the interior of a soybean field. The presence of fewer Japanese beetles in a field edge that borders soybean was similar to the observation that fewer Japanese beetles were present in field interiors than in field edges. Both sweep-net samples and visual counts provided evidence that densities of Japanese beetles in field edges bordered by soybean were similar to densities of Japanese beetles in soybean field interiors. Therefore, a break in vegetation is needed to classify the edge of a soybean field (e.g., corn, grass, or road).

I collected leaflets to estimate percentage defoliation in soybean field edges and interiors to understand the effect of Japanese beetle density on levels of soybean herbivory. However, in both 2009 and 2010, percentage defoliation in all soybean fields was low. In 2009, there was no significant effect of sample location (edge versus interior) on estimates of percentage defoliation in the four intensively sampled fields. Field edges had an average of 5.1% defoliation, whereas field interiors had an average of 3.06% defoliation. Although not significant, the differences in percentage defoliation between field edges and field interiors seemed to reflect that more Japanese beetles were found in field edges than in field interiors. In 2010, edges of soybean fields had an average of 4.7% defoliation, significantly more than the average of 2.38% defoliation in field interiors. Although the difference was significant, percentage defoliation in 2010, regardless of sample location in the field, was far below the economic threshold of 15 to

20% defoliation between bloom and pod fill that would warrant insecticide application (Steffey and Gray 2009).

The amount of soybean injury and corresponding densities of Japanese beetles that I observed while conducting this research suggest that some producers are initiating insecticide applications before treatment is warranted. Although densities of Japanese beetles were significantly greater in 2009 than in 2010, percentage defoliation was similar in both years and never exceeded the economic threshold. I observed low levels of injury caused by Japanese beetles, and there were no differences in yield associated with slight differences in injury. Therefore, my data suggest that greater densities of Japanese beetles and higher percentages of defoliation than what I observed would be needed to warrant insecticide application. An economic threshold of 15 to 20% defoliation between bloom and pod-fill would require 40 to 50 Japanese beetles per meter of soybean row (Figure 5, 2009, Figure 6, 2010).

Yields of soybean were not significantly different between soybean field edges and field interiors in 2009 and 2010. Based on densities of Japanese beetles, corresponding percentage defoliation, and no significant difference in yield, my observations showed that soybean plants can tolerate insect feeding. Although densities of Japanese beetles were consistently greater in soybean field edges than in field interiors, percentage defoliation did not differ greatly between field edges and interiors. Nor was a yield effect observed. Producers need to understand that a soybean plant's ability to compensate for some loss of foliage can offset the need for an insecticide application that is triggered by observations of leaf feeding injury.

Scouting for Japanese beetles in both soybean field edges and interiors is an essential practice in pest management. Japanese beetles tend to be aggregated in field edges, so scouting both field edges and interiors will give producers a more accurate representation of the distribution and population levels of Japanese beetles throughout a field. Soybean yield was not adversely affected by relatively low densities of Japanese beetles and percentage defoliation, so the need for insecticide application was not apparent. Sampling only along field edges likely will result in an overestimation of Japanese beetle density in a field, which might persuade producers to make an unwarranted insecticide application. Results from scouting both field edges and interiors might enable producers to target insecticide applications only in field edges, thereby saving time and money.

Management decisions can be formed from estimating Japanese beetle densities by both sweep-net samples and visual counts of Japanese beetles per meter of soybean row. Visual counts give producers a more convenient and quicker approach for understanding Japanese beetle densities. Visual counts would enable producers to sample many locations quickly to gain a representation of Japanese beetle populations within a soybean field. Greater knowledge of pest densities, especially Japanese beetles, in different locations within soybean fields would improve a producer's ability to manage insects effectively while holding true to integrated pest management (IPM) principles.

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Table 1. Mean number of Japanese beetles ± SE and mean comparisons by sample location for intensively sampled soybean fields, 2009 and 2010

Year		2009			2010	
Sample location	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
Interior	125	0.28 ± 0.03 b	2.06 ± 0.27 a	143	0.09 ± 0.01 a	0.50 ± 0.09 a
Edge	126	1.09 ± 0.20 a	6.19 ± 0.93 a	144	0.27 ± 0.04 a	0.72 ± 0.14 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 2. Mean number of insects per sweep ± SE and mean comparisons by sample location for intensively sampled soybean fields, 2009 and 2010

Year		2009			2010		
Location	*n*	Bean leaf beetle	Grasshoppers	Soybean looper	*n*	Bean leaf beetle	Grasshoppers	Soybean looper
Interior	125	0.03 ± 0.01 a	0.00 ± 0.00 a	0.01 ± 0.00 a	143	0.02 ± 0.00 b	0.00 ± 0.00 a	0.04 ± 0.01 a
Edge	126	0.02 ± 0.00 a	0.01 ± 0.00 a	0.01 ± 0.00 a	144	0.03 ± 0.01 a	0.01 ± 0.00 a	0.03 ± 0.00 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 3. Mean number of Japanese beetles ± SE and mean comparisons by field border for intensively sampled soybean fields, 2009 and 2010

Year	2009			2010		
Field border	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
Corn	58	1.48 ± 0.38 a	8.69 ± 1.72 a	84	0.34 ± 0.06 a	0.82 ± 0.18 a
Grass	32	1.24 ± 0.36 b	5.69 ± 1.64 b	0[a]	---	---
Road	24	0.28 ± 0.05 c	2.29 ± 0.62 b	48	0.22 ± 0.03 a	0.73 ± 0.25 a
Soybean	137	0.29 ± 0.03 c	2.17 ± 0.27 b	155	0.08 ± 0.01 b	0.46 ± 0.08 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

[a]No samples were taken next to grass.

Table 4. Mean number of insects per sweep ± SE and mean comparisons by field border for intensively sampled soybean fields, 2009 and 2010

Year	2009				2010			
Field border	*n*	Bean leaf beetle	Grasshoppers	Soybean looper	*n*	Bean leaf beetle	Grasshoppers	Soybean looper
Corn	58	0.02 ± 0.01 a	0.02 ± 0.00 a	0.00 ± 0.00 a	84	0.02 ± 0.01 a	0.01 ± 0.00 a	0.02 ± 0.00 a
Grass	32	0.01 ± 0.00 a	0.01 ± 0.00 ab	0.01 ± 0.00 a	0[a]	---	---	---
Road	24	0.05 ± 0.01 a	0.01 ± 0.00 a	0.01 ± 0.00 a	48	0.02 ± 0.01 a	0.01 ± 0.00 a	0.03 ± 0.01 a
Soybean	137	0.03 ± 0.01 a	0.00 ± 0.00 b	0.01 ± 0.00 a	155	0.02 ± 0.00 a	0.00 ± 0.00 a	0.04 ± 0.01 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

[a]No samples were taken next to grass.

Table 5. Percentage defoliation ± SE, yield ± SE, and mean comparisons by sample location for intensively sampled soybean fields, 2009 and 2010

Year	2009		2010	
Sample location	Defoliation (%)[a]	Yield (bu/acre)[b]	Defoliation (%)[c]	Yield (bu/acre)[d]
Interior	3.10 ± 0.25 a	60.76 ± 0.79 a	2.38 ± 0.17 b	71.46 ± 0.93 a
Edge	5.06 ± 0.44 a	58.46 ± 0.97 a	4.07 ± 0.28 a	68.70 ± 0.94 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.
[a]For interior, $n = 125$; for edge, $n = 126$.
[b]For interior, $n = 35$; for edge, $n = 36$. Data were not transformed.
[c]For interior, $n = 143$; for edge, $n = 144$.
[d]For interior, $n = 30$; for edge, $n = 30$. Data were not transformed.

Table 6. Percentage defoliation ± SE, yield ± SE, and mean comparisons by field border for intensively sampled soybean fields, 2009 and 2010

Year	2009		2010	
Field border	Defoliation (%)[a]	Yield (bu/acre)[b]	Defoliation (%)[c]	Yield (bu/acre)[d]
Corn	5.89 ± 0.80 a	59.86 ± 1.41 a	3.88 ± 0.36 a	69.16 ± 1.74 a
Grass	5.10 ± 0.76 b	55.48 ± 1.86 b	---	---
Road	3.71 ± 0.62 b	61.07 ± 2.12 a	3.89 ± 0.43 a	68.01 ± 1.78 a
Soybean	3.15 ± 0.24 b	60.44 ± 0.75 ab	2.67 ± 0.20 a	71.46 ± 0.93 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.
[a]For corn, $n = 58$; for grass, $n = 32$; for road, $n = 24$; for soybean, $n = 137$.
[b]For corn, $n = 16$; for grass, $n = 11$; for road, $n = 6$; for soybean, $n = 38$. Data were not transformed.
[c]For corn, $n = 84$; for grass, $n = 0$; for road, $n = 48$; for soybean, $n = 155$.
[d]For corn, $n = 18$; for road, $n = 12$; for soybean, $n = 30$. Data were not transformed.

Table 7. Mean number of Japanese beetles ± SE and mean comparisons by week for intensively sampled soybean fields, 2009

Week	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
One	72	1.51 ± 0.34 a	8.18 ± 1.53 a
Two	72	0.45 ± 0.06 a	3.42 ± 0.52 a
Three	54	0.38 ± 0.05 a	1.93 ± 0.41 a
Four	53	0.20 ± 0.02 a	1.87 ± 0.32 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $n = 251$, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 8. Mean number of Japanese beetles ± SE and mean comparisons by week for intensively sampled soybean fields, 2010

Week	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
One	71	0.07 ± 0.01 a	0.31 ± 0.09 a
Two	72	0.14 ± 0.02 a	0.33 ± 0.09 a
Three	72	0.24 ± 0.06 a	1.53 ± 0.26 a
Four	72	0.27 ± 0.05 a	0.26 ± 0.09 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $n = 287$, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 9. Mean number of Japanese beetles ± SE and mean comparisons by sample location for all sampled soybean fields, 2009 and 2010

Year	2009			2010		
Sample location	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
Interior	385	0.30 ± 0.03 b	1.95 ± 0.16 b	311	0.11 ± 0.01 a	0.46 ± 0.06 a
Edge	386	1.06 ± 0.12 a	5.59 ± 0.52 a	301	0.35 ± 0.03 a	0.99 ± 0.12 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 10. Mean number of insects per sweep ± SE and mean comparisons by sample location for all sampled soybean fields, 2009 and 2010

Year	2009				2010			
Sample location	*n*	Bean leaf beetle	Grasshoppers	Soybean looper	*n*	Bean leaf beetle	Grasshoppers	Soybean looper
Interior	385	0.02 ± 0.00 a	0.00 ± 0.00 a	0.01 ± 0.00 a	311	0.04 ± 0.01 a	0.00 ± 0.00 a	0.04 ± 0.00 a
Edge	386	0.02 ± 0.00 a	0.01 ± 0.00 a	0.01 ± 0.00 a	301	0.03 ± 0.00 a	0.01 ± 0.00 a	0.03 ± 0.00 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 11. Mean number of Japanese beetles ± SE and mean comparisons by field border for all sampled soybean fields, 2009 and 2010

Year	2009			2010		
Field border	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row	*n*	Mean no. Japanese beetles per sweep	Mean no. Japanese beetles per meter of row
Corn	149	1.71 ± 0.28 a	8.40 ± 1.11 a	142	0.43 ± 0.05 a	1.27 ± 0.20 a
Grass	116	0.78 ± 0.15 b	4.31 ± 0.71 b	48	0.31 ± 0.07 a	0.98 ± 0.35 a
Road	92	0.51 ± 0.15 b	2.96 ± 0.54 b	69	0.38 ± 0.07 ab	0.97 ± 0.23 ab
Soybean	414	0.33 ± 0.03 b	2.13 ± 0.18 b	353	0.10 ± 0.01 c	0.41 ± 0.06 b

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 12. Mean number of insects per sweep ± SE and mean comparisons by field border for all sampled soybean fields, 2009 and 2010

Year	2009				2010			
Field border	*n*	Bean leaf beetle	Grasshoppers	Soybean looper	*n*	Bean leaf beetle	Grasshoppers	Soybean looper
Corn	149	0.03 ± 0.01 a	0.02 ± 0.00 a	0.01 ± 0.00 a	142	0.02 ± 0.00 b	0.01 ± 0.00 a	0.03 ± 0.00 a
Grass	116	0.02 ± 0.01 a	0.00 ± 0.00 b	0.01 ± 0.00 a	48	0.04 ± 0.01 a	0.01 ± 0.00 a	0.02 ± 0.01 b
Road	92	0.03 ± 0.01 a	0.01 ± 0.00 b	0.01 ± 0.00 a	69	0.03 ± 0.01 b	0.01 ± 0.00 a	0.02 ± 0.01 ab
Soybean	414	0.02 ± 0.00 a	0.00 ± 0.00 b	0.01 ± 0.00 a	353	0.04 ± 0.01 ab	0.00 ± 0.00 a	0.04 ± 0.00 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Data were analyzed using a log transformation; actual means and standard errors are shown.

Table 13. Yield ± SE and mean comparisons by sample location for all sampled soybean fields, 2009 and 2010

Year		2009		2010
Location	*n*	Yield (bu/acre)	*n*	Yield (bu/acre)
Interior	168	59.48 ± 0.47 a	136	68.13 ± 0.70 a
Edge	170	58.65 ± 0.55 a	130	65.22 ± 0.76 b

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Actual means and standard errors are shown.

Table 14. Yield ± SE and mean comparisons by field border for all sampled soybean fields, 2009 and 2010

Year		2009		2010
Field border	*n*	Yield (bu/acre)	*n*	Yield (bu/acre)
Corn	73	58.12 ± 0.76 b	59	67.06 ± 1.07 a
Grass	50	57.13 ± 0.99 c	28	60.06 ± 2.01 b
Road	33	60.72 ± 1.53 a	22	66.71 ± 1.19 a
Soybean	182	59.66 ± 0.45 ab	157	67.76 ± 0.64 a

Means in the same column and followed by the same letter do not differ significantly (PROC MIXED, $P < 0.10$). Actual means and standard errors are shown.

FIGURES

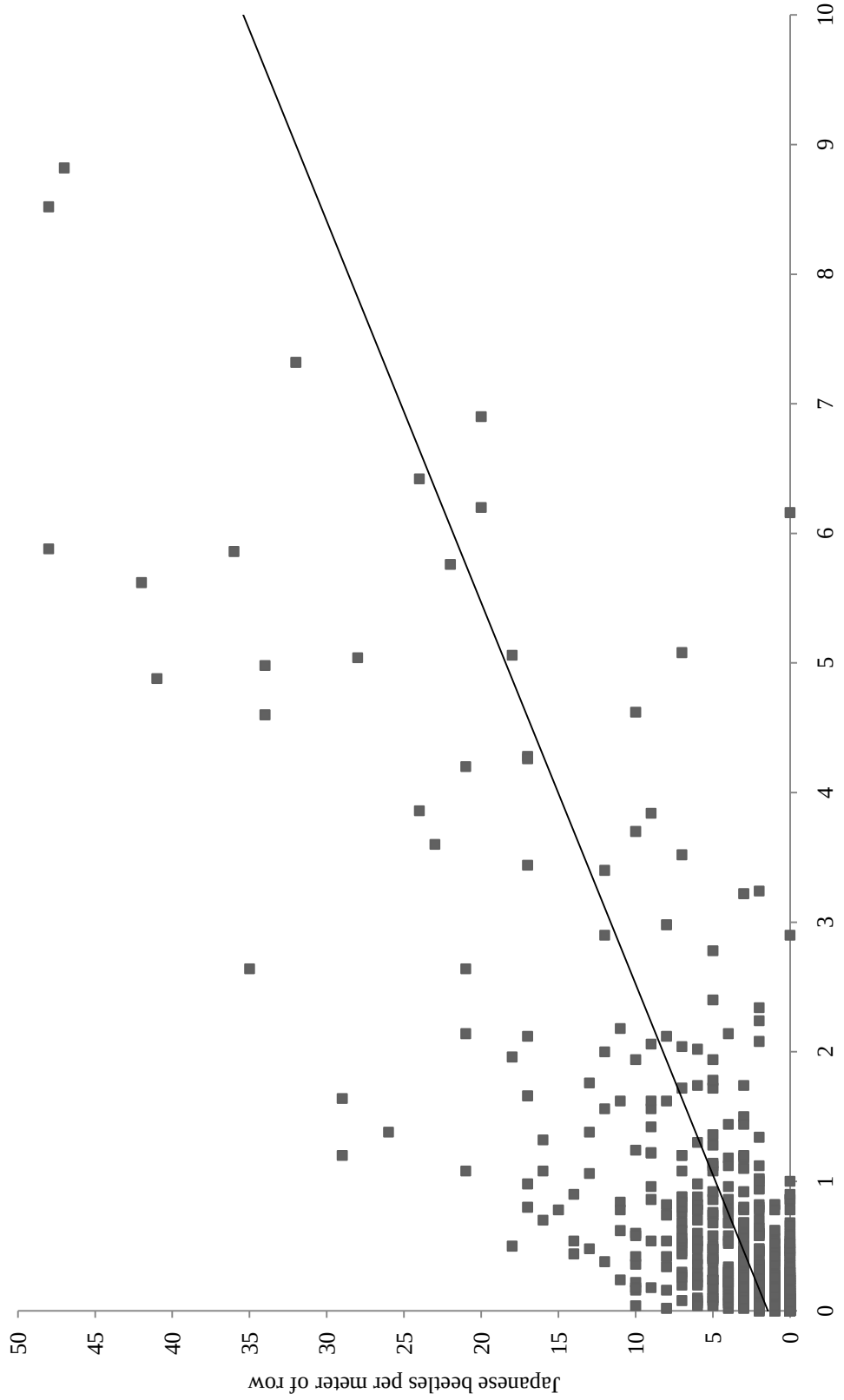

Figure 1. Regression between densities of Japanese beetles estimated by sweep-net samples and visual counts in Illinois soybean fields, 2009. Data were analyzed using a log transformation; actual values are shown (PROC REG, $n = 771$, $R^2 = 0.6180$, $F = 1{,}244.05$, $P < 0.0001$).

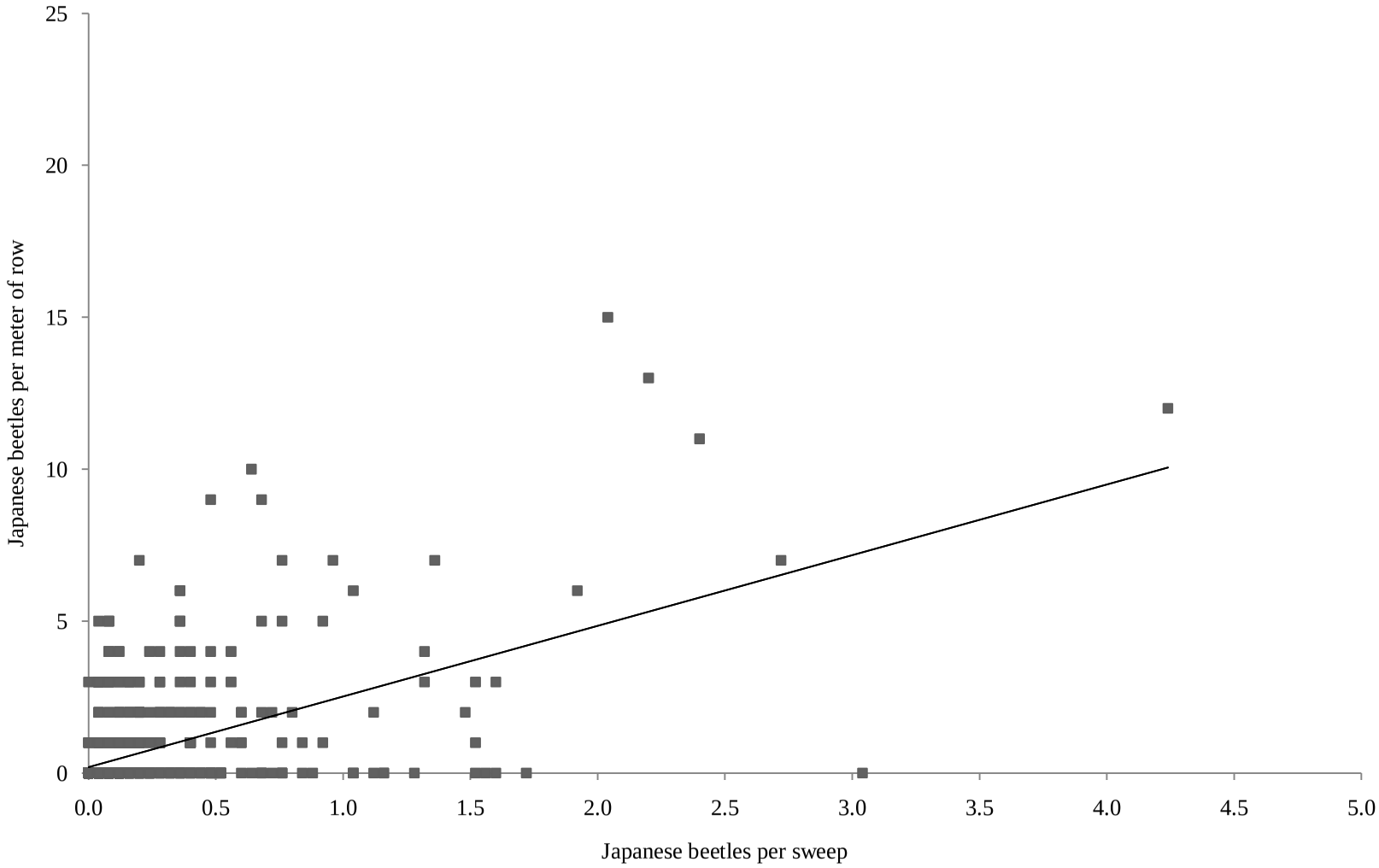

Figure 2. Regression between densities of Japanese beetles estimated by sweep-net samples and visual counts in Illinois soybean fields, 2010. Data were analyzed using a log transformation; actual values are shown (PROC REG, $n = 621$, $R^2 = 0.2220$, $F = 176.61$, $P < 0.0001$).

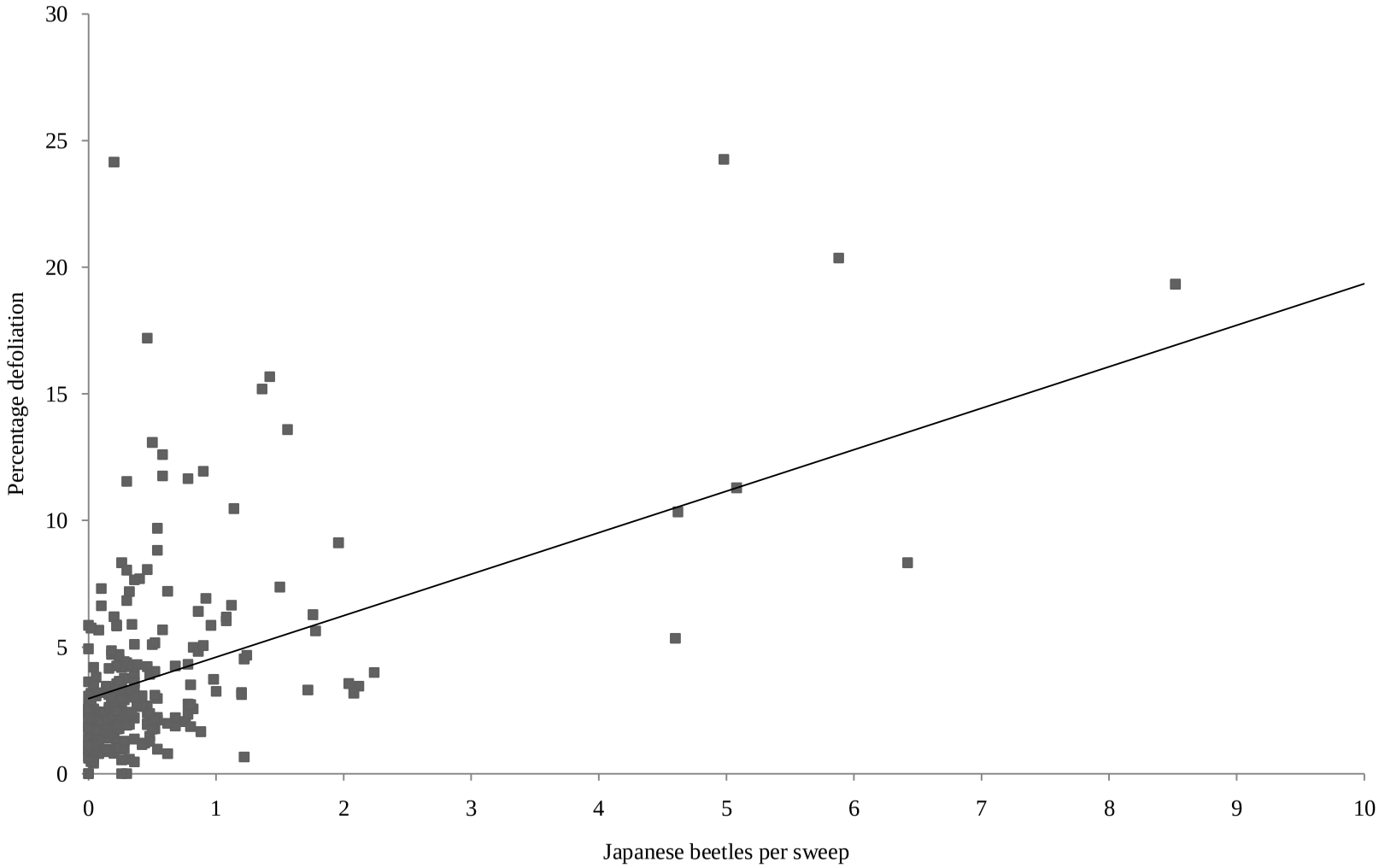

Figure 3. Regression between densities of Japanese beetles per sweep and percentage defoliation in Illinois soybean fields, 2009. Data were analyzed using a log transformation; actual values are shown (PROC REG, n = 251, R^2= 0.3782, F = 151.47, P < 0.0001).

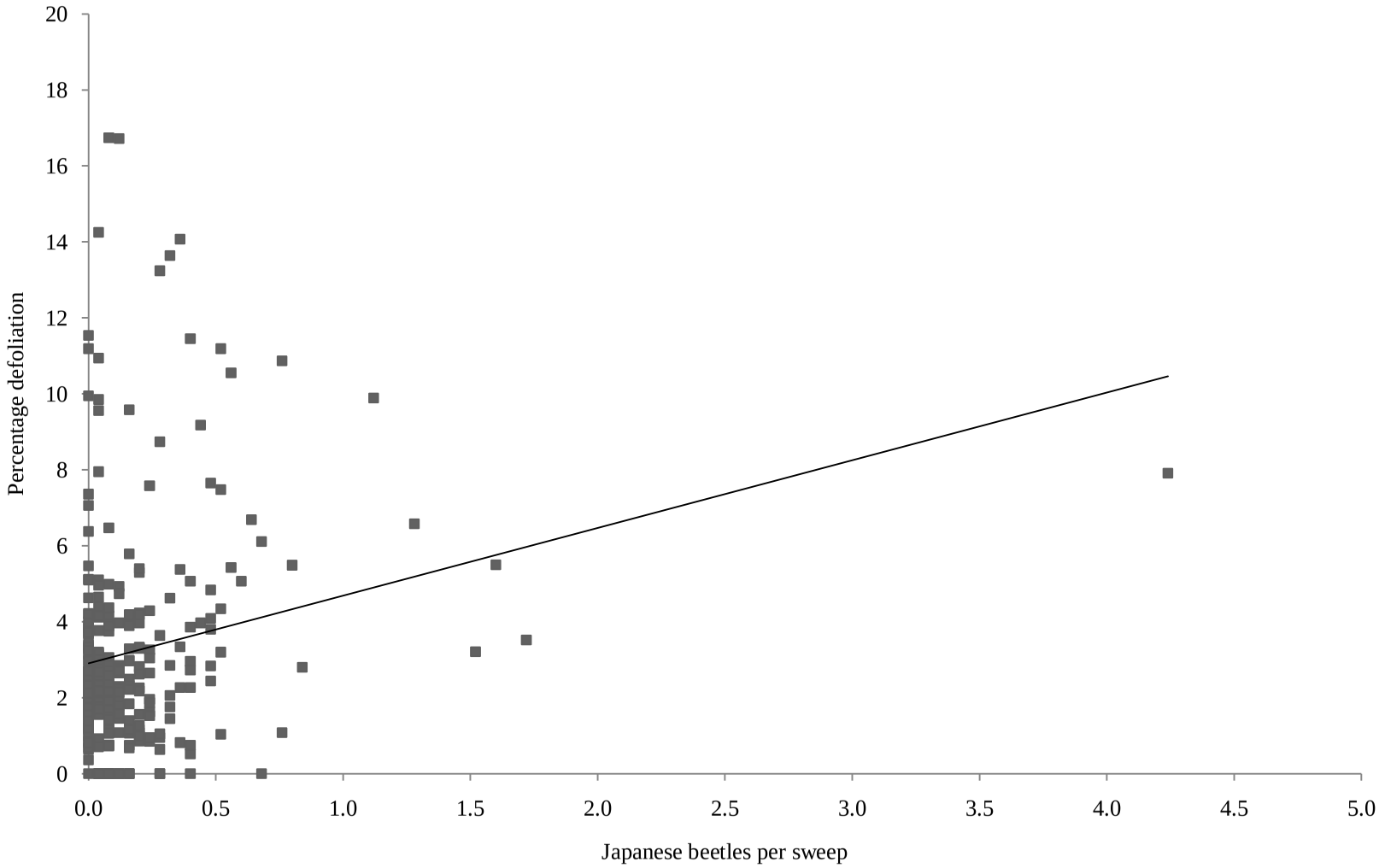

Figure 4. Regression between densities of Japanese beetles per sweep and percentage defoliation in Illinois soybean fields, 2010. Data were analyzed using a log transformation; actual values are shown (PROC REG, $n = 287$, $R^2 = 0.0501$, $F = 15.02$, $P = 0.0001$).

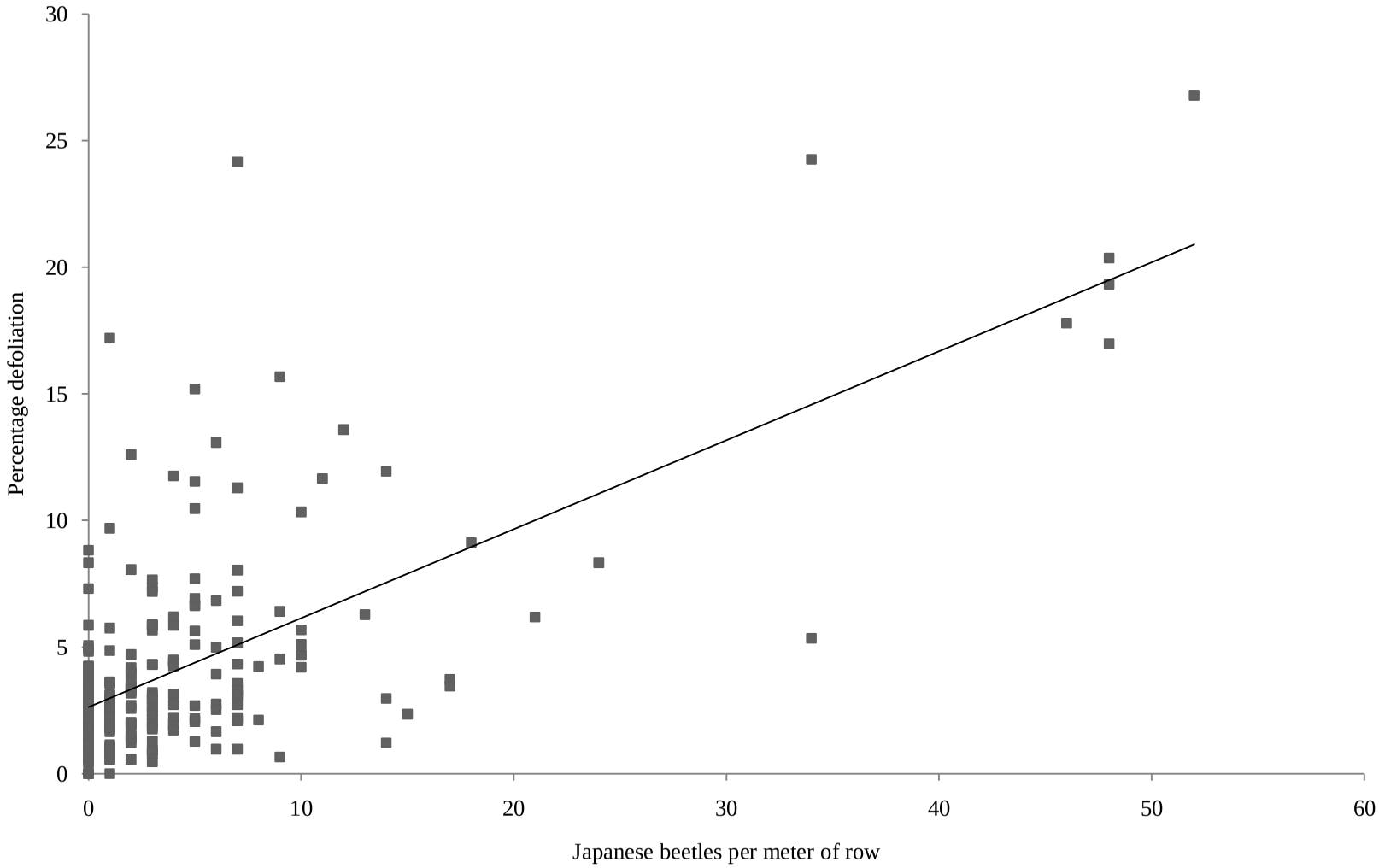

Figure 5. Regression between Japanese beetles per meter of row and percentage defoliation in Illinois soybean fields, 2009. Data were analyzed using a log transformation; actual values are shown (PROC REG, $n = 251$, $R^2 = 0.4102$, $F = 173.21$, $P < 0.0001$).

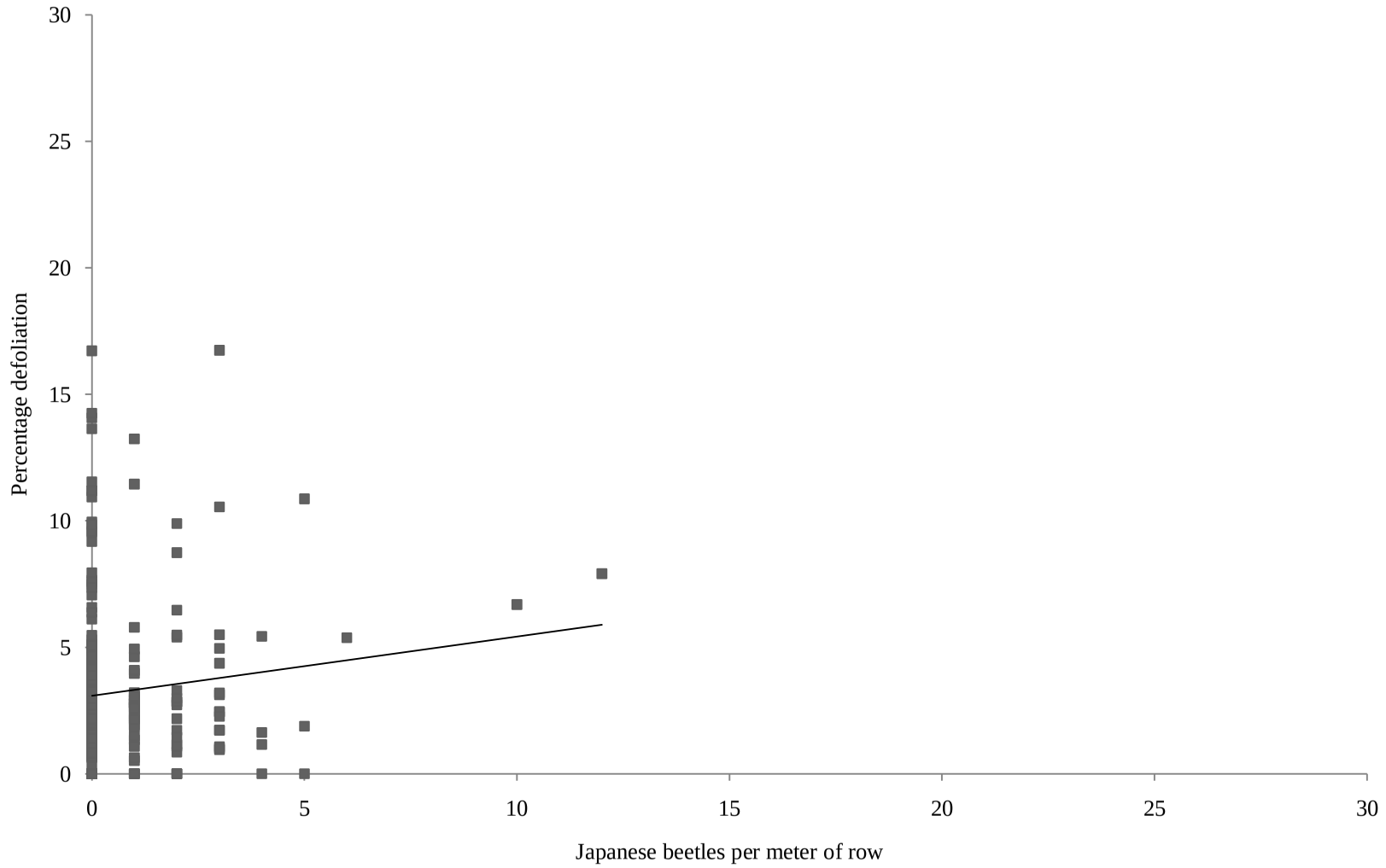

Figure 6. Regression between Japanese beetles per meter of row and percentage defoliation in Illinois soybean fields, 2010. Data were analyzed using a log transformation; actual values are shown (PROC REG, $n = 287$, $R^2 = 0.0105$, $F = 3.03$, $P = 0.0827$).

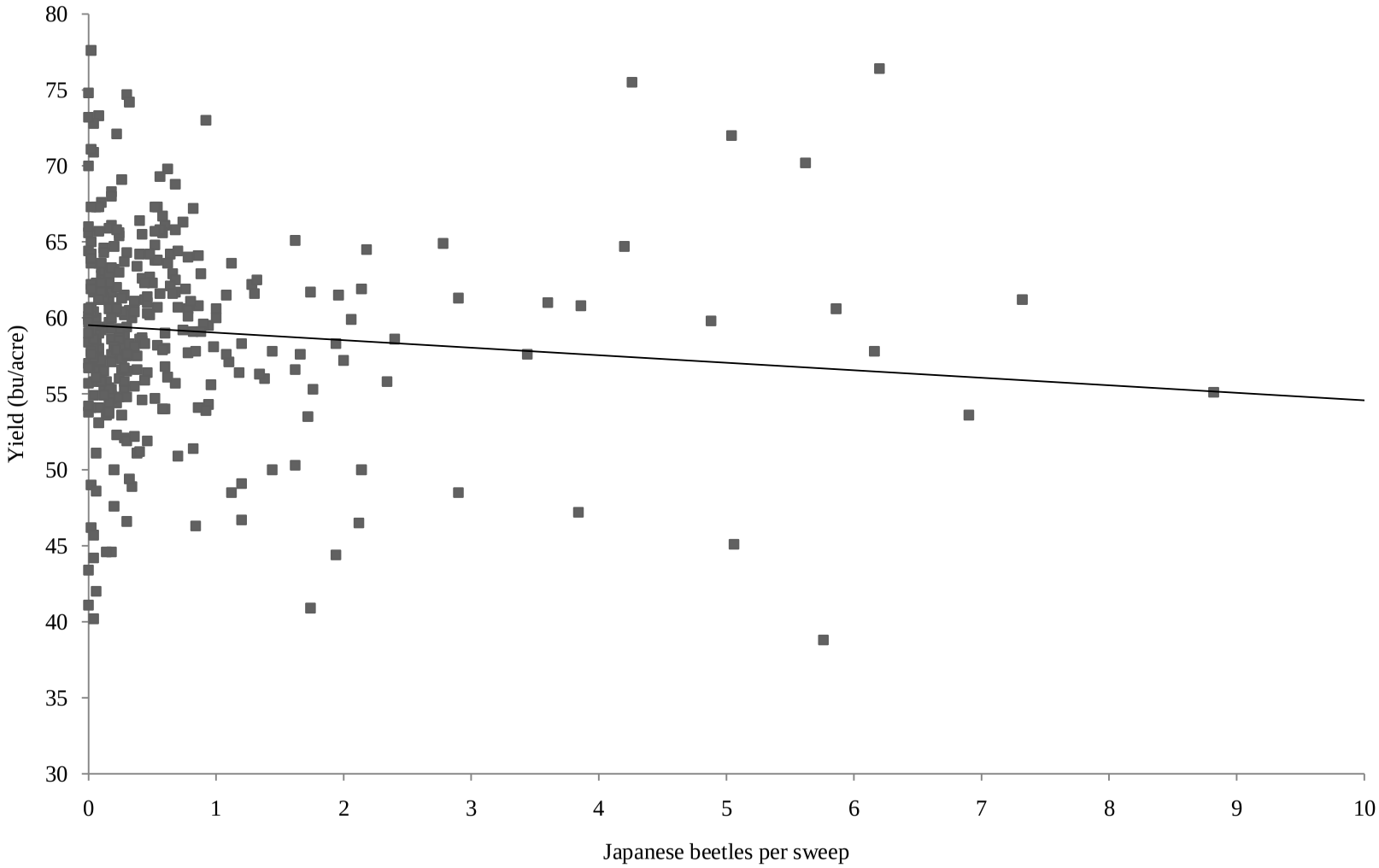

Figure 7. Regression between densities of Japanese beetles per sweep and yield in Illinois soybean fields, 2009. Densities of Japanese beetles were analyzed using a log transformation; yield data were not transformed. Actual values are shown (PROC REG, $n = 338$, $R^2 = 0.0117$, $F = 3.96$, $P = 0.0474$).

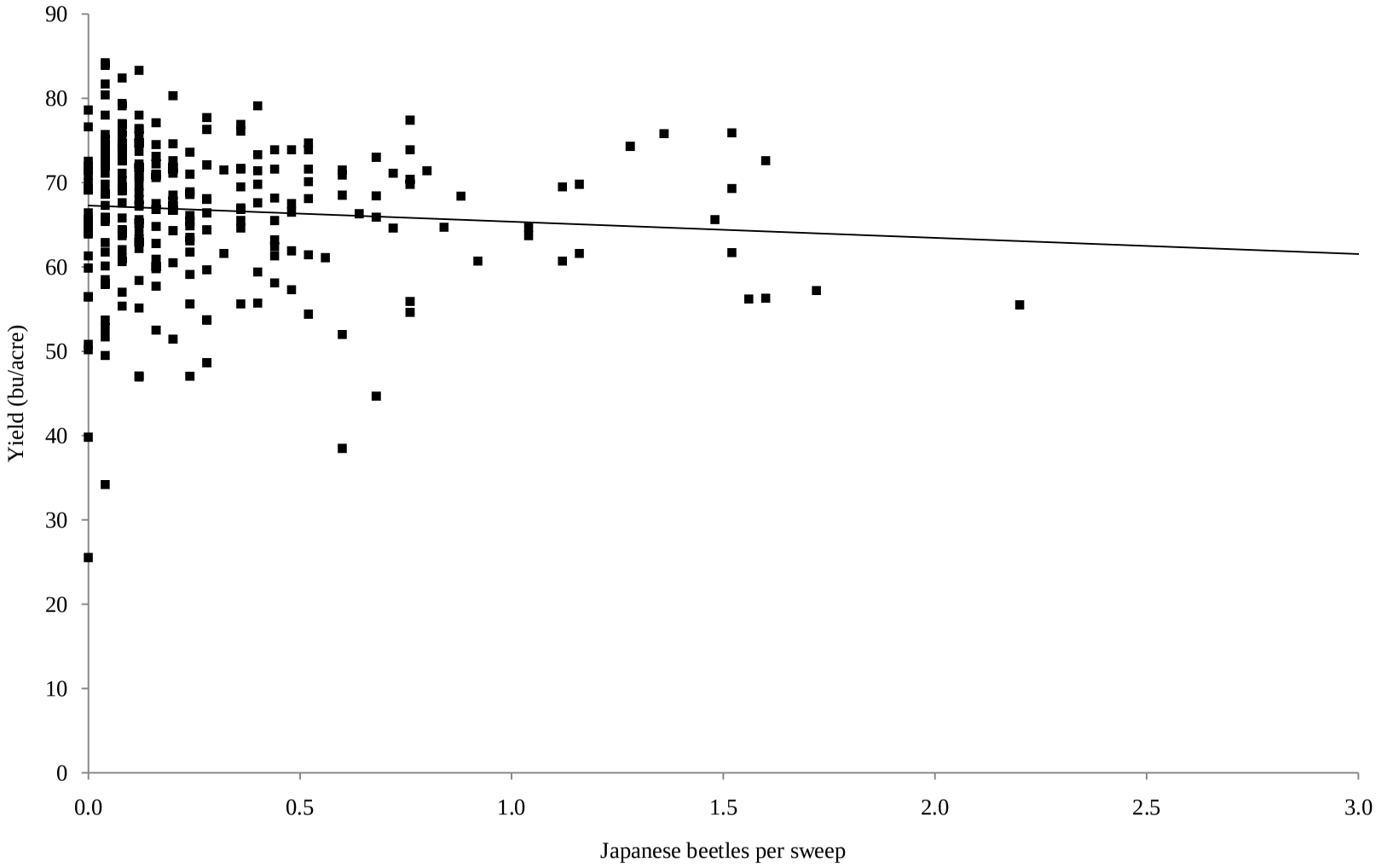

Figure 8. Regression between densities of Japanese beetles per sweep and yield in Illinois soybean fields, 2010. Densities of Japanese beetles were analyzed using a log transformation; yield data were not transformed. Actual values are shown (PROC REG, $n = 266$, $R^2 = 0.0066$, $F = 1.75$, $P = 0.1867$).