INTEGRATING PEST AND POLLINATOR MANAGEMENT: ASSESSING THE IMPACT OF COMMERCIAL WATERMELON PRODUCTION ON PESTS AND POLLINATORS

by

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To all those that made my time at Purdue so enjoyable, I am ever grateful.

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ABSTRACT

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Fruit set in cucurbit crops such as watermelon is entirely dependent upon pollinators, which makes them an important aspect of grower management. This reliance on pollinators means that growers must consider them when making pest management decisions, especially when using pesticides, which can have a negative impact on pollinators. Thus, pest management in watermelon production faces a potential trade-off between pests and pollinators. The ways in which growers manage this trade-off could have a large impact on the communities of both groups and the yield of the crop. During the 2017 and 2018 growing seasons, I worked with 16 commercial watermelon growers on 30 fields in Indiana and Illinois. Each of these growers implemented unique strategies for pest and pollinator management. I set out to investigate pest management practices, how to better implement integrated pest and pollinator management, and how these management impacts pest and pollinator communities and grower outcomes. A diverse array of pollinators was identified, with communities being highly variable between sites. Fields that were treated with insecticides had both lower pest densities as well as native pollinator visitation than those that were not. Bee species richness was best predicted by pest densities, not management variables such as toxicity or number of insecticide applications. Despite the variation in management, no field ever exceeded the economic threshold. The implementation of integrated pest and pollinator management (IPPM) practices such as, scouting methodology, and increased pest tolerance could decrease insecticide use in commercial watermelon production. This has the potential to decrease

non-target impacts on pollinators and could lead to greater pollinator diversity and improved fruit set.

INTRODUCTION

Insect management is among the most important decisions farmers must grapple with for effective crop production. Insect pests can reduce crop yield through direct damage and by vectoring diseases, while beneficial insects can increase yield through pollination and predation of pests. Insecticides are frequently used to control pests but could negatively impact beneficial insects such as pollinators. This creates a trade-off that growers must navigate to maximize yields. The potential loss of pollination could outweigh the benefits of insecticide use to control pests. This is especially true in crops which are tolerant to pest damage and resistant to insect vectored diseases.

Integrated Pest Management (IPM) is a holistic set of tools used to manage pests in an ecologically and economically sustainable manner (Stern et al. 1959, Smith 1962, Geier 1966, Pedigo 1989, Higley & Wintersteen 1996). IPM has historically considered environmental factors such as conserving beneficial insects like pollinators. Recently, however, the communication and application of IPM strategies has not sufficiently included environmental sustainability such as pollinator management (Peterson et al. 2018). The pest control component of IPM has been elevated to be the focal point of management rather than an aspect of the overall management plan for the system (Peterson et al. 2018). Due to the emphasis on pest control and the reduction of environmental sustainability considerations in modern IPM, I will use the term integrated pest and pollinator management (IPPM) to highlight the re-integration of this approach. IPPM is a strategy that considers pollinator health along with integrated pest management strategies which are used to comprehensively reduce pest insects to avoid economic damage (Stern et al. 1959, Smith 1962, Geier 1966, Pedigo 1989, Higley & Wintersteen 1996). The addition of the word pollinator emphasizes the crucial role that pollinators play in many agricultural settings, the importance of using management strategies which prioritize pollinators, and fits in with the increasing level of concern surrounding them. IPPM includes traditional methods of pest scouting, cultural pest control, and even insecticidal treatment, but only when necessary, but incorporates pollinator habitat preservation and timing of applications to minimize pollinator exposure. Widespread adoption of IPPM has the potential to increase yield and prioritize pollinators in agricultural settings. Research in cantaloupe shows that IPM increases yield compared to the conventional prophylactic insecticide pest management strategy (Brust et al. 1996, Brust & Foster 1999). This research indicates that the costs associated with excessive insecticide treatments are greater than their benefits. It is not yet clear why IPM increases yield, but increased fruit set due to improved pollination may play a role (Stanley et al. 2015). Adoption of IPPM amongst watermelon growers is expected to maximize profits by balancing the trade-off between pest management and managing pollinators.

The improved yield in IPM that was observed in cantaloupe could also occur in other closely related crops. Watermelon is not susceptible to the damaging bacterial wilt (*Erwinia tracheiphila*) that affects other Cucurbitaceae crops and is vectored by pests but are tolerant to yield loss due to pest damage (Foster 2016). Watermelon fruit set is also entirely dependent upon successful pollination (Adlerz 1966, Walters 2005). These factors make watermelon a great model crop for exploring the trade-offs between pest and pollinator management. Currently, watermelon growers are using a variety of management strategies ranging from organic production to prophylactic insecticide treatment. Each of these management strategies offer costs and benefits that could influence yield. If pest management using insecticides is too intensive, growers risk harming beneficial insects. If pest management is insufficient, growers may experience yield losses due to pest damage. The primary goal of this study is to identify pest management strategies in watermelon crops which allow for successful pest suppression while minimizing insecticide exposure to pollinators. I predict that Indiana watermelon growers are applying neonicotinoids and other insecticides when insect pest densities are lower than economic thresholds (ET) resulting in unnecessary non-target pollinator exposure. The ET is a defined pest density at which growers have been advised to treat with insecticides to prevent pests from reaching densities that would cause economic injury. Applications below ET's are unlikely to provide any yield benefits as a result of pest suppression. If this prediction is correct, then there may be room for growers to reduce insecticide inputs, lowering the risk of pollinator exposure while protecting yields.

I set out to better understand current grower management practices and the potential benefits when implementing IPPM principles. To do this, I focused on how a variety of management practices impact cucumber beetle populations and pollinator visitation, species richness, and pollination. Examining these dynamics across an axis of management such as pesticide input and pesticide residues in plant tissue and soil will allow us to identify and implement IPPM strategies. the goal is to prioritize pollinator health while maintaining pest populations below damaging densities.

LITERATURE REVIEW

Watermelon Production

Watermelon is a crop in the family Cucurbitaceae, which includes other economically important crops such as cucumber, squash, pumpkin, and muskmelon. Indiana is consistently among the top watermelon producing states in the U.S. (USDA-NASS 2017). The importance of this crop is especially evident in southwestern Indiana where watermelon production is highest in the state. The production of fruit in watermelon is entirely dependent upon pollinators transferring pollen from male flowers to the stigma of female flowers (Adlerz 1966, Walters 2005). When pollination occurs, and the female flower is fertilized, the small ovary beneath the flower sets fruit. A greater number of pollinator visits has been shown to linearly increase percent fruit set, number of fruits, and fruit weight (Walters 2005). Seedless varieties of watermelon are commonly grown due to market preference. This complicates the pollination of watermelons because it introduces a reliance on cross-pollination (Maynard & Elmstrom 1992, NeSmith & Duval 2001). Seedless varieties of watermelon are triploid and do not produce viable pollen but still require viable pollen for the fertilization of female flowers and fruit set (Maynard & Elmstrom 1992, NeSmith & Duval 2001). Seeded diploid varieties of watermelon with viable pollen must be intercropped with the more marketable seedless varieties (Maynard & Elmstrom 1992). These plants are called pollenizers and while they are still capable of producing fruit, that fruit is not as marketable as seedless fruit. Pollenizer plants are recommended to make up between a quarter and a third of the watermelon plants in a field to ensure sufficient cross pollination (NeSmith & Duval 2001).

Watermelon is an ideal crop to evaluate the intersection between insecticide use, pest populations, and pollinator health. Watermelon is a high value specialty crop that has a low tolerance for insect damage in the market. The high value and low tolerance have led to intensive pest management by growers. The system is further complicated by the important role that pollinators play in fruit set of watermelon. Growers understand this reliance on pollinators and attempt to maximize pollination. Managed honey bee hives are commonly placed in and around watermelon fields to improve fruit set. Growers have also begun to place commercially available bumble bee colonies (*Bombus impatiens*) throughout their fields. This practice is supported by research that shows bumble bees can more effectively pollinate watermelon compared to honey bees (Stanghellini et al. 1998). Native unmanaged species are also more efficient watermelon pollinators on a per bee basis (Goodell & Thomson 2007, Winfree et al. 2008, Garibaldi et al. 2013). Increased knowledge on the value of pollinators and the impacts of crop management on pollinators could lead to the development of improved management through IPPM principles.

Pollinators

Pollinators are among the most important factors in the reproduction of flowering plants. Pollination is essential in agriculture, with 35% of crops being dependent on pollinators (Klein et al. 2017). Honey bees (*Apis mellifera* L.) alone account for $15 billion of agricultural production due to pollination every year in the U.S. (Morse & Calederone 2000). When native pollinators are considered that figure becomes even larger. Because of this incredible value, pollinators are an important aspect of the management decisions of all farmers and must be considered, effectively deployed, and managed. This knowledge has placed a spotlight on pollinators that has led to increased interest and research into optimizing pollination and devising strategies that can be implemented to do so. The two approaches to optimizing pollination in a particular commodity are through increasing the densities of managed species and making agricultural habitats more favorable for wild pollinators.

Honey Bees (Apis mellifera)

The European honey bee (*Apis mellifera*) is among the most important, valuable, and charismatic insect species in the world. However, it is not native to the Americas. Honey bees were brought to the U.S. as a managed species valued for their honey production as early as the 1600's (Whitfield et al. 2006). The European honey bee is the only species of honey bee in the U.S. and are of great importance due to their pollination services in agricultural commodities. As a managed species, which forms large colonies, they are effective pollinators that can be easily moved for crop pollination. This, along with honey production, has created a large and economically important beekeeping industry in the U.S. that has complimentary but often competing interests with farmers. The management of honey bees means that growers and beekeepers can find themselves at odds when it comes to crop management (Krupke & Long 2015). Pest management decisions could have an impact on the bees, which could lead to colony death and reduced pollination services and honey production (Di Prisco et al. 2013, Goulson et al. 2015). This relationship has been a large factor in the increased adoption of IPPM principles. Honey bees are highly eusocial, which means that they form large colonies with most individuals acting as workers while one queen bee is responsible for all reproduction. Because of this life history, honey bee colonies can be as large as 30,000 individuals that perform specialized tasks such as nursing, guarding, thermoregulation, and foraging (Winston 1991). The primary food resources for honey bees are pollen and nectar from flowering plants (Winston 1991). These large colonies require a great deal of workers to collect these resources and thus make great pollinators. Growers recognize the value that honey bees play in production, making them the most widely managed pollinator species in the world. Individual colonies are often transported across the country to meet crucial periods for pollination in a wide variety of crops. Thus, honey bees are also the most widely studied insect pollinator.

Native Pollinators and Managed Bumblebees

Many other species of insect pollinators also have large economic impacts but are far less studied (Garibaldi et al. 2013, Hopwood et al. 2016). There are ca. 3,500 species of native bees in the U.S., ranging from bumble bees that form colonies, to solitary ground nesting bees. Despite being underappreciated and underrepresented in the scientific literature, many crops rely more heavily on native bees and flies for pollination than managed honey bees (Kremen et al. 2002, Goodell & Thomson 2007, Winfree et al. 2007, Winfree et al. 2008, Garibaldi et al. 2013, Hopwood et al. 2016). In systems that are highly dependent upon pollination, honey bees contribute less to fruit-set than do native pollinators (Winfree et al. 2007, Garibaldi et al. 2013). Along with the improved efficiency of native pollinators, greater species richness of pollinators provides enhanced pollination in many agricultural crops (Garibaldi et al. 2014). When both honey bees and other insect pollinators are present there is an additive effect that improves pollination (Garibaldi et al. 2013). In fact, managed honey bee colonies alone should not be relied upon to replace the pollination of other insects (Garibaldi et al. 2013). Reliance on honey bees alone introduces greater vulnerability in pollination services due to environmental factors as well as pathogens and parasites that threaten the sustainability of a single pollinator (Rader et al. 2013). The value and efficiency of native pollinators highlights the importance for the agricultural industry to protect the health of all insect pollinators.

Unlike honey bees, many native bees are solitary or primitively eusocial. This means that individuals are either alone or part of much smaller social groups (Goulson 2003). Native pollinators could be more vulnerable to risks as a result of their reduced social group size. The loss of an individual female solitary bee represents the loss of a reproductive individual and all the progeny she may have produced. Native pollinators must perform all the tasks that a honeybee colony perform with far fewer individuals. Reproductive individuals must found nests and forage, which are among the most dangerous activities for pollinators (Goulson 2003). When completing these tasks, individuals can encounter deadly insecticides, predators, pathogens, and risk getting lost (Goulson et al. 2015, Klein et al. 2017). This increased sensitivity to reproductive individuals and the lack of management and support by beekeepers makes the threat to native pollinators even greater. It is far more difficult to assess native pollinator populations and the impact of risks from insecticides, pathogens, and predators due to their smaller colonies or solitary lifestyle and hard to locate nests. Despite the important role native pollinators play in crop pollination, they are not frequently considered in grower management decisions (Kremen et al. 2002, Winfree et al. 2008). To reduce our reliance on a single pollinating species, we need to better understand the impacts of agricultural practices on our native pollinator species.

One native pollinator, the common eastern bumblebee (*Bombus impatiens*) is effective at pollinating many important crops, including watermelon and blueberry (Stanghellini et al. 1998, Stubbs & Drummond 2001, Winfree et al. 2007, Campbell et al. 2018). It is also the first species native to the U.S. that has been successfully reared and managed for pollination services. Colonies of *B. impatiens* are reared year-round by two commercial suppliers, purchased by growers and placed near crops to aid in pollination. This has become a popular option for growers, especially those in unique systems such as greenhouse production, which cannot rely on native pollinators. Managed *B. impatiens* colonies are also a good tool for researchers to better understand the impacts that agricultural settings can have on native pollinators. Like any managed species, they cannot be used to generalize for all native pollinators or even wild bumblebees. They do, however, represent a middle ground between these many species and the honey bees, which have frequently been used to approximate native pollinators in the past. Despite the popularity of managed *B. impatiens* colonies, little is known about the impact these colonies can have on pollination and fruit set or the necessary stocking rates and economic benefits of increased pollination. For these reasons, the managed *B. impatiens* colonies are a good option for growers that are looking to optimize pollination but cannot be used as a replacement for native pollinators.

Pollinator Declines

Unfortunately, many of the efforts to promote pollinator health are occurring because of pollinator declines seen across the globe (Potts et al. 2010). This phenomenon is happening to both managed and wild species. Colony collapse disorder in honey bees has caused large decreases in managed honey bee colonies and beekeepers are experiencing over winter losses far greater than were historically seen (National Research Council 2007). The rusty patched bumble bee (*Bombus affinis*) recently became the first bumble bee species in the U.S. to be listed as endangered and many more pollinators are facing this risk (Hatfield et al. 2015). There are many factors contributing pollinator declines such as loss of habitat, land use change, climate change, the spread of pathogens, parasites, and increased risk due to insecticide exposure (Potts et al. 2010).

Pests

The striped cucumber beetle (*Acalymma vittatum*) is one of the primary targets of insecticide use among cucurbit growers (Foster & Flood 2005). Striped cucumber beetles overwinter in sheltered field margins as adults. In the spring, they move to cucurbit fields to feed and lay eggs that hatch into larvae and ultimately become the second generation (Nixon 2014, Foster 2016). Striped cucumber beetle larvae feed on the roots of cucurbits and adults feed on vines, leaves, and fruits (Gould 1943, Foster & Brust 1995). Adult feeding can be especially damaging when plants are small and vulnerable at the beginning of the season. Direct feeding damage is not the primary cause of concern among most cucurbit growers. The striped cucumber beetle is a vector for the bacterium *Erwinia tracheiphila*, which causes bacterial wilt in cucurbits that leads to complete loss of the plant (Brust 1997). This disease is so damaging that susceptible cucurbits such as muskmelons and cucumbers have an ET of just one beetle per plant (Foster 2016). Relatively low beetle presence in these crops necessitates control. The damage that striped cucumber beetles cause in cucurbits makes it an excellent focal pest for this study. It is crucial that cucurbit growers can effectively control striped cucumber beetles and insecticides such as neonicotinoids are among the most commonly used chemistries.

I will examine the complex pest management of the striped cucumber beetle in watermelon. Unlike other cucurbits, watermelon is not susceptible to bacterial wilt (Foster 2016). This means that the presence of striped cucumber beetles is of less concern to watermelon growers because they cannot spread the devastating bacterium. Despite this important factor, striped cucumber beetles remain an important pest that can cause damage through feeding at both the adult and larval stages. In watermelon, the ET is 5 beetles per plant (Foster 2016). Growers are advised to deploy insecticides only once densities have reached the ET. Despite the advised ET, discussions and surveys among watermelon growers indicate that treatment often occurs at far lower beetle densities. This is often due to application during tank mixes with fungicides. Fungicides typically require more applications and insecticides can be added for little cost to growers. This is also related to the belief that if some insecticide is good for pest control then more must be better. This reasoning typically leads to unnecessary applications of insecticides, which are in opposition to IPPM. There are many insecticides recommended for striped cucumber beetle control that offer different application methods, effectiveness and toxicity to pollinators and other non-target insects.

Among these choices, various neonicotinoid insecticides are commonly used such as acetamiprid, clothianidin and thiamethoxam foliar sprays; as well as imidacloprid and thiamethoxam soil drenches (Foster 2016). These many choices in pest control among neonicotinoids alone plays a large role in the vastly different management strategies that growers use.

Insecticides

Insecticide use is one of the leading concerns regarding pollinator decline (Krupke et al 2012, Hopwood et al. 2016) and is perhaps the most amendable. Insecticides are also a practical and necessary means of managing pest insects. Neonicotinoid insecticides are synthetic insecticides, which were developed due to the effective pest control of their botanical analog, nicotine. Neonicotinoids are currently the most widely-used class of insecticides (Sparks 2013, Douglas & Tooker 2015). Although, the prevalence of neonicotinoids may be underrepresented due to the lack of surveys on seed treatments (Sparks 2013, Douglas & Tooker 2015). This makes the potential impact of neonicotinoids even greater. The popularity of neonicotinoids for pest management applications is due to their low mammalian toxicity, insect specificity, effectiveness, and systemic action. Systemic insecticides allow the insecticide to be translocated throughout the tissues of the plant. This is a valuable trait in the defense of plants against pests that may damage many areas of the plant. They are also insect specific due to their nicotinic acetylcholine receptor agonist mode of action. This specificity is due to the much higher rate of nicotinic ACh receptors in invertebrates than in vertebrates. Neonicotinoids are relatively safe for humans and other mammals while being highly toxic to pests and non-target insects, some of which are beneficial, including pollinators.

The large number of neonicotinoids used can reach pollinators in many ways including direct contact while being applied, through pollen and nectar, contacting residues in soil or on plants, or contaminated water and nesting materials (Krupke et al 2012, Dively & Kamel 2012, Bonmatin et al. 2015). Treatment of nearby crops can also lead to residues in untreated crops due to drift. Exposure of pollinators to neonicotinoids can have both lethal and sub-lethal effects, including disrupted cognitive abilities, altered behavior, reduced communication, and even reduced queen production in bumble bees (Desneux et al. 2007, Whitehorn 2012, Goulson 2013). Effects of neonicotinoids vary greatly in pollinator species, and no one species is a suitable predictor of how another species will be affected (Hopwood et al. 2016). Despite this, there is little known about the effects of neonicotinoids on most pollinators outside of honey bees. In fact, solitary bees are not even considered in risk assessment for insecticides such as neonicotinoids (Sgolastra et al. 2018).

Neonicotinoid use has produced controversy across the globe. Many argue that the non-target effects of neonicotinoids are too great to allow for their continued use. Others believe that they are far too important a tool in pest management without many viable replacements. The European Union's 2013 suspension of neonicotinoids in crops that are attractive to pollinators has signaled a potential shift in neonicotinoid usage (European Commission 2013, Hopwood et al. 2016). The 2018 confirmatory assessment banning imidacloprid, clothianidin, and thiamethoxam for outdoor use has placed an even greater level of scrutiny on the situation. Despite this action in Europe, the debate continues in the U.S. and much of the world. As it stands, neonicotinoids are currently widely used, and we must attempt to find effective management strategies that prioritize pollinator health while allowing for sufficient pest suppression.

Along with neonicotinoids, there are several other insecticide classes that have been widely used in agricultural pest management. Among these options are pyrethroids, which are frequently used in cucurbit production systems. Pyrethroids are the synthetic analog of the botanical compound pyrethrum, which are natural insecticides of plants in the genus *Chrysanthemum*. These insecticides are sodium channel modulators and have a similar mode of action to the infamous DDT but are far less persistent. They act by modulating the inactivation gate of the sodium channel, which causes the repeated firing of action potentials. This leads to neuroexcitation that causes knockdown and mortality. Unlike neonicotinoids, pyrethroids are not systemic but they can also have both lethal and non-lethal impacts on pollinators (Desneux et al. 2007).

Insecticides are a common tool in pest control, but they are not the only effective strategy growers deploy. Despite the effectiveness of IPM (Brust et al. 1996, Brust & Foster 1999), many growers continue to use insecticides as a preventative measure rather than a last resort. This preventative usage can be seen with insecticide treated seeds that directly oppose the ideal IPM usage of insecticides.

IPPM: Integrated Pest and Pollinator Management

Integrated pest and pollinator management is a holistic approach, which combines strategies such as conserving/promoting natural enemies, temporal avoidance of pests, resistant crop varieties, crop rotations, pollinator habitat, and insecticide risk mitigation, among many others. IPM relies in large part on scouting insect pests and only deploying insecticides at the ET (Foster 2016). This is the point that the value of losses caused by a pest exceed the cost of avoiding the damage. Deploying insecticides only once the ET has been met is an important aspect in limiting harm to pollinators, natural enemies, and potential resistance among the target pests (Foster 2016). Establishing an ET and implementing a method to effectively scout for pests are the first steps to IPM in a system. In watermelon, an ET has been established for striped cucumber beetles at 5 beetles per plant (Foster 2016). Although the ET has been established, there is not a scouting protocol that has been shown to be able to effectively assess pest densities. Without this scouting protocol, growers that are scouting their fields and using the ET cannot be sure that they are sampling enough to effectively assess the density of pests in their field. This represents a hurdle to the adoption of IPM practices in watermelon production that must be resolved.

Cucurbit growers face an important trade-off in insecticide use between pest suppression and pollinator health that I will examine in this study. They must suppress harmful pests such as the striped cucumber beetle while working to protect pollinators. This is challenging because the same insecticides that are used for pest suppression are harmful to pollinators. IPPM practices offer the best solution for Indiana watermelon growers. The inclusion of pollinator specific management such as temporal and spatial avoidance when treating with insecticides, as well as pollinator habitat establishment and preservation are crucial for IPPM. These practices along with traditional IPM practices have the potential to improve pollinator communities in commercial watermelon fields. This strategy will allow for growers to effectively manage pests below economically damaging levels while prioritizing pollinator health that could improve yield through increased fruit set.

CHAPTER 1: WATERMELON PEST MANAGEMENT

Introduction

Farmers must consistently make evidence-based decisions in the management of their crops; the accuracy of these decisions can mean the difference between a successful season and economic losses. Although insect management is crucial to the success of agricultural production, it is often one of the most challenging due to the conflict between managing insect pests and preserving beneficial insects. When this relationship is imbalanced, growers could experience yield loss from pest damage and disease if management is too lax or loss of pollination and natural enemies if management is too intense. The implementation of Integrated Pest and Pollinator Management (IPPM) is an effective way of navigating this trade-off. The use of the term IPPM rather than IPM is due to the important role of pollinator management in many agricultural systems and the modern implementation of IPM being more pest focused with less emphasis on ecological sustainability (Peterson et al. 2018). IPPM is a holistic strategy which implements a variety of tools to manage pest and beneficial insects in an ecologically and economically sustainable manner (Stern et al. 1959, Smith 1962, Geier 1966, Pedigo 1989, Higley & Wintersteen 1996, Biddinger and Rajotte 2015). It is crucial that growers have the necessary knowledge, tools, and strategies to successfully implement IPPM. These tools include pest prevention or avoidance, scouting, cultural pest control, and insecticide treatment when necessary. The implementation of IPPM has the potential to better balance the trade-off between pest and beneficial insects while simultaneously avoiding unnecessary economic expenditures (Pedigo 1989, Brust et al. 1996, Peterson et al. 2018).

The challenges associated with balancing insect management are especially true in the plant family Cucurbitaceae (cucurbit), which includes several economically important crops such as watermelon, pumpkin, muskmelon, cucumber, and squash. These crops depend on pollinators to produce fruit but are highly impacted by damaging insect pests (Walters 2005). The primary pest of concern in Indiana and much of the cucurbit growing regions in the US is the striped cucumber beetle (SCB), *Acalymma vittatum* (F.) (Foster and Brust 1995). SCB can cause damage to plants throughout their lifecycle and can damage cucurbits across two generations each growing season (Gould 1943, Foster and Brust 1995). In addition to the direct feeding damage, SCB are a vector of the devastating bacterium *Erwinia tracheiphila*, which causes bacterial wilt of cucurbits and can result in significant yield losses (Brust 1997). Because of this, tolerance for SCB in some cucurbit crops is very low, with economic thresholds of 1 beetle per plant in cucumbers and muskmelon (Brust & Foster 1999). Unlike other cucurbit crops, watermelons are not susceptible to bacterial wilt, so the only concern is direct feeding damage (Foster 2016). Thus, the economic threshold has been set at 5 beetles per plant (Foster 2016).

Despite the merits of IPPM, many farmers continue to use intensive pest management strategies which rely upon insecticides as a preventative measure rather than a last resort. Discussions and surveys with growers indicate that watermelons are often treated with insecticides more frequently than the threshold would require (unpublished data). There are various reasons for this but the ease of insecticide application, low cost insecticide tank mixes with fungicides which are frequently applied, ineffective or nonexistent scouting and decision rules, and even mistrust in the process of IPPM are potential hurdles for improved implementation. Additionally, growers often manage watermelons in a similar manner to muskmelon due to a lack of knowledge of the differences in susceptibility to bacterial wilt across these two related crops. Although these precautionary treatments are likely viewed as low cost insurance, the practice of preventative pest control leads to increased toxicity to beneficial insects from insecticide input and higher residues of active ingredients present in the field.

Intensive insecticide usage can be both economically and ecologically costly and may increase non-target exposure without offering any benefits associated with pest management (Potts et al. 2010, Mallinger et al. 2015, Hajek & Eilenberg 2018). Insecticides cause both lethal and sub-lethal effects on beneficial insects. The repeated treatment of insecticides can create a more toxic environment which contains residues in plant tissues such as pollen and nectar, and in soil and ground water, increasing nontarget impacts on beneficial insect communities (Krupke et al 2012, Dively & Kamel 2012, Bonmatin et al. 2015). Insecticides have been cited as a primary factor contributing to worldwide declines in both managed and native pollinators (National Research Council 2007, Potts et al. 2010, Hatfield et al. 2015). Loss of pollinators can reduce fruit set, which negatively impacts yield (Goulson 2013, Garibaldi et al. 2014, Mallinger & Gratton 2015). Insecticides also harm natural enemies, resulting in more frequent outbreaks of secondary pests such as aphids and mites as well as reduced control of primary pests due to the development of resistance (Croft & Brown 1975, Hopwood et al. 2013, Chagnon et al. 2015, Douglas & Tooker 2016). Implementing an effective and efficient scouting methodology and promoting adherence to IPPM strategies is the best way to reduce unnecessary insecticide applications and improve grower outcomes such as yield and reduced insecticide expenditures. Implementing pest scouting protocols is crucial for the evidence-based insect management decisions that growers must make (Stern et al. 1959, Smith 1962, Geier 1966, Foster 1986, Pedigo 1989, Higley & Wintersteen 1996, Brust et al.1996, Biddinger and Rajotte 2015).

One hindrance to greater adoption of IPPM strategies by growers is the availability of effective and efficient sampling protocols. Scouting can be challenging because many insect pests such as SCB are aggregated on individual plants (Foster 1986, Ferguson et al. 2003). This patchy distribution across the field makes it harder for growers to confidently assess densities through scouting. The level of aggregation striped cucumber beetles exhibit in watermelon fields has not been assessed. Because of this, growers do not know how many plants they need to sample to confidently assess pest densities in their fields. Growers who scout for SCB are currently faced with the option of scouting too little and being unable to assess density or the unlikely option of scouting too much which is costly and inefficient This knowledge gap for sampling pests inhibits the adoption of IPPM. These are important factors in the decision-making process because scouting has opportunity costs for the grower or their employees.

To institute a scouting plan, growers must assess the costs and benefits associated with doing so. Scouting plans need to be feasible, reliable, and economically beneficial in comparison to 'insurance sprays' for widespread adoption. An economic assessment of scouting for SCB in watermelon can best be done by showing that pest thresholds are not exceeded as frequently as growers are applying pesticides. Any insecticide applications that can be eliminated save money and may quickly overtake the costs of scouting. An economic analysis of pest scouting, treatments, and threshold-based management will provide growers with a comprehensive understanding of the costs and benefits of each individual pesticide application and the management strategy associated with it.

The economic feasibility of IPPM can be further supported by understanding the background pest pressure and the variation in pest pressure seen across a variety of management practices. If the pest densities in relation to the economic threshold in the system are strongly impacted by management, more conservative growers may be hesitant to adopt an IPPM strategy. If differences in pest densities are not highly associated with the intensity of management then adoption of less intensive, IPPM based strategies will more likely be widely embraced. This distinction is important to understand when assessing pest management strategies and providing growers with science-based management recommendations. To further the knowledge of how management influences pest densities, it is valuable to assess the inputs of insecticides and the level of insecticides that are present in plant tissue that SCB come in contact with. This will provide an understanding of how much of an impact that insecticide-based management has on pest densities. If SCB have high background densities, then you would expect the majority of the variation in density to be explained by insecticide-based management. If the background density is already low and would not frequently reach the ET then the impact of insecticide-based management will not be as great.

The objective of this study is to provide SCB scouting protocols and threshold-based pest management recommendations for commercial watermelon growers in Indiana. To do this, I assessed the degree of SCB density and aggregation, calculated optimal sample sizes to assess SCB densities, quantified the amount of time it takes to effectively scout, compared the cost of a scouting plan with the cost of insecticide applications, and developed scouting methodology that can be effectively used in watermelon IPPM. In addition, I examined variation in SCB density based on current grower practices and measured neonicotinoid residues in watermelon leaf tissue. Lastly, I calculated an insecticide toxicity rating based upon the inputs each field received. Insecticide residues and toxicity related to SCB densities provide valuable information on how grower management decisions impact pest populations. This study provides growers with recommendations based upon IPPM principles and the assessment of SCB in Indiana watermelon fields in the context of current practices.

Materials and Methods

Field Sites

SCB were sampled in fifteen commercial watermelon fields in Indiana and Illinois between 23 May and 16 August 2017 and fifteen additional fields in Indiana between 21 May and 14 August 2018 (Figure 1). Fourteen of the fifteen farms were sampled in both years, even though field location varied between years, whereas two farms were only sampled one year. Pesticide spray records were collected from 28 of the 30 fields, results requiring pesticide records analyzed the 28 fields with available records while all other variables include all 30 fields. Fields varied in size, management practices, and inputs determined by growers, ranging from frequent prophylactic applications of conventional insecticides to organic production. None of the growers used a formal scouting program for SCB to inform insecticide applications; however, all growers were aware of the threat of SCB. A subset used informal scouting that informed insecticide application decision based on personal experience rather than the suggested EIL.

Pest Sampling

Fields were sampled weekly from transplant to initiation of flowering and bi-weekly thereafter. Each field was sampled between 6 and 12 times depending on transplant date and weather. Each sampling event consisted of walking five transects in 2017 and four transects in 2018. Linear transects were positioned randomly, perpendicular to the field edge, and spaced at least 10 m apart from one another. Transects were run along the plant rows and were alternated between the beginning and end of the row. Plants were sampled at 25, 100, 175, and 250 m along each transect to account for potential variation in beetle counts occurring at the field edge vs. core. On fields less than 250 m in length, the sampled plants were evenly spaced across the entire length of the field. I counted the number of SCB on a total of 20 plants during each scouting event in 2017 and 16 plants in 2018. This change in sampling intensity was in response to 2017 data, which indicated that the sample number needed to accurately detect the beetle threshold was lower than expected.

SCB are commonly found inside flowers as well as on leaves, especially the underside of leaves when it is hot. Therefore, at each sampling location, vines were carefully overturned to visually observe the top and underside of each plant, including stems, leaves, and flowers. The soil and plastic mulch were also inspected since beetles often reside beneath the plant. Early in the season, individual plants were easily distinguishable from one another; however, as the vines grew together, a 1-m^2 area was designated as an individual plant.

In total, I conducted 281 individual farm visits, sampling 5,016 plants in 30 fields across the two years. Beetle counts were averaged per field across the plants sampled during each visit to calculate the mean number of beetles per plant during each sampling period. In 130 of the 281 visits, no beetles were observed at any location. These data were excluded when calculating aggregation and recommended sampling size.

SCB Aggregation

Understanding the spatial distribution of pests is crucial to developing scouting recommendations. Spatial distribution can be measured with the variance to mean ratio of pest counts (Ruesink 1980, Foster 1986). This ratio was used to assess dispersion of SCB across the 151 visits when beetles were observed. The mean beetles per plant (m) and variance (s^2) were used to calculate the variance to mean ratio. When $s^2 = m$, the population is assumed to be randomly distributed, while $s^2 < m$ means the population is uniformly distributed and $s^2 > m$ indicates aggregation.

Another measure of spatial dispersion introduced by Iwao (1968) uses linear regression on Lloyd's mean crowding (m_c), defined as $m_c = m + \left(\left(\frac{s^2}{m}\right) - 1\right)$, which expresses the number of total individuals per individual present, to mean density (Lloyd 1967). This creates a linear relationship with the intercept (a) and the slope (b) used to assess dispersion. Pest density mean was regressed on mean crowding for each of the 151 visits when beetles were observed. An $a > 0$ and $b > 1$ indicate an aggregated pest distribution, while $a = 0$ and $b = 1$ indicate random distributions.

Taylor's power law relates sample variance to the sample mean with the expression $s^2 = a\bar{x}^b$ where ($\bar{x}$) is the mean and (s^2) is the variance (Taylor 1961). These variables were calculated, and a linear regression was performed for $\log s^2$ on $\log \bar{x}$ using the same 151 visits. The a value was quantified by taking the untransformed intercept ($a = 10^{intercept}$) while the b value was the slope of the regression. These a and b values were then used to determine the sample size (n) needed to scout with the recommended 25% precision ($c = 0.25$) (Foster 1986) using Ruesink's (1980) equation: $n = \frac{a\bar{x}^{b-2}}{c^2}$.

Economic Analysis

To assess costs related to pest management and scouting, I created matrices that include a variety of strategies focused on comparing the cost of scouting vs. the cost of prophylactic insecticidal treatments. The first of these matrices provides a range of sampling times and hourly wages for scouts based on field data recorded in 2018. To assess the cost of implementing a scouting regimen the amount of time to complete a transect of four plants was recorded on 505 transects in 2018. Hourly wages for scouts were assumed to range from the minimum wage in Indiana of $7.25 per hour to $15.00 per hour which was based upon the average wage rate of $14.29 for all hired farm workers in Indiana's region for summer 2018 (USDA NASS 2018). The second matrix provides many different insecticide options along with the cost of use. This was created using insecticide spray records from participating growers along with the acreage of application and cost per acre of the insecticide applied from each grower over the two years. Insecticide spray records were collected from growers at 28 of the 30 fields and encompass a range of pest management strategies used in commercial watermelon production. The cost of insecticides was compiled from either direct expenditure reported by growers or prices sourced from the NDSU Extension Insect Management Guide (Knodel et al. 2019). All prices were based on the actual product used or a comparable product. I then developed a cost/benefit analysis of pest management using insecticides prophylactically vs. a scouting-based regime.

Leaf Tissue Collection

Leaf samples were taken throughout the season during six sampling dates per field, which were approximately weeks 1, 2, 3, 6, 9 and 12 after watermelon transplant. Sampling began when plants were large enough to tolerate the loss of a leaf, typically plants had about four total leaves at this stage which occurred one to two weeks post-transplant. Leaves were collected from plants used in pest sampling, thus 20 leaves were used to create a sample in 2017 and 16 leaves comprised a sample in 2018. The most distal fully expanded leaf along a vine of the plant was selected. A single sample was composed of all leaves collected from a field each week, which were combined to form a single analytical replicate. Upon collection, leaves were placed on ice in a cooler, brought to the lab and stored in a -20°C freezer until sample preparation. To create an analytical tissue sample, all leaves from a sample were stacked and cut in cross sections using sterilized scissors.

The leaf tissue cross sections were cut further to roughly homogenize the sample to approximately 5 mm^2 pieces. A 1 g sample was then collected and placed into a 7 mL Precellys tube with 2 g of ceramic beads. To further lyse and homogenize the sample, 2 mL of double deionized (dd) water was added to the sample and placed in the Precellys 24 lysis homogenizer. The machine was operated at 5,000 rpm for four cycles of 25 seconds. Upon completion of homogenization, pesticide residues were extracted using the protocol described below.

Pesticide Quantification

Homogenized leaf tissue was analyzed following the QuEChERS approach of Long and Krupke (2016). The homogenized sample, including 2 mL of dd water was combined with 2 additional mL of dd water, 4 mL of acetonitrile (ACN), internal standards (acetamiprid, clothianidin, imidacloprid, and thiamethoxam), and a QuEChERS salts mix of 1.2 g magnesium sulfate ($MgSO_4$) and 0.3 g of sodium actetate (NaOAc) into a 15 mL centrifuge tube. Samples were then vortexed for one minute with a S8220 Deluxe Mixer Vortex (Scientific Products) and shaken on a VWR W-150 Waver Orbital Shaker for 10 minutes at high speed before being centrifuged at 2,500 RPM for 10 minutes. One mL of supernatant was then transferred into a 2 mL Agilent Dispersive SPE tube for highly pigmented sample extractions (Agilent, Santa Clara, CA. part no. 5982-5321). The samples were vortexed and shaken before being centrifuged at 15,000 RPM for 5 minutes. The entire supernatant was collected from the 2 mL tube and transferred to 1.5 mL Eppendorf tube. These tubes were then evaporated overnight in a speed vacuum. Dried samples were resuspended in 1 mL of ACN, vortexed, shaken, and centrifuged at 15,000 RPM for instrumental analysis.

The QuEChERS analysis took place on the Purdue University campus at the Bindley Bioscience Center. Pesticides were extracted from samples and analyzed using liquid chromatography-tandem mass spectrometry (LC-MS/MS). This method allowed for the precise detection and identification of pesticides present in samples down to concentrations of parts per billion (ppb. In the neonicotinoids, which were the focus of this study, limits of detection (LOD) were 0.3 ppb. In total, 189 leaf tissue samples were screened for 13 common insecticides following the protocol described in Long and Krupke (2016). This analysis provided information about the residues of insecticides present in leaf tissue which beetles would be exposed to when feeding on the plants. This information was used to assess the efficacy of insecticidal residues in plant tissues for managing SCB densities.

Toxicity Ratings

The insecticide records collected from growers at 28 out of 30 fields were also used to assess the intensity of the pest management regime of each field. This was done in three ways: first, the presence or absence of pre-treatment using insecticide seed treatment, transplant drench, or insecticide application prior to or at transplant as a prophylactic application. The second management assessment relied upon the number of unique insecticide applications on the crop over the course of the season. The third management assessment focused on potential non-target implications by assigning a toxicity score based on the rate of application and toxicity to bees of all insecticides applied at each field. This followed the approach of Mallinger et al. (2015) and utilized the "bee-toxicity value" for active ingredients listed in the 2017 EIQ database (Eshenaur et al. 2017). The toxicity score equation was used to assess the intensity of insecticide-based pest management for each field. The rate of insecticide application was multiplied by percent active ingredient and EIQ bee toxicity value to get the toxicity score of individual insecticide applications. Insecticide applications for each field were then summed to get the total toxicity score for each field. The first formula is effective for insecticide applications reported in solid weight while the second can be used when reported in volume of liquid applied.

Toxicity Score = Σ[Rate (oz of weight/acre) × Percent active ingredient × EIQ bee toxicity value]

Toxicity Score = Σ[Rate (fl. oz/acre) × Percent active ingredient (oz AI/fl. oz) × EIQ bee toxicity value]

This calculation focused on the insecticide applications alone as a means of understanding the intensity of pest management for each field. This method represents a conservative estimate of the impacts of pesticides on pollinators as there is mounting evidence that other pesticides can also negatively impact beneficial insects.

Statistical Analysis

A multiple-linear regression approach was used to assess the impact that neonicotinoid insecticide residues in plant tissue have on SCB densities. Regression models were selected using all-subsets regression which performs an exhaustive search for the subsets of explanatory variables which best explain the model (R version 3.50, leaps package). This approach was used to select the most parsimonious subset of explanatory variables for neonicotinoid residues and to assess the predictive power of neonicotinoids on SCB densities. Additionally, the insecticide toxicity rating was regressed on the maximum weekly SCB density and season-long average SCB densities to assess the impact of pest management intensity in individual fields on SCB densities (R version 3.50). The maximum weekly SCB density and season-long average densities were also analyzed using an ANOVA with the fields being broken into four management groups based upon calculated insecticide toxicity scores. The groups were split into no treatment, low intensity, medium intensity, and high intensity (Insecticide Toxicity Score of 0, 1-100, 100-200, and >200 respectively). A Tukey test was used to assess relationships between groups when ANOVA results were significant.

Results

Aggregation and Sampling

Each of the dispersion indices indicate that striped cucumber beetles have an aggregated distribution in watermelon fields (Figure 2 and Table 2). At the striped cucumber beetle ET of 5 beetles per plant, sampling 8 randomly selected plants will provide an estimate of mean density that will allow for accurate decision making (Table 3).

Scouting Economics

The mean time to complete a transect was nearly nine minutes. To account for variation in the amount of time it takes to scout I considered two sampling times, 10 and 20 minutes per four plant transect. The 10-minute transect is similar to the pace set in our study, while the 20-minute transect will allow for more leisurely scouting and account for greater distances to walk on large fields. Based on the recommended sampling of 8 plants, scouting a field at the 10- and 20-minute paces could reasonably be completed in between 20 and 40 minutes. A weekly scouting plan should take place for nearly 12 weeks throughout the watermelon growing season and would require a total of between 4 and 8 hours of work per field to effectively detect beetles at threshold levels. I then compared these times with potential labor costs for scouts ranging from the Indiana minimum wage of $7.25 an hour to $15.00 an hour. This represents a total cost of between $29 and $120 to scout a field for SCB on a weekly basis across the season with trained scouts (Table 5).

Insecticide Economics

Across the two seasons and 28 fields that reported insecticide applications, a range of 0 to 10 insecticide applications were made with an average of 4.5 applications per field. Each insecticide application was converted to cost per acre. Treatment costs ranged from $4.62 /acre to $143.43/acre. The 15 insecticide active ingredients used varied in cost from $0.18/oz to $8.59/oz with a cost per acre ranging from $1.02/acre to $57.15/acre based upon reported rates of applications (Table 5). Practical insecticide costs ranging from the cheapest to most expensive active ingredients were calculated at fields of various sizes. (Table 7). The cost of the cheapest insecticides on small fields were as low as $1 per application while the most expensive treatments on large fields could cost as much as $5,715 per application. The average cost of insecticides ($9.75/acre) on the average field of 20 acres would cost $195 per application.

Pest Densities

SCB were consistently observed at densities well below the ET of five beetles per plant. The ET was never reached at any of the 30 fields from 2017 and 2018 across 281 visits (Figure 3). In fact, SCB densities were so low that an average of two or more beetles per plant was only observed during 4% of the visits. Nearly half (130) of all scouting visits over the two years found no SCB at all.

Insecticide Input and Residue Impact on Pest Densities

To assess the relationship between pest densities and insecticide use, I analyzed insecticide residues which pests may come in contact with in watermelon leaf tissues and inputs collected from growers. Each of the four primary neonicotinoid insecticides were detected in leaf tissue samples (Table 8). In many samples, trace amounts of neonicotinoids were present, although, samples exceeding 1,000 ppb were observed. The variation observed in residues in these samples is the result of the variation in pest management strategies among commercial watermelon growers. Clothianidin was the most influential explanatory variable in the neonicotinoid and pest linear regression model but there was no significant relationship between clothianidin residues observed in leaf tissue and the SCB density on the same day. Residues of clothianidin and the other neonicotinoids were not correlated with SCB density ($F_{1,176} = 1.684$, $p = 0.196$, $R^2 = 0.009$; Figure 4; Table 9). Intensity of pest management was assessed for each field using three methods. Pre-treatment of insecticides was used in 9 of the field sites, insecticide applications ranged from 0 to 10, and the toxicity scores ranged from 0 to 420 (Table 10). Toxicity scores had a significant negative relationship with maximum SCB densities observed in fields ($F_{1,26} = 5.218$, $p=0.03671$, Adjusted $R^2 = 0.1351$; Figure 5; Table 9) and had a negative, although insignificant, relationship with the average SCB density across the entire season ($F_{1,26} = 4.152$, $p=0.0519$, Adjusted $R^2 = 0.1046$; Table 9). Despite the significance of the relationship, when fields which were not treated with insecticides were excluded from the analyses there was no significant relationship between SCB maximum or average densities ($p>0.05$). To better analyze the impact of fields which were not treated, fields were broken into four intensity of management groups (no treatment, low, medium, and high intensity). The groups had a significant impact on the SCB maximum ($F_{3,24}=9.289$, $p=0.000294$) and the season-long average SCB density ($F_{3,24}=8.351$, $p=0.000561$) in the analysis of variance test. The post-hoc analyses showed that the no treatment group had significantly higher SCB max ($p<0.005$) and season-long average SCB density ($p<0.001$) than each of the other groups (low, medium, and high intensity) (Figure 6). None of the insecticide treatment groups were significantly different from each other in either the maximum SCB or average SCB densities ($p>0.05$). This indicates the intensity of management based upon insecticide toxicity to pollinators is having the expected negative effect on SCB densities, but only when no treatment is compared to treated fields. Despite the increased SCB densities in no treatment fields, no field exceeded the threshold of 5 SCB per plant at any point during the 2017 or 2018 growing seasons.

Discussion

The results of this study show that management of SCB in commercial watermelon production is highly variable and current practices allow for a reduction in the number of applications of insecticides. Scouting and threshold-based management are expected to be an effective means of achieving this reduction, aligning with long-held IPM recommendations (Stern et al. 1959, Smith 1962, Geier 1966, Pedigo 1989, Higley & Wintersteen 1996). Pests can be confidently assessed at densities well below the ET in a short and cost-effective amount of time. This is especially evident when examining the variation in pest management strategies, the cost of insecticide applications and scouting, and the impact of management on yield, pests, and beneficial insects. Across the study, SCB densities were found to be consistently below the ET of 5 beetles per plant regardless of the intensity of insecticide-based management. Without a single field reaching threshold at any point over the two years it is clear that pesticide applications can be reduced. The variation seen in insecticide use did not have an impact on pest densities with relation to the threshold. This means that the less intensive strategies with lower insecticide inputs are sufficient for managing pests at densities which are unlikely to cause economic damage. The fields with no insecticide applications never exceeded the SCB ET. The fields with more intensive pest management strategies likely could have used less intensive management akin to other fields in the study and would not have been negatively impacted by pests. In order to decrease the intensity of pest management I recommend that commercial watermelon producers institute a weekly pest scouting protocol as described. Scouting in this manner will allow growers to confidently assess the densities of pests on a weekly basis and determine whether any insecticide treatment is necessary. This protocol will also help growers to forecast for future treatments through weekly sampling which will help identify mounting pest populations. These results, and the economic analysis of the pest scouting protocol described here provide overwhelming evidence of the valuable component of IPPM for commercial watermelon production. Based on observed pest densities across the study, less intensive management strategies are expected when growers implement a scouting protocol. Implementing scouting and thresholds will decrease the amount of insecticides used in the system and eliminating even one insecticide application will result in a net savings due to scouting. Any further eliminated applications will represent even greater savings. When compared to the cost of the average insecticide application, scouting is a small cost that represents an opportunity to save a large sum of money on unnecessary insecticide applications and minimizing nontarget effects to pollinators and natural enemies.

The low SCB densities seen at all fields could be explained by low background densities of the pest, or effective management using insecticides. However, I have shown here that SCB are being effectively managed in all cases despite a wide variety of practices ranging from organic to prophylactic insecticide management. Given these differences in management and the lack of difference in pests from an economic threshold perspective, unnecessary applications are being made in some instances, incurring costs to growers beyond the sticker price of the chemical. Similar results indicating overuse of insecticides have been shown in other cropping systems (Brust & Foster 1999, Slone & Burrack 2016). This conclusion is supported by the neonicotinoid linear model which showed that the presence of neonicotinoid residues in leaf tissues had no predictive power on the SCB population observed in the field. This result means that in this system the presence of increased doses of neonicotinoids in watermelon plants is not responsible for low pest densities in those fields. This is perhaps a counterintuitive result that shows that SCB densities in fields are not reliant upon the rates of neonicotinoids in those fields. Looking at this more closely, fields with low neonicotinoid residues were no more likely to have higher levels of SCB than those with high neonicotinoid residues. Additionally, no field reached ET regardless of management strategy or neonicotinoid residues. This calls into question the efficacy and practicality of the popular insecticides when background pest densities are low due to their unknown toxicity to SCB and their high cost to growers. There are other likely explanations for the low densities of SCB observed, such as low background pest pressure and a landscape which contains high rates of insecticides that are successfully suppressing pest populations. Additionally, a wide variety of insecticides are used in the management of SCB. Due to this variation in insecticide use, individual compounds or classes may not strongly influence pest densities, but the overall insecticide toxicity present in fields does. This is supported by the impact that the insecticide toxicity rating has on both average and maximum SCB densities in watermelon fields. Both of these SCB density metrics were negatively impacted by the season-long insecticide toxicity score in that field. Though, this relationship only existed when fields which did not treat with insecticides were included in the analysis, when they were excluded there was no relationship between insecticide toxicity score and SCB densities. When analyzed as intensity of management groups, no insecticide treatment had higher densities of pests than all other management types, but none of those levels of management intensity were significantly different from each other. This means that increased insecticide use is unlikely to reduce SCB densities when compared to fields which were treated with a low insecticide intensity strategy. SCB are being effectively reduced by the use of insecticides but increased toxicity in insecticide management has no effect on SCB densities. Despite the decreased density of treated fields compared to non-treated fields, none of the fields ever exceeded threshold across the 2017 and 2018 season. This means that all fields are sufficiently managing SCB regardless of toxicity rating and the fields with higher toxicity ratings are unlikely to see any pest related benefits but are likely increasing contact with beneficial insects.

In addition to the economic benefits of implementing a pest scouting regimen, it also follows IPPM and reduces potential nontarget impacts on pollinators, which are required for watermelon fruit set. Future research will focus on the impacts of pest management in watermelon on pollinators. It is clear that pollination is crucial in this system and that managed pollinators should not be relied on exclusively; native pollinators more effectively pollinate watermelon (Kremen et al. 2002, Winfree et al. 2007, Winfree et al. 2008, Garibaldi et al. 2013). Previous research in cantaloupe shows that IPPM actually increases yield when compared to conventional prophylactic insecticide management (Brust et al. 1996, Brust & Foster 1999). This increase in yield could be due to the negative impact that intensive pest management can have on native pollinator communities (Mallinger et al. 2015, Rundlöf et al. 2015, Stanley & Raine 2016). This is an important area of research for better understanding the impact of pest management in commercial watermelon production.

The results of this work show that SCB in watermelon is perceived by growers to be a greater threat than I detected. Given the variation in current practices and observed beetle densities, there is strong evidence to suggest that there is room for reductions in the amount of insecticides that are currently used in watermelon production, while still preserving the economic viability of the crop. Regardless of pest management strategy, all 30 fields over the two years were effectively managing pests. SCB were never observed at the economic threshold of 5 beetles per plant, and never reached levels threatening the threshold in most fields. This intensity of management concern can be remedied through the adoption of IPPM practices focused on scouting and threshold-based management. Adoption of well-defined scouting protocols has been shown to effectively reduce superfluous insecticide treatment in other cropping systems, which are costly and could prove harmful to beneficial insects (Brust et al. 1996, Brust & Foster 1999, Slone & Burrack 2016). Threshold-based management in watermelon from an IPPM perspective is also supported by the economic analysis of scouting. The reduction of even one superfluous insecticide application is expected to more than cover the cost of an entire season's worth of scouting costs. In some cases, growers may have been able to eliminate even more insecticide applications which could represent a savings of thousands of dollars. This method becomes more attractive due to the low predictive power of neonicotinoids in plants on SCB densities in the field. Individual management regimes are important but may be overemphasized when background pest densities are low. These results provide a definitive case for the implementation of threshold-based IPPM in commercial watermelon production

CHAPTER 2: WATERMELON POLLINATORS

Introduction

Pollinators are crucial for the production of many important crops such as cucumbers, blueberries, almonds (Adlerz 1966, Walters 2005, Klein et al. 2017). These crops all rely on pollen transfer by insects for successful fruit set. However, no formal research has been done to assess pollinator communities present in midwestern watermelon production. Without an understanding of pollinator communities, it has been challenging for growers and researchers to assess the impact that management has on them. Despite this knowledge gap, pollinators have become an consideration in the management of these crops; however, pollinators are in decline across much of the globe, with many native species experiencing population declines and managed species experiencing greater overwintering losses than in the past (Potts et al. 2010, Hatfield et al. 2015, Hopwood et al. 2016). This is concerning from the point of losing biodiversity and also alarming farmers who rely on pollination services for crop production. A number of stressors are contributing to the decline in pollinators, such as decreased habitat, transmission of pathogens and parasites, climate change, and pesticide use (Kleijn & Raemakers 2008, Potts et al. 2010, Garibaldi et al. 2011).

Perhaps the most agriculturally relevant and amenable of these factors is the increased risk from insecticides (Krupke et al 2012, Hopwood et al. 2016). While lower volumes of some active ingredients are being used, the use of other chemistries with more toxic effects to pollinators are on the rise (Douglas & Tooker 2015). Additionally, prophylactic treatments such as seed coatings and transplant applications are rapidly increasing (Douglas & Tooker 2015). Pollinators have been shown to come into contact with insecticides through a variety of exposure routes. Insecticide residues have been observed in lethal doses in pollen and nectar, soil, ground water, and dust in the air (Krupke et al 2012, Dively & Kamel 2012, Bonmatin et al. 2015). These insecticides can be both lethal, killing the pollinator outright, and non-lethal, leading to decreased navigation, foraging efficiency, memory, and reproductive ability (Desneux et al. 2007, Whitehorn 2012, Goulson 2013). The impact of insecticides on pollinators is especially problematic due to the reliance upon them in many agricultural settings.

There is an inherent conflict between pest and pollinator management due to the strong reliance on insecticides in agriculture. Growers must balance this trade-off between pests and pollinators in a manner that emphasizes pollinator health while keeping pest populations at densities that will not reduce yield. Neither crops, nor the pest insects that damage them, can be managed in a vacuum. The well-being of pollinators and their ability to successfully pollinate crops must be considered in all decisions. This creates a challenge that is difficult for growers to successfully navigate and could lead to negative impacts in the absence of evidence-based management practices. In order to best balance pests and pollinators, growers should implement integrated pest and pollinator management (IPPM) strategies. IPPM is a holistic method, which combines a variety of crop management strategies that set out to optimize grower profits through adequate pest management and environmental stewardship (Biddinger and Rajotte 2015). This requires an understanding of the impacts of pesticide use on pollinators and making decisions which mitigate this risk. IPPM strategies include temporal and spatial avoidance of pollinators by limiting applications during bloom, applying when pollinators are not actively foraging, relying on non-insecticidal control options, establishing pollinator habitat which does not receive pesticide applications, and the use of chemicals with lower pollinator toxicity, among many others (Biddinger and Rajotte 2015). These strategies have all been implemented in various IPM settings but widescale adoption in the context of IPPM has not occurred, and therefore offers room to improve the suitability of agricultural habitats for the required pollinators navigating these spaces (or something like that). Implementing IPPM requires a holistic approach, which emphasizes ecologically sustainable management that reduces stressors associated with pollinators in an agricultural context.

. Watermelon producers have taken an interest in better implementing pollinator management in response to improved knowledge about pollinator declines and the rising costs associated with managed pollination services. Watermelon require over 1,600 pollen grains and between 10-60 visits by pollinators for full fruit set (Winfree et al. 2007). Many watermelon growers are becoming increasingly aware of the impacts of their pesticide use on pollinators. Currently, most growers rely on the use of managed pollinators like honey bees (*Apis mellifera* L.) and have implemented strategies to reduce their contact with insecticides. Some have also engaged in providing more pollinator habitat (personal communication). The implementation of pollinator management strategies has been done with the hope that they will have a positive impact on pollination in the crop, but it may also play a role in the preservation of pollinator species found in watermelon fields, some of which are in decline. These practices are supported by research showing that increased pollinator diversity could enhance fruit set and act as a biological insurance policy (Winfree et al. 2007, Garibaldi et al. 2013, Garibaldi et al. 2014, Mallinger & Gratton 2015).

Pollinator management is complicated due to the pest pressures that watermelon growers must contend with. Watermelon is a highly valued specialty crop that is vulnerable to insect mediated yield loss. The pest of concern and primary target of insecticide treatment in watermelon in the Midwestern United States is the striped cucumber beetle (SCB) (*Acalymma vittatum*) (Foster & Flood 2005). SCB are capable of damaging watermelon at the larval stage, feeding on plant roots, and the adult stage where they feed on vines, leaves, and fruits (Gould 1943, Foster & Brust 1995). Adult feeding can be especially damaging when plants are small and vulnerable at the beginning of the season. SCB are also a vector of the devastating bacterium, *Erwinia tracheiphila* which causes bacterial wilt in many Cucurbitaceae crops. Watermelon, however, is not susceptible to bacterial wilt (Foster 2016). Due to this lack of susceptibility, greater densities of the pest are economically tolerable. In watermelon, the ET for SCB is 5 beetles per plant (Foster 2016). Insect management decisions in this cropping system requires approaches that effectively control cucumber beetles while minimizing insecticide exposure to pollinators.

Seedless watermelon's reliance on pollination and the increased costs associated with commercial pollination services provides the motivation and opportunity to implement IPPM strategies. I set out to assess the pollinator communities in commercial watermelon fields under varying management strategies. This allowed me to better understand what factors of management are influencing pollinator communities and how that relates to pest management. To do this, I assessed the impact of neonicotinoid residues and insecticide inputs on pollinator communities. In addition, pollinator communities were assessed in relation to pest densities to better understand the primary trade-off in management that growers must balance. Finally, the impact of pollinator communities on floral visitation and pollination events were examined to better understand how pollinator communities may be influencing pollination and fruit set leading to yield. These results, when compared with the findings of chapter one, will provide a holistic examination of the ways in which growers manage commercial watermelon and provides evidence based IPPM recommendations.

Materials and Methods

Field Sites

I worked in fifteen commercial watermelon fields in Indiana and Illinois in 2017 and fifteen additional fields in Indiana in 2018. I worked with a total of 16 growers, with 14 of those managing fields in both years. Fields varied in size, management practices, and inputs determined by growers, from frequent prophylactic applications of conventional insecticides to organic production practices, but all were planted with seedless watermelon varieties. Pollinator management varied across sites with some growers utilizing high stocking rates of managed honeybees and bumblebees and others relying on native pollinators or neighboring honeybee hives.

Pollinator surveys

During the watermelon flowering period, pollinator visitation was measured on observation areas of focal flowers twice per field (except for one field in 2018 that was only sampled once). Observations took place between 7:30 am and 1:30 pm when pollinators are most actively foraging and on sunny days with low-moderate wind. In each field, 16 patches of flowers were identified along four randomly positioned transects, extending 250 m perpendicular from the field edge. Transects contained four sampling points at 25, 100, 175 and 250 m, or spread evenly across smaller fields (Rader et al. 2013). Each patch consisted of 2-10 watermelon flowers, depending on availability. During sampling, all insect visits to flowers in the observation patch during a three-minute observation period were recorded. Pollinators were identified to the lowest possible taxonomic level; this varied widely, from ones that are easily identified to species (e.g., honeybees) to others that can only be identified to genus or family (e.g., halictids). During the observation period I recorded the number of flowers visited, and transition visits which include pollination events (i.e., pollinators transitioned from male to female flowers or vice versa) that each individual pollinator made within the patch. Pollinator visitation data for the two seasons is reported to the lowest taxonomic grouping possible using field observation and identification. Collected specimen were used to inform identification or grouping of pollinator visitation data when necessary. The relative contributions to pollination via floral visits and pollination events was measured by taxonomic group.

Additionally, pollinators were collected on each of the two sampling dates after all observations were completed. Each sampling unit consisted of all the pollinators that were collected for 30 person-minutes using handheld insect vacuums (2820GA Heavy Duty Hand-Held Vac/Aspirator, BioQuip, Rancho Dominguez, CA). Individuals randomly walked through fields, collecting any insect observed on a flower. Handling time was accounted for by the addition of 30 seconds for each collected pollinator, i.e., the 30-minute collection period did not include sample processing time. Specimens were stored in individual vials and temporarily placed on ice, before ultimately being stored in a freezer upon return to the lab. Collected specimens were pinned, counted, and identified to species (Michener et al. 1994, Gibbs 2011, Gibbs et al. 2017). I used these data to calculate species richness, Shannon's diversity index (H), and species evenness (J').

Pesticide Inputs and Toxicity Ratings

Pesticide application records were collected for all fields, including the identity of the pesticide used (trade name and active ingredient), rate, method (seed coating, foliar spray, soil drench), and frequency/timing (number of applications and when they occurred). The insecticide records collected from growers were used to assess pest management strategies at each location. This was quantified in two ways. First, the use of systemic insecticides at-planting as a prophylactic application. The second management assessment focused on potential non-target implications by assigning a toxicity score based on the rate of application and toxicity to bees of all insecticides applied at each field (Equation 1 and 2). This followed the approach of Mallinger et al. (2015) and utilized the "bee-toxicity value" for active ingredients listed in the 2017 EIQ database (Eshenaur et al. 2017). Insecticide applications for each field were summed to calculate the total Toxicity Score for each field. Alternative equations were used based upon the method of application and available information on the label.

Toxicity Score = Σ[Rate (oz of weight/acre) × Percent active ingredient × EIQ bee toxicity value]

Toxicity Score = Σ[Rate (fl. oz/acre) × Percent active ingredient (oz AI/fl. oz) × EIQ bee toxicity value]

This calculation focused on the insecticide applications alone as a means of understanding the intensity of pest management for each field. This method represents a conservative estimate of the impacts of pesticides on pollinators as there is mounting evidence that other pesticides can also negatively impact beneficial insects.

Soil and Flower Collection

I sampled pesticide residues in a variety of substrates including soil, which could impact ground-nesting bees, and flowers. Soil cores were taken twice at each field, once prior to watermelon transplant in May and once at the end of the field season in August. The early season sample reflects any residues remaining from crops in previous years (e.g., rotation with seed-treated corn or soybean), whereas late season samples were considered primarily to reflect inputs occurring during the watermelon growing season. Each field was divided into four quadrants. In each quadrant, I collected 10 soil cores (500 cc volume; 10 cm depth below the soil surface), which were homogenized in the field using a bucket to mix and crush the soil to generate a single 10 g soil sample. Soil was placed on ice in airtight bags, after which they were stored in a -20°C freezer.

Samples were dried at room temperature in the dark for one week, then homogenized using a sterilized pestle to release excess moisture and passed through a 600 µm sieve to remove rocks and other large particles. The sieved soil was weighed to create a uniform 3 g sample and stored at -20°C until pesticide residue analysis.

Flower samples were taken twice at intervals of two to four weeks apart per field. Collection times coincided with pollinator observations, i.e., 7:30 am to 1:30 pm. During each sample, 150 male flowers were taken from at least 25 unique plants per field. Male flowers were chosen because of the nutritional importance of pollen for bee health and the common occurrence of systemic pesticides in pollen compared with nectar (Goulson 2013). In addition, the vast majority (>80%) of watermelon flowers are male and thus represent the greatest resource for pollinators in these fields. Seedless varieties of watermelon require pollen from pollinizer plants to be effectively pollinated. These varieties are typically intercropped and make up between one quarter and one third of the crop. Pollenizer plants were neither selectively collected nor avoided in the flower collection. Flowers were stored in one-gallon plastic bags on ice until being brought to the lab where they were kept at 4°C for up to 48 hours. The pollen-anther complex was removed from flowers with sterilized forceps, weighed to 3 g, placed in a 50 mL centrifuge tube, and homogenized with a sterilized pestle. Homogenized samples then were stored at -80°C until pesticide residue analysis.

Pesticide Quantification

Soil and flower samples were analyzed to identify pesticides and their concentrations via the QuEChERS (Quick-Easy-Cheap-Effective-Rugged-Safe) extraction method (Anastassiades et al. 2003). Homogenized soil and pollen-anther samples were analyzed using the same QuEChERS extraction method (Nixon 2016). The 3 g samples present in 50 mL centrifuge tubes were combined with 15 mL of dd water, 15 mL of Acetonitrile (ACN), internal standards, and a QuEChERS salts mix of 6 g magnesium sulfate ($MgSO_4$) and 1.5 g of sodium actetate (NaOAc). The salts are used to facilitate the extraction process into the ACN extraction solvent. Internal standards allow for accurate quantification of the concentration of those standards in the sample. Samples were then vortexed for one minute with a S8220 Deluxe Mixer Vortex (Scientific Products) and shaken on a VWR W-150 Waver Orbital Shaker for 10 minutes at high speed. After vortex and shaking, samples were centrifuged at 2,500 RPM for 10 minutes for phase separation. Upon completion of the centrifuge cycle, 10 mL of the supernatant was added to a 15 mL Agilent Dispersive SPE tube for fatty sample extractions (part no. 5982-5158). Samples were then vortexed and shaken in the same manner as above, then centrifuged at 4,000 RPM for 5 minutes. Six mL of supernatant was transferred into a 15 mL centrifuge tube and evaporated overnight in a speed vacuum (SC250EXP, ThermoFisher Scientific). Dried samples were then resuspended in 1 mL of ACN, vortexed, shaken, and centrifuged at 4,0000 RPM for 5 minutes for instrumental analysis.

The QuEChERS analysis took place on the Purdue University campus at the Bindley Bioscience Center. Pesticides were extracted from samples and analyzed using liquid chromatography-tandem mass spectrometry (LC-MS/MS). This method allowed for the precise detection and identification of pesticides present in samples down to concentrations of parts per billion. In the neonicotinoids, which were the focus of this study, limits of detection (LOD) were 0.1-0.3 μg/L. In total, 189 leaf tissue samples were screened for the four neonicotinoid insecticides (clothianidin, imidacloprid, thiamethoxam, and acetamiprid) following the protocol described in Long and Krupke (2016). Neonicotinoids were the focus of this study due to their overwhelming usage in agricultural settings. Although pyrethroid insecticides are also commonly used in watermelon production, they were not included because of detection and quantification limitations.

Statistical Analyses

The data were analyzed with general linear models using R, version 3.50. Regression models were used to assess the impact of measured independent variables on measured response variables within the same field. Independent variables used in the regression analyses included the calculated insecticide toxicity rating, the average and maximum SCB densities, and bee species richness among others. Response variables measured in these analyses included bee species richness, floral visitation, and SCB densities among others. Models were created through simple linear regression or multiple-linear regression as necessary. Multiple-linear regression models were selected using all-subsets regression which performs an exhaustive search for the subsets of explanatory variables which best explain the model (R version 3.50, leaps package). This approach selects the most parsimonious subset of independent variables to create a model which best explains the variation in the dependent variable. All analyzed regression models are included in a regression table which includes the dependent and independent variables incorporated in the model, the coefficient estimates, p-value and Adjusted R^2 value (Table 4)

Results

Pollinator Community

A diverse array of pollinators was observed visiting watermelon flowers during the 2017 and 2018 seasons. Floral observations showed that native pollinators play an important role in this system, with 72% of all flower visits coming from non-honeybee pollinators. The pollinator group with the largest number of visitations was sweat bees (Halictidae), comprising 40% of all flower visitations. Other native pollinators that play an important role include *Bombus sp.*, *Melissodes bimaculatus,* Syrphidae and others making up a combined 32% of flower visits (Figure 2).

These results were supported by the pollinator collections from fields, which took place following visual observations (Table 2). In total, 34 species of bees were collected visiting watermelon flowers, representating 20 genera and varying from highly prolific species such as the managed *Apis mellifera* and native *Augochlora pura* and *Lasioglossum pilosum* to single individuals such as *Sphecodes confertus* and *Megachile brevis*. In total, 1,031 bees were collected across the 30 field sites and two years. Species richness ranged from 2 to 15 species collected in a single field with an average species richness of 6.5. The diversity and evenness of the communities varied greatly, with ranges of Shannon's diversity index from 0.2 to 2.13 and evenness from 0.14 to 0.89 (Table 3).

Watermelon flowers were visited significantly more by native pollinators such as halictids, syrphid flies, and bumblebees, than by managed honeybees ($t = -3.89$, $df = 27$, $p < 0.001$) (Figure 8). Native pollinator visitations also significantly decreased as a result of the intensity of management based upon insecticide toxicity scores (ANOVA, $F_{3,24} = 4.714$, $p = 0.001$). This relationship was driven by fields which did not treat with insecticides. Native pollinator visitation was significantly higher in untreated fields than in the low, medium, or high intensity groups ($p < 0.05$). There was no significant difference in native pollinator visitation between the low, medium, and high management intensity groups ($p > 0.05$)

Insecticide Residues

Insecticide inputs varied from 0-10 unique applications. In all, 14 different chemicals were used across all of the farms. The most commonly used insecticides were permethrin, lambda-cyhalothrin, and spiromesifen. The most commonly used insecticide classes were pyrethroids, making up over 60% of all applications and neonicotinoids which accounted for over 10% of applications. Despite the wide variety of chemicals applied across the study, most growers relied on a relatively low diversity of chemicals and classes for pest management. The insecticides used contributed to a widely varied toxicity rating among fields, from no insecticide fields with ratings of 0 to high input fields which had ratings as high as 420. Across all reported fields, the average toxicity rating was 145. Of the 30 fields included in the study, there were four fields which did not receive a single insecticide application, two of which were certified organic. Despite this, none of these fields were ever observed to have exceeded the SCB ET of 5 beetles per plant.

All four neonicotinoids were detected in pollen, soil, and leaf tissue samples (Table 4). In all, less than 12% of the 493 total samples did not exceed the method detection limit for any of the four neonicotinoids. Clothianidin was the most commonly detected active ingredient in each of the three sample types, with detection as high as 85% of all soil samples. Although it was the most frequently detected, clothianidin was often the active ingredient with the lowest median, mean, and maximum concentrations of the four neonicotinoids that I screened. Clothianidin was also the only neonicotinoid that was never applied by any grower. The high presence of clothianidin is likely due to its high usage in other crops such as corn and soybeans (Douglas & Tooker 2015). Additionally, thiamethoxam, which was used in four fields, is a chemical precursor that is converted to clothianidin in plants and insects (Nauen et al. 2003). The Acetamiprid was detected in far fewer samples but was commonly observed in the highest concentrations.

Regression Analyses

Insecticide toxicity score had some level of explanatory value in predicting components of the pollinator community. When compared to pollinator community metrics such as bee species richness, Shannon's diversity, or evenness the insecticide toxicity score was not a significant explanatory variable ($p>0.05$). The variation of management did have an impact on these response variables however. When average SCB densities per field were regressed on bee species richness there was a significant positive relationship ($p=0.011$, Adjusted $R^2=0.1823$; Figure 4). This suggests that higher densities of SCB observed in fields across the course of the season was a significant predictor for bee species richness. Bee species richness from pollinator collections was also a positive significant predictor of flower visitation rates observed in visual observations ($p=0.013$, Adjusted $R^2=0.1725$; Figure 5). As bee species richness in a field increased so did the rate of flower visitation in that field. Neonicotinoid residues were not significant predictors of any pollinator health, community, or pollination metrics in the analysis. All models and analyzed variables are presented in Table 4.

Discussion

A wide variety of pollinators were observed in commercial watermelon fields. The majority of these pollinators were unmanaged native species that offer a valuable service to watermelon growers and could decrease the vulnerability a reliance on managed honeybees creates. Native pollinators also offered a greater contribution to floral visitations than did honeybees. This finding supports previous research which showed that native pollinators contribute more to pollination and fruit set than their managed counterparts (Winfree et al. 2008, Garibaldi et al. 2013). A rich pollinator community has a positive impact on watermelon yields. Increased floral visitation by a diverse community of pollinators is an important factor in successful pollination and fruit set in watermelon. This evidence is supported by previous research which shows that native pollinators are more effective at pollinating many crops and that diverse communities increase pollination (Kremen et al. 2002, Goodell & Thomson 2007, Winfree et al. 2007, Winfree et al. 2008, Garibaldi et al. 2013, Mallinger & Gratton 2015). Of the 34 species of bees collected in watermelon fields in this study, only five species were observed in more than 10 fields. It is unclear how much lost pollination and fruit set these species could represent, but it is possible that improving upon the diversity of the pollinator community in a field could have a significant impact on the yield by creating an additive effect that has been shown to improve pollination in watermelon, blueberry, almond, and other crops (Winfree et al. 2007, Garibaldi et al. 2013, Garibaldi et al. 2014). The important role of native pollinators offers a strong incentive for growers to consider them in management decisions. This is heightened due to the sensitivity of insecticide use that native pollinator visitations exhibit. The fields that did not treat with insecticides had significantly higher pollinator visitation than fields that did treat. There was no difference between pollinator visitation due to the intensity of management levels however. The use of any insecticides had a negative impact on native pollinator visitations which could severely limit overall visitation and potentially fruit set.

The management of commercial watermelon fields impacts the pollinator community and the health of pollinators foraging in those habitats. These impacts are likely to reduce fruit set, given that the majority of pollinator visits are attributed to non-managed species (Figure 7). This is not occurring through clear causal relationships between insecticide inputs or residues present in the field but likely through complex interactions between various factors. This has been shown in a variety of systems where multiple factors such as parasites and disease, habitat loss, climate change, and pesticides can have additive or even synergistic impacts on pollinators (Goulson et al. 2015, Klein et al. 2017). This complexity can be seen when examining the relationship between pollinator communities and pest densities. Fields that had greater pest densities also had more diverse pollinator communities. This relationship is likely due to factors that cannot be fully captured based off of season-long pest management practices. Many of the fields included in this study had insecticide residues in sub-lethal levels which would not be expected to have negative impacts on pollinators on their own, however a number of different insecticides were used and detected in low rates. This could lead to a cocktail of insecticides that pollinators are being exposed to in low rates that could have a large impact on individuals and communities. (Brittain & Potts 2011, Raimets et al. 2018) These impacts would be challenging to quantify but could play a role in the low explanatory value for residues and inputs on pollinators shown here. Additionally, the insecticide toxicity score does not consider variation in management strategies such as IPPM practices. This could mean that fields that were calculated to have higher toxicity may actually have lower contact toxicity due to spatial or temporal avoidance of pollinators. This limitation is challenging to quantify but could play a role in how grower management impacts pollinators. Pollinator communities are likely facing a host of management related challenges which are present during single years, persist from past years, and are taking place on the landscape level. This can come from treatments on neighboring crops such as corn which are intensively managed and utilize neonicotinoid seed coatings while occupying much of the landscape (Brittain et al. 2010, Krupke et al. 2012, Goulson 2013, Hladik et al. 2014, Lawrence et al. 2016). This combined impact of various factors over multiple years could help to explain why pollinator communities are more strongly predicted by the densities of pests than any management-based variables.

Through conversation it was clear that all growers understood the important role pollinators play in watermelon production. However, there was a great deal of variation in knowledge of native pollinators and how crop management practices could impact this pollinator community. Developing a better understanding of native pollinator communities and the management practices that impact them is crucial for preserving pollinators in agricultural settings. Preserving pollinators requires growers to embrace IPPM principles such as scouting and reducing pollinator toxicity from insecticide inputs, and to alter their long-held beliefs on pests in watermelon. If commercial watermelon producers are able to increase their tolerance to SCB, leading to less insecticide inputs, then pollinator communities are likely to reap the benefits of that decision.

The widescale use of insecticides in agricultural systems has created an environment in which pollinators are able to encounter a host of chemicals through multiple exposure routes such as pollen and nectar, dust, soil, and groundwater (Krupke et al. 2012, Stoner and Eitzer 2012, David et al. 2016, Hladik et al. 2016) This could explain why many of the relationships between pollinators and grower management practices were not significant. The management of a field is unlikely to have a large impact within the same season, but it can lead to sub-lethal effects that reduce fitness, behavior, foraging ability, and navigation and can potentially lead to long-term declines in pollinator communities (Morandin et al. 2005, Desneux et al. 2007, Williams et al. 20110, Brittain & Potts 2011, Whitehorn et al. 2012, Goulson 2013, Rundlöf et al. 2015). Within season management may be having a greater influence on proximate factors of bee health like behavior and fitness. The cumulative impact of these stressors could lead to long-term loss of native pollinators that could explain why conventionally managed fields have lower diversity and evenness than organic management fields in this study. The impacts of repeated stressors over many years has the ability to suppress pollinator populations as a result of the decreased health that occurs within a season. Growers must consider their management in the ultimate, rather than proximate sense because the impacts of their decisions may build up to have negative impacts on pollinators.

The implementation of IPPM practices in commercial watermelon production is likely to have a long-term positive impact on the pollinator communities present within their fields. In the closely related cantaloupe, IPPM practices have been shown to have a positive effect on yield, which is likely due to the ability to confidently assess pest populations, tolerate pests below damaging levels and reduce insecticide inputs which could be reducing pollination (Brust et al. 1996, Brust & Foster 1999). Watermelon offers another opportunity to improve upon long-held management practices by implementing scouting protocols and increasing tolerance to SCB to the ET of 5 beetles per plant, reducing insecticide use. In order to increase adoption of this practice, more research needs to be done to verify the positive impacts on yield which will help to increase adoption efforts. This study indicates that IPPM is likely to reduce insecticide applications which is likely to have a positive impact on pollinator communities and pollination due to reduced non-target contact without experiencing pest mediated losses. IPPM practices in watermelon production have the potential to reform the way in which the crop is managed while improving outcomes for both producers and beneficial insects such as pollinators.

CONCLUSIONS

This research indicates that there is room for reductions in insecticide application while still maintaining pest levels below the ET. Many growers are managing their fields more intensively than is necessary based upon pest densities. This intensive management has led to widescale use of insecticides which are often being used prophylactically or with little knowledge of pest densities. Implementation of the described scouting protocol is a cheap and effective means of assessing pest densities and eliminating prophylactic applications. The elimination of prophylactic applications is supported by the result that only the difference between applying insecticides and not has an impact on SCB densities. Once insecticides were applied, more intensive management did not result in fewer SCB than did less intensive management. Although insecticide application does reduce pest densities, no field exceeded the ET regardless of management. This result indicates that in some cases, no insecticide applications are necessary for maintaining pest densities below the ET. When scouting is used alongside threshold-based management I predict that growers will be able to reduce their insecticide applications. This is important due to the potential impact that unnecessary insecticide applications may have on beneficial insects such as pollinators.

Pollinators are a crucial component of commercial watermelon production and have been recently emphasized by growers and researchers alike. My research shows that a diverse array of pollinators is present in watermelon fields and could provide valuable contributions to pollination. This is valuable when considered alongside results that show that native pollinators account for a greater proportion of flower visitation than do honey bees. A diverse and abundant pollinator community has been shown to improve pollination and fruit set but grower management impacts these communities. Despite, the lack of evidence that residues and the toxicity of inputs have a significant impact on pollinators, I show that pest densities are a positive predictor for pollinator species richness. This means that many aspects of pest management could be having additive or synergistic effects on pollinator communities.

Future directions of this work should focus on better understanding the interactions between a number of potential factors that could be having a negative impact on pollinators. One area that should be further examined is other pesticides used in watermelon production that are increasingly being shown to impact pollinator health, either through direct effects or synergism with insecticides. My study was limited to only insecticides, and only examined residues for neonicotinoids. Additionally, the impacts of pesticide use in other crops should be examined to better assess the impact of watermelon management compared to extra-field management on pollinators in watermelon fields. A number of other factors that have been shown to negatively impact pollinators should be examined as well. These include, disease, land use, and climate change. All of these factors are likely to have a cumulative effect that likely explains the difficulty in assessing the impact of insecticide use in watermelon fields on the pollinator communities in those fields. Finally, more research should be completed on the impact and efficacy of specific pollinator groups and species on watermelon pollination and fruit set. We know that a diverse array of pollinators is present and that they have been shown to have an important role in pollination, but their relative contributions are mostly unknown. This could be an important consideration for growers that are attempting to bolster pollination.

Although the impact of management on pollinators is likely complex, with a variety of entangled factors, implementing IPPM strategies is expected to remedy some of these concerns. These strategies include scouting and threshold-based management, eliminating prophylactic insecticide treatment, conserving or establishing pollinator habitat, and to mitigate risk to pollinators. Mitigating pollinator risk can be achieved through temporal and spatial avoidance as well as selecting chemicals that are less toxic to pollinators. These IPPM practices will serve as a valuable set of tools and will allow for the needs of commercial watermelon growers to be met in a manner which balances, pests, pollinators and economic viability.

Table 1: Name, location, field size, and description of operation of watermelon fields used in 2017 and 2018. Over the two years, 16 commercial operations were used in the study, with 14 participating both years and two participating for one year each. The description of operation abbreviations represents the variation in management practices. Conventional (C) and Organic (O) operations were represented as well as primarily melon production (M) operations and diversified (D) operations. The diversified operations were differentiated from primarily melon production operations by the presence of three or more on-farm crops.

Farm #	Location	Field Size (ac) 2017	Field Size (ac) 2018	Description of Operation
1	LaGrange, IN	1.78	1.52	C, D
2 (2017 only)	Millersburg, IN	3.29		C, D
3 (2018 only)	Goshen, IN		1.32	C, D
4	Battle Ground, IN	2.00	6.65	C, D
5	Rossville, IN	0.686	0.365	O, D
6	Spencer, IN	0.578	4.53	C, D
7	Vallonia, IN	20.5	17.9	C, D
8	Merom, IN	100.0	57.2	C, M
9	Haddon, IN	22.4	8.84	C, D
10	Bruceville, IN	43.0	7.62	C, M
11	Lawrenceville, IL 2017, Vincennes, IN 2018	31.7	54.9	C, D
12	Washington, IN	2.50	2.21	C, D
13	Vincennes, IN	15.7	34.1	C, M
14	Johnson, IN	28.0	6.77	C, M
15	Johnson, IN	13.7	10.6	C, M
16	Decker, IN	29.5	26.5	C, M

Table 2: Mean, variance to mean ratio, mean crowding, Iwao's regression a and b, and Taylor's power law a and b calculations used to assess SCB aggregation in commercial watermelon fields during 2017 and 2018 field seasons.

Mean (m)	Variance to Mean Ratio (s^2/m)	Mean Crowding (m_c)	Iwao's Regression (a)	Iwao's Regression (b)	Taylor's Power Law (a)	Taylor's Power Law (b)
0.664	**1.833**	**1.291**	**0.468**	**1.238**	**1.653**	**1.138**
	$s^2/m > 1$ indicates aggregated distribution		$a > 0$ indicates aggregated distribution	$b > 1$ indicates aggregated distribution		

Table 3: Number of plant samples (rounded to the nearest whole number) necessary to assess various mean densities of striped cucumber beetles with 25% precision. Recommended plant samples of 8 required to detect between 4 or more beetles per plant highlighted in light grey.

Mean Density ($\bar{x}$)	0.5	1	2	3	4	5	10
Number of Samples (n)	48	26	15	10	8	7	4

Table 4: The cost of scouting for the entire season (12 weeks) was calculated using the recommended sampling of 8 plants at two paces, 10 minutes per 4 plant transect, and 20 minutes per 4 plant transect with an employee earning $7.25, $10, $12.50, and $15 an hour. This will allow for growers to accurately assess the cost for implementing a scouting protocol at their field using specific sampling variables.

Hourly wage of scout	10 minutes/transect	20 minutes/transect
$7.25/hour	$29	$58
$10/hour	$40	$80
$12.50/hour	$50	$100
$15/hour	$60	$120

Table 5: The active ingredients used during the 2017 and 2018 watermelon seasons along with the trade names of those active ingredients. The cost/oz. range based upon the insecticide expenditure received from growers or the NDSU Extension Insect Management Guide (Knodel et al. 2019) for the product used or a comparable product. The cost/acre range was calculated using the cost/oz multiplied by the oz/acre rate that was used by growers.

Active Ingredient	Trade Names	Cost/Oz. Range	Cost/Acre Range
Abamectin	Abacus, Agri-Mek, Reaper, Tide Timectin	$1.09 - $2.11	$7.38 -$17.44
Acetamiprid	Assail	$6	$24 - $36
Bifenthrin	Bifenthrin, Bifenture EC, Brigade, Sniper	$0.66 - $0.90	$1.80 - $5.76
Chlorantraniliprole	Coragen IC	$7.63	$22.89 - $57.15
Cyantraniliprole	Verimark IC	$7.11	$15.36
Cyfluthrin	Tombstone	$2.19	$5.48 - $6.13
Dimethoate	Dimethoate	$0.77	$5.92
Fenpyroximate	Portal XLO	$0.79	$25.35
Flubendiamide	Belt	$8.59	$12.89
Flupyradifurone	Sivanto	$2.57	$17.99
Imidacloprid	Advise Four, Malice 2F	$0.29 - $1.58	$4.64 - $16.59
Lambda-Cyhalothrin	Grizzly, L-C, Lambda-Cyhalothrin, Warrior	$0.86 - $2.47	$1.72 - $4.94
Permethrin	Permethrin, Permup, Pounce	$0.18 -$0.35	$1.02 - $2.10
Spiromesifen	Oberon	$2.24 - $3.49	$17.90 - $27.92
Thiamethoxam	Platinum	$2.16	$10.80

Table 6: The active ingredients used during the 2017 and 2018 watermelon seasons along with the field where they were applied in 2017 and 2018. The number of applications is in parentheses if greater than one. The total number of applications of the product across both years and all fields. The EIQ Bee Toxicity number was retrieved from the 2017 EIQ database (Eshenaur et al. 2017) and used to calculate the toxicity score for each field. The range of rates of each active ingredient applied across all fields are reported in fl. oz/acre unless otherwise noted. The calculated toxicity score range of the active ingredients based upon EIQ numbers and (Mallinger et al. 2015). *Cyantraniliprole does not have a reported EIQ Bee Toxicity; the Flubendiamide EIQ Bee Toxicity used instead. Cyantraniliprole and Flubendiamide are in the Diamide class. Flubendiamide has the lowest reported EIQ Bee Toxicity for all Diamides and is therefore a conservative approach. **Flupyradifurone does not have an EIQ Bee Toxicity. Flupyradifurone and Acetamiprid are both Group 4 Insecticides. Acetamiprid is the group 4 insecticide with the lowest EIQ value and was used in the calculation as a conservative replacement.

Active Ingredient	Field # (Applications) in 2017	Field # (Applications) in 2018	# of Applications	EIQ Bee Toxicity	Rate Range (fl. oz/acre)	Toxicity Score Range
Abamectin	6, 10, 15, 16 (2)	8, 10, 15	8	28.5	3.5 - 16	1.87 - 8.55
Acetamiprid	10, 15, 16	10, 11, 13	6	17.1	4 - 6 oz/acre (dry)	20.52 - 30.78
Bifenthrin	7 (8), 8 (3)	3, 6, 7 (7), 8 (2), 15	23	28.5	2 - 7	14.25 - 49.875
Chlorantraniliprole	8 (2)	8 (2)	4	18.81	3 - 7.49	11.78 - 29.41
Cyantraniliprole	8		1	5.7*	2.16	2.57
Cyfluthrin	1 (4), 6 (2), 10 (3), 16	10	11	28.5	2.5 -2.8	17.81 - 19.95
Dimethoate	1		1	28.5	16	228
Fenpyroximate	11, 8	11	3	3	32	4.8
Flubendiamide	10		1	5.7	1.5	4.27

Table 6 continued

Flupyradifurone	15		1	17.1**	7	24.99
Imidacloprid	4, 6	4, 8, 16	5	28.5	4 - 16	57 - 172.07
Lambda-Cyhalothrin	1 (2), 4 (2), 6 (2), 11 (2)	4, 6 (3), 11 (4), 13, 16	18	28.5	1.5 - 3	7.12 - 14.82
Permethrin	1 (2), 8 (2), 9 (3), 12 (7), 13 (2)	8 (2), 9 (3), 12 (7), 16	29	15	3 - 10	18 - 60
Spiromesifen	8, 10 (2), 11, 13,	8, 10 (2), 11 (2), 13, 16	12	5.7	8	11.4
Thiamethoxam	11, 13	11, 13	4	28.5	5	35.62

Table 7: The cost per acre that could be saved by reducing one insecticide application over the course of the season on fields of varying sizes. Field sizes were selected from the range encountered in the study: 1 acre represents small-scale production; 5 acres was a typical small plot; 20 acres was the average of all fields; 50 acres was a typical large-scale plot; 100 acres was the largest field in the study. Insecticide per application rates were selected from reported costs of common-use insecticides: $1.00 per acre is the lowest cost insecticide, a low rate permethrin treatment; $5.00 per acre is approximately the cost of many cheap insecticides; $9.75 per acre is the average cost of all reported insecticide applications; $30.00 per acre is approximately the cost of many expensive insecticides; $57.15 per acre is the highest reported cost insecticide, a high rate chlorantraniliprole treatment.

	1 acre	5 acres	20 acres	50 acres	100 acres
$1/acre	$1	$5	$20	$50	$100
$5/acre	$5	$25	$100	$250	$500
$9.75/acre	$9.75	$48.75	$195	$487.50	$975
$30/acre	$30	$150	$600	$1,500	$3,000
$57.15/acre	$57.15	$285.75	$1,143	$2,857.50	$5,715

Table 8: Summary of neonicotinoid insecticides (Clothianidin, Imidacloprid, Thiamethoxam, and Acetamiprid) detected in samples from pollen, soil, and leaf tissues collected in participating watermelon fields in 2017 and 2018. The table includes the percent of total samples with residues detected above 0.3 ppb method detection limit, median and mean AI in ppb detected in samples exceeding the method detection limit, and the range AI in ppb of all collected samples. Neonicotinoids were screened in 74 pollen samples, 240 soil samples, and 179 leaf tissue samples

Sample Type	Compound	% > Method Detection Limit	Median (ppb AI)	Mean (ppb AI)	Range (ppb AI)
Pollen	Clothianidin	24.32	1.177	1.577	0 - 4.566
Pollen	Imidacloprid	16.22	1.083	2.070	0 - 6.886
Pollen	Thiamethoxam	8.11	1.723	7.125	0 - 34.0
Pollen	Acetamiprid	5.41	16.927	35.639	0 - 107.61
Soil	Clothianidin	85.00	1.527	2.006	0 - 8.37
Soil	Imidacloprid	62.50	1.667	7.152	0 - 183.523
Soil	Thiamethoxam	13.33	0.525	3.872	0 - 99.16
Soil	Acetamiprid	6.67	9.515	15.673	0 - 60.947
Leaf Tissue	Clothianidin	79.33	1.525	4.142	0 - 142.01
Leaf Tissue	Imidacloprid	49.72	1.710	27.809	0 - 453.53
Leaf Tissue	Thiamethoxam	31.28	5.015	115.441	0 - 2712.29
Leaf Tissue	Acetamiprid	6.15	1.290	712.901	0 - 3891.94

Table 9: Regression analyses performed with the Independent and Dependent variables listed along with the F, p, and Adjusted R^2 statistics from each analysis.

Independent Variables	Dependent Variables	F-Statistic	p-value	Adjusted R^2
SCB Density	Clothianidin Residues in Leaf Tissues (ppb) (Imidacloprid, Thiamethoxam, and Acetamiprid excluded from model)	$F_{1,176}$ =1.684	0.196	0.009
Insecticide Toxicity Score	Maximum SCB Density	$F_{1,26}$ = 5.218	0.0308	0.1351
Insecticide Toxicity Score	Average SCB Density	$F_{1,26}$ = 4.152	0.0519	0.1046
Average SCB Density	Bee Species Richness	$F_{1,28}$ = 7.465	0.0108	0.1823
Bee Species Richness	Watermelon Flower Visitation	$F_{1,28}$ = 7.046	0.01295	0.1725

Table 10: The table includes an economic and intensity of management assessment for each field. Insecticide cost per acre was calculated with the price per fluid ounce of insecticide multiplied by the per acre application rate for all insecticides applied across the season. Intensity of management was assessed with three approaches, the presence or absence of a prophylactic pre-treatment, the number of insecticide applications across the watermelon growing season, and the insecticide toxicity score for bees. In addition to these approaches, individual active ingredients used and the number of applications of each is included. The table is sorted by the presence of a pre-treatment and then in descending order of the number of insecticide applications. *Cyantraniliprole does not have a reported EIQ Bee Toxicity; the Flubendiamide EIQ Bee Toxicity used instead. Cyantraniliprole and Flubendiamide are in the Diamide class. Flubendiamide has the lowest reported EIQ Bee Toxicity for all Diamides and is therefore a conservative approach. **Flupyradifurone does not have an EIQ Bee Toxicity. Flupyradifurone and Acetamiprid are both Group 4 Insecticides. Acetamiprid is the group 4 insecticide with the lowest EIQ value and was used in the calculation as a conservative replacement.

Pre-Treatment	# of Insecticide Applications	Insecticide Applications of Chemicals	Field	Year	Insecticide Toxicity Score	Insecticide Cost per Acre
Yes	10	Bifenthrin 3x, Permethrin 2x, Spiromesifen, Chlorantraniliprole 2x, Fenpyroximate, Cyantraniliprole*	8	2017	241.26	$140.36
Yes	9	Imidacloprid (Drench), Chlorantraniliprole x2, Spiromesifen, Permethrin 2x, Bifenthrin 2x, Abamectin	8	2018	261.89	$143.43

Table 10 continued

Yes	9	Thiamethoxam (Tray Treatment), Lambda-Cyhalothrin 4x, Spiromesifen 2x, Acetamiprid, Fenpyroximate	11	2018	138.46	$142.81
Yes	5	Imidacloprid (Drench), Cyfluthrin 2x, Lambda-Cyhalothrin 2x	6	2017	210.19	$46.30
Yes	5	Thiamethoxam (Tray Treatment), Lambda-Cyhalothrin 2x, Spiromesifen, Fenpyroximate	11	2017	74.05	$71.48
Yes	4	Thiamethoxam (Drench), Spiromesifen, Permethrin 2x	13	2017	143.02	$42.32
Yes	4	Thiamethoxam (Drench), Spiromesifen, Lambda-Cyhalothrin, Acetamiprid	13	2018	83.79	$72.42

Table 10 continued

Yes	3	Imidacloprid (Drench), Lambda-Cyhalothrin 2x	4	2017	201.71	$26.47
Yes	2	Imidacloprid (Drench), Lambda-Cyhalothrin	4	2018	186.89	$21.53
No	9	Lambda-Cyhalothrin 2x, Cyfluthrin 4x, Permethrin 2x, Dimethoate	1	2017	401.17	$39.81
No	8	Cyfluthrin 3x, Spiromesifen 2x, Abamectin, Flubendiamide, Acetamiprid	10	2017	109.57	$124.33
No	8	Bifenthrin 8x	7	2017	114	$14.40
No	7	Bifenthrin 7x	7	2018	99.75	$12.60
No	7	Permethrin 7x	12	2018	420	$12.60
No	7	Permethrin 7x	12	2017	420	$12.60
No	5	Spiromesifen 2x, Cyfluthrin, Acetamiprid, Abamectin	10	2018	75.82	$109.46
No	4	Abamectin 2x, Cyfluthrin, Acetamiprid	16	2017	57.57	$65.01

Table 10 continued

No	4	Lambda-Cyhalothrin 3x, Bifenthrin	6	2018	48.65	$12.28
No	4	Permethrin, Lambda-Cyhalothrin, Imidacloprid, Spiromesifen	16	2017	168.52	$36.38
No	3	Permethrin 3x	9	2018	144	$5.40
No	3	Permethrin 3x	9	2017	144	$5.40
No	3	Abamectin, Acetamiprid, Flupyradifurone**	15	2017	57.05	$61.07
No	2	Abamectin, Bifenthrin	15	2018	34.91	$16.68
No	1	Bifenthrin	3	2018	49.87	$4.62
No	0	N/A	2	2017	0	$0
No	0	N/A	1	2018	0	$0
No	0	N/A	5	2017	0	$0
No	0	N/A	5	2018	0	$0

Table 11: All collected and identified species of bees present in commercial watermelon fields during the 2017 and 2018 seasons. Pollinators are listed by species with the total individuals of that species collected, the number of fields out of 30 in which each species was present, and the range of individuals collected in fields in which that species was present.

Species/Group	Total Collected	# of Watermelon fields present out of 30	Range in fields present
Apis mellifera	540	29	1-76
Bombus impatiens	70	20	1-16
Bombus pensylvanicus	1	1	1
Melissodes bimaculatus	67	22	1-10
Melissodes druriellus	1	1	1
Agapostemon splendens	17	9	1-6
Agapostemon virescens	1	1	1
Augochlora pura	62	9	1-18
Augochloropsis metallica	2	2	1
Halictus confusus	10	4	1-5
Halictus ligatus	35	7	1-23
Halictus parallelus	3	2	1-2
Halictus sp. (unidentified)	6	4	1-3
Lasioglossum bruneri	3	2	1-2
Lasioglossum imitatum	29	9	1-8
Lasioglossum leucocomum	5	3	1-2
Lasioglossum leucozonium	1	1	1
Lasioglossum oceanicum	5	4	1-2
Lasioglossum pilosum	52	14	1-18
Lasioglossum versatum	36	18	1-5
Lasioglossum zephyrum	1	1	1
Lasioglossum sp. (unidentified)	12	8	1-4
Nomia nortoni	1	1	1
Sphecodes confertus	1	1	1

Table 11 continued

Calliopsis andreniformis	26	3	1-23
Ceratina calcarata	18	3	1-11
Coelioxys sayi	1	1	1
Holcopasites caliopsidis	2	2	1
Hylaeus annulatus	1	1	1
Megachile brevis	1	1	1
Nomada tiftonensis	1	1	1
Peponapis pruinosa	3	3	1
Triepeolus remigatus	11	4	1-4
Xylocopa virginica	6	5	1-2

Table 12: Farm specific insecticide toxicity scores and pollinator community metrics including species richness of bees, Shannon's Diversity Index (H) and Evenness metric (J'). The table is arranged by field in descending order of insecticide toxicity score. * Flupyradifurone does not have an EIQ Bee Toxicity, Acetamiprid EIQ Bee Toxicity used for Toxicity Score Calculations. Flupyradifurone and Acetamiprid are both Group 4 Insecticides. Acetamiprid is the group 4 insecticide with the lowest EIQ value so it was chosen as a conservative replacement.

Farm	Year	# of Insecticide Applications	Insecticide Toxicity Score	Bee Species Richness	Shannon's Diversity (H)	Evenness (J')
12	2018	7	420	8	1.790	0.861
12	2017	7	420	5	1.152	0.716
1	2017	9	401.17	5	1.127	0.701
8	2018	9	261.89	5	0.543	0.338
8	2017	10	241.26	7	1.229	0.632
6	2017	5	210.19	5	1.067	0.663
4	2017	3	201.71	7	1.176	0.604
4	2018	2	186.89	8	1.703	0.819
16	2017	4	168.52	2	0.143	0.206
9	2018	3	144	5	0.613	0.381
9	2017	3	144	7	1.226	0.630
13	2017	4	143.02	5	1.062	0.660
11	2018	9	138.46	11	2.137	0.891
7	2017	8	114	5	0.923	0.573
10	2017	8	109.57	8	1.452	0.698
7	2018	7	99.75	13	1.951	0.761
13	2018	4	83.79	6	1.153	0.644
10	2018	5	75.82	8	1.453	0.699
11	2017	5	74.05	5	0.778	0.483
16	2017	4	57.57	7	1.507	0.775
15	2017	3*	54.05	5	0.909	0.565

Table 12 continued

3	2018	1	49.87	4	1.034	0.746
6	2018	4	48.65	8	1.712	0.823
15	2018	2	34.91	5	1.378	0.856
2	2017	0	0	4	0.569	0.411
1	2018	0	0	7	1.732	0.890
5	2017	0	0	10	2.031	0.882
5	2018	0	0	15	2.177	0.804

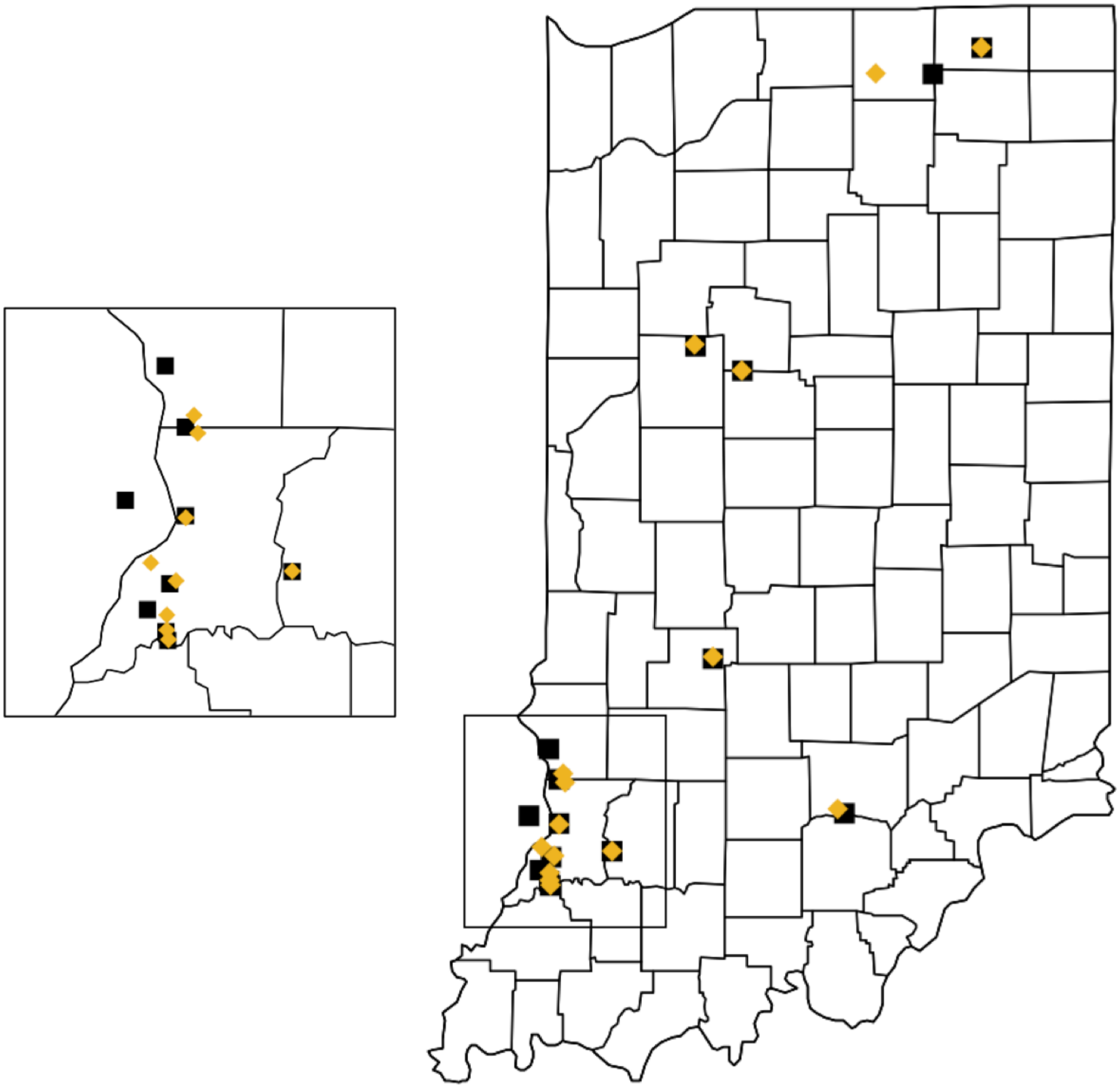

Figure 1: Indiana map with the locations of field sites in 2017 and 2018. Black squares represent field sites in 2017, gold diamonds represent field sites in 2018. The inset map on the left of the figure is a close-up of Knox and neighboring counties. This is the primary watermelon production region in Indiana and where 18 of the 30 field sites from 2017 and 2018 were located. One field was located over the Indiana border in Lawrenceville, IL in 2017.

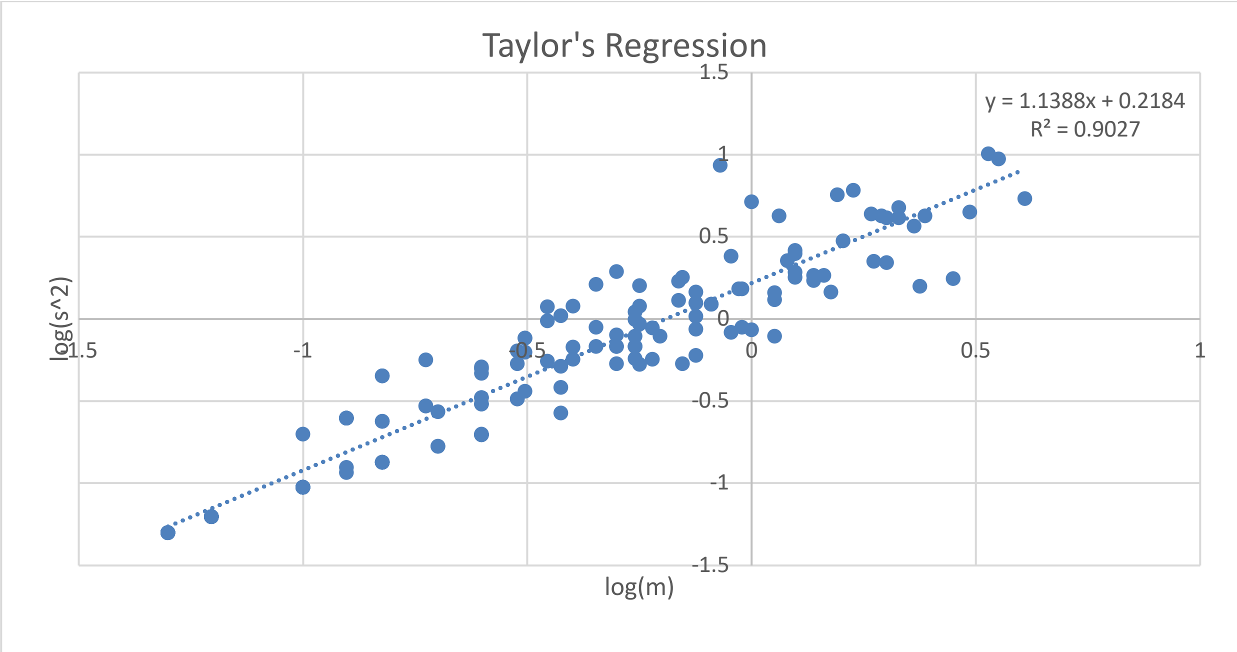

Figure 2: Taylor's Regression plot showing the significant and positive relationship between the log transformed mean and log transformed variance. The linear regression line generated from this analysis was used to calculate Taylor's Power Law using the equation $s^2 = a\bar{x}^b$ which was used to determine the sample size required to effectively scout for SCB.

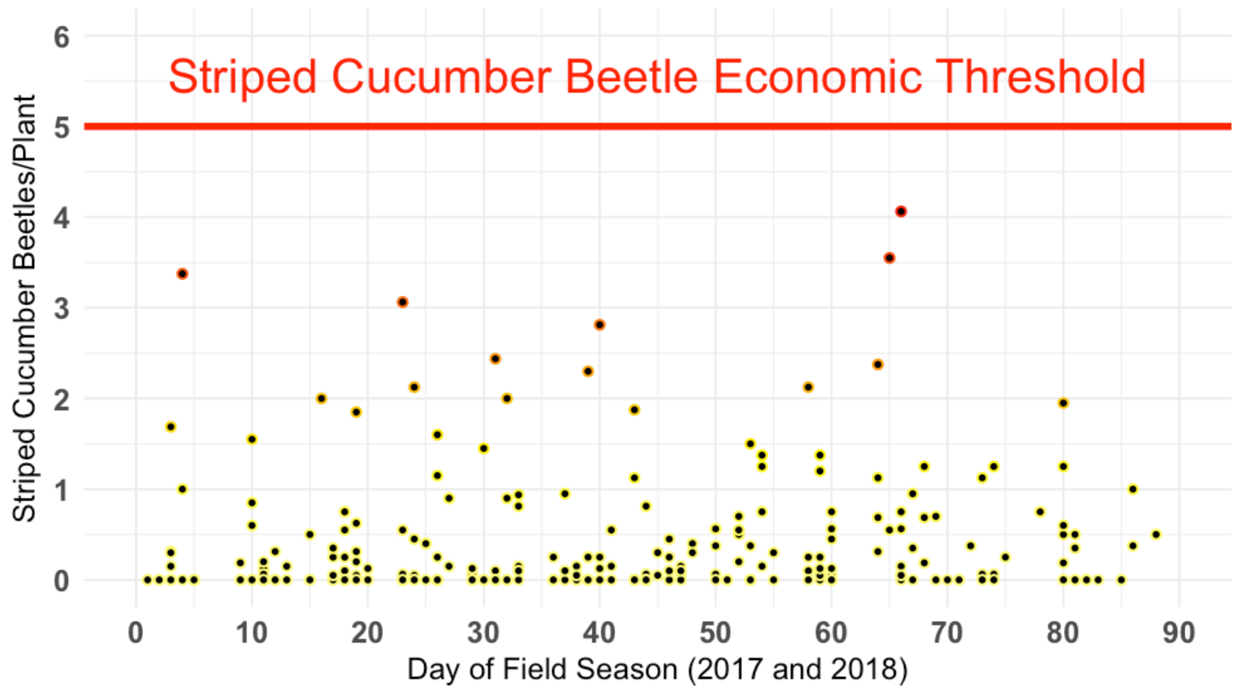

Figure 3: Mean SCB densities per watermelon plant for all 30 field sites across the 2017 and 2018 field seasons. The threshold of 5 SCB per plant is indicated with the horizontal red line. No sampling date in any field during the two seasons reached threshold.

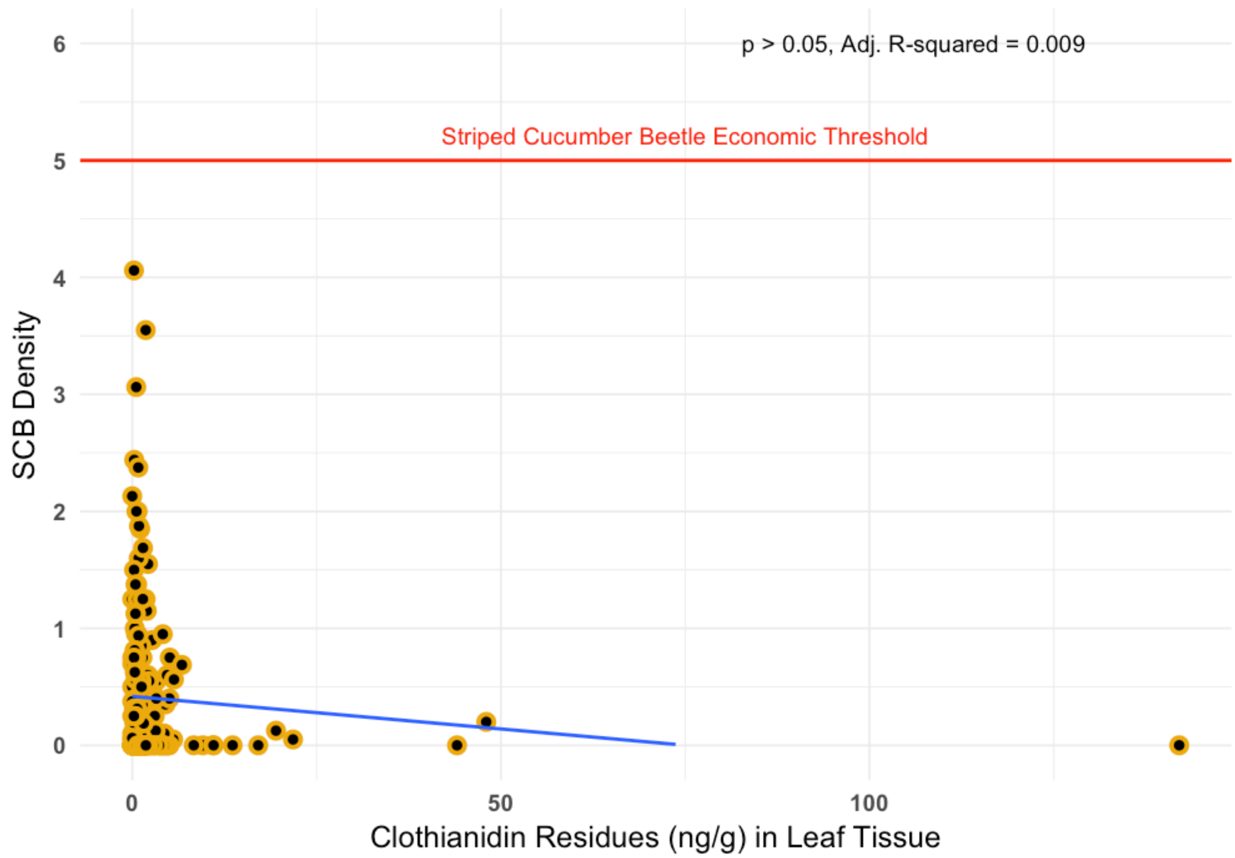

Figure 4: Linear regression plot showing the relationship between Clothianidin residues in leaf tissue on SCB densities during the same date as the leaf tissue collection. Each of the four neonicotinoid insecticides which were measured were used in a multiple linear regression model and none of the neonicotinoids had a significant relationship with pest densities. Clothianidin was the most predictive variable and thus is displayed in the figure to show the lack of a significant relationship.

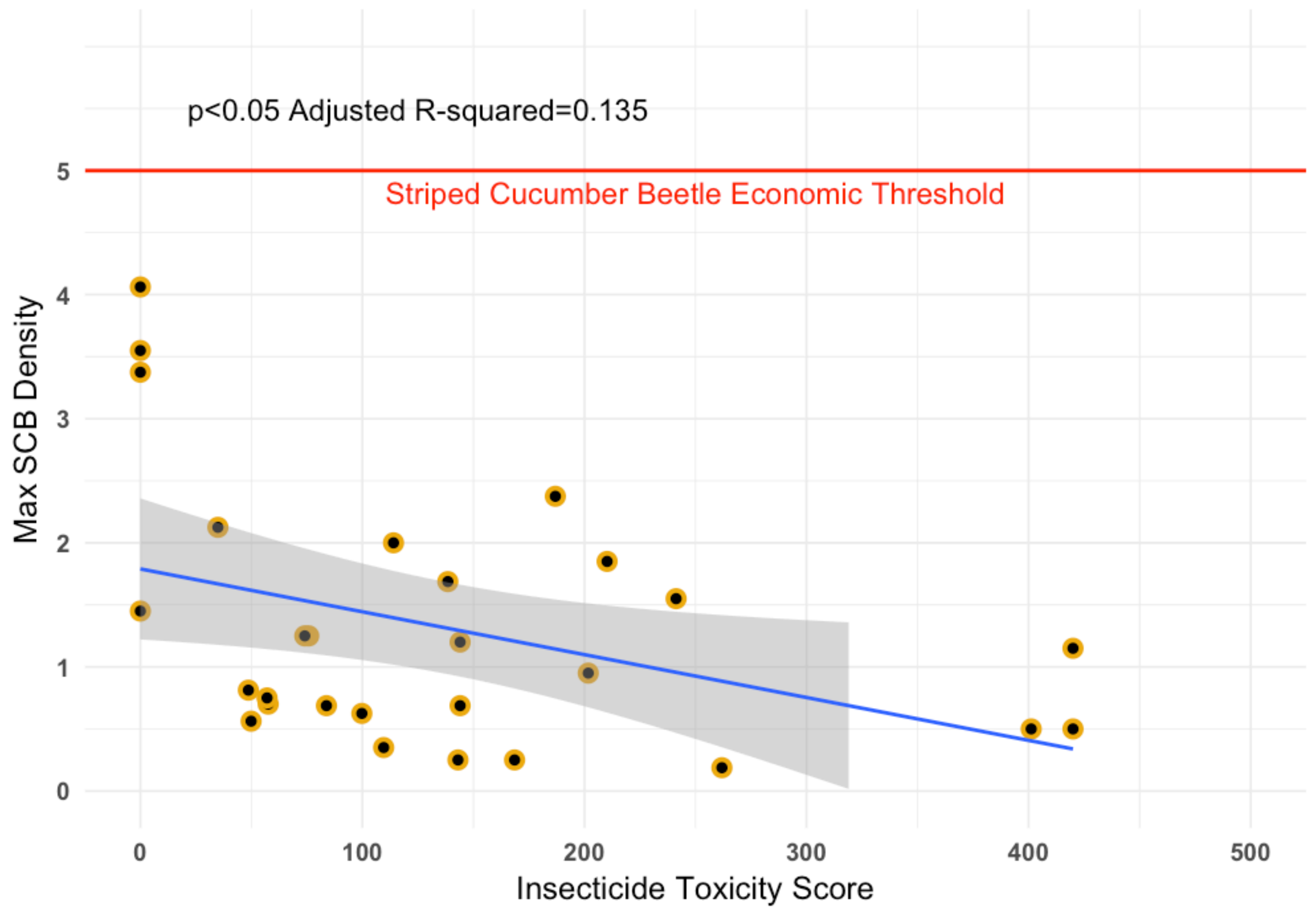

Figure 5: Linear regression plot showing the significant negative relationship between the insecticide toxicity score and the maximum SCB density observed in each field. The 95% confidence interval is indicated by the grey shaded area surrounding the blue line.

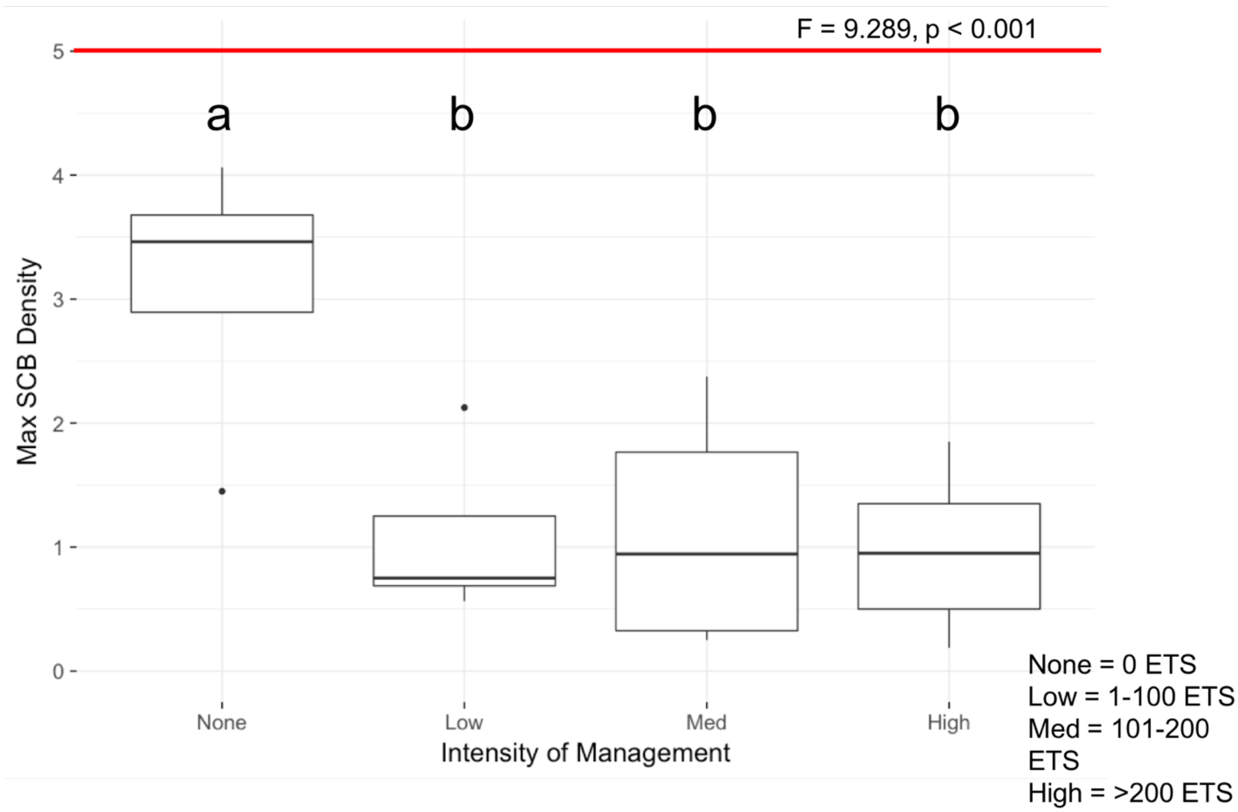

Figure 6: A boxplot showing the significant increase in max SCB densities of fields which were not treated with insecticides (Insecticide Toxicity Score = 0) compared to low, medium and high intensity fields (Insecticide Toxicity Score of 1-100, 100-200, and >200 respectively). Low, medium, and high intensity fields were not significantly different from each other. The threshold for SCB was never observed in any field during the 2017 or 2018 field seasons.

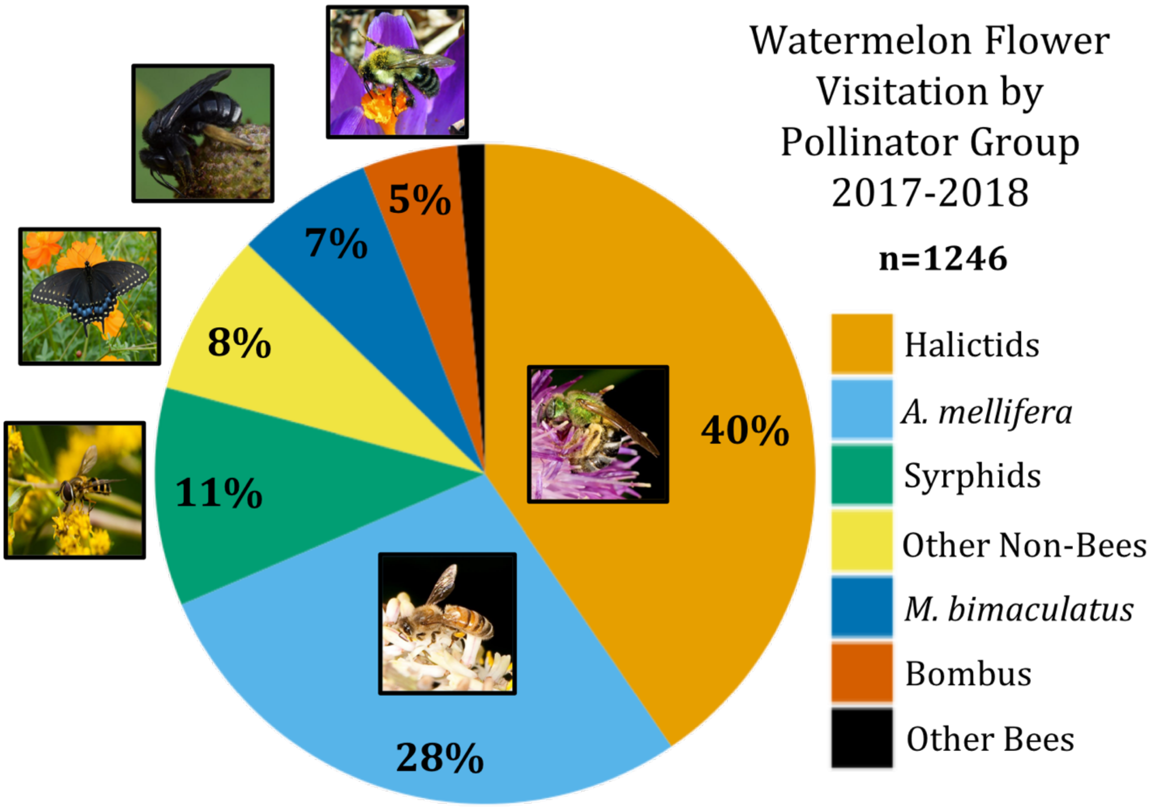

Figure 7: Pie chart showing the visitation rates of pollinator groups on watermelon flowers at 30 commercial watermelon fields during the 2017 and 2018 season. Pollinator visitation data was generated during visual observations in the field.

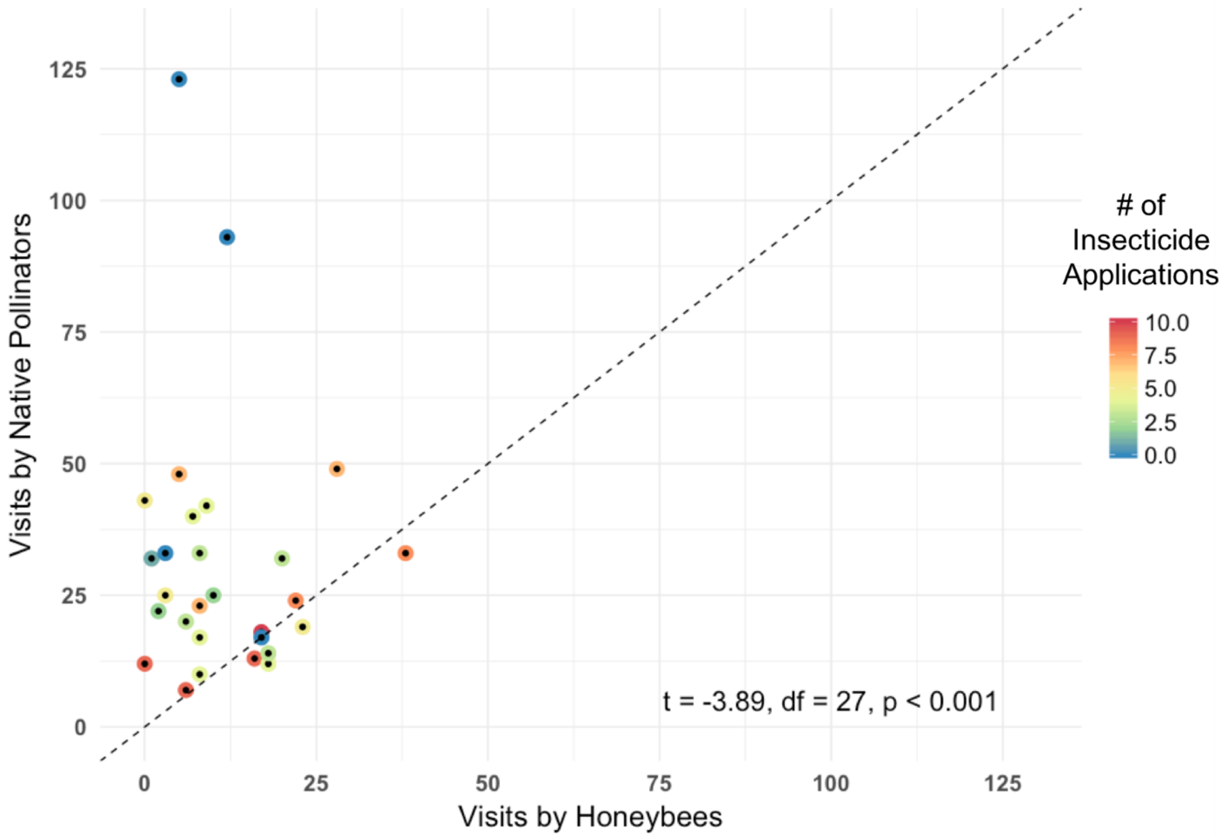

Figure 8: Pollinator visits comparison of honeybees along the x-axis and all native pollinators combined on the y-axis. The dashed line represents equal contributions from honeybees and native pollinators. Dots above the line had higher native pollinators visitation, while dots below the line had higher honeybee visitation. Each dot represents one field site with the color of the dot being associated with the number of insecticide applications at that field with hot colors representing more applications.

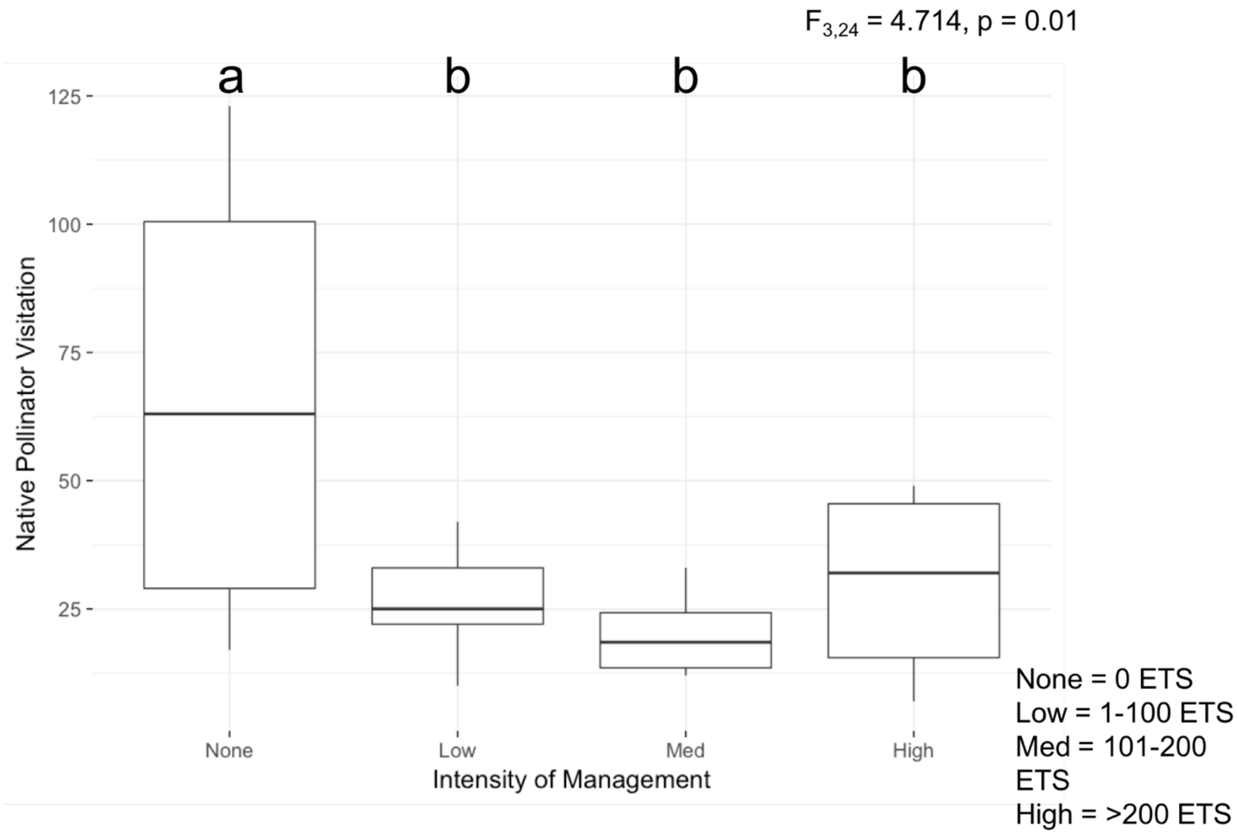

Figure 9: Boxplot showing the significant increase in native pollinator visitation of fields which were not treated with insecticides (Insecticide Toxicity Score = 0) compared to low, medium and high intensity fields (Insecticide Toxicity Score of 1-100, 100-200, and >200 respectively). Low, medium, and high intensity fields were not significantly different from each other.

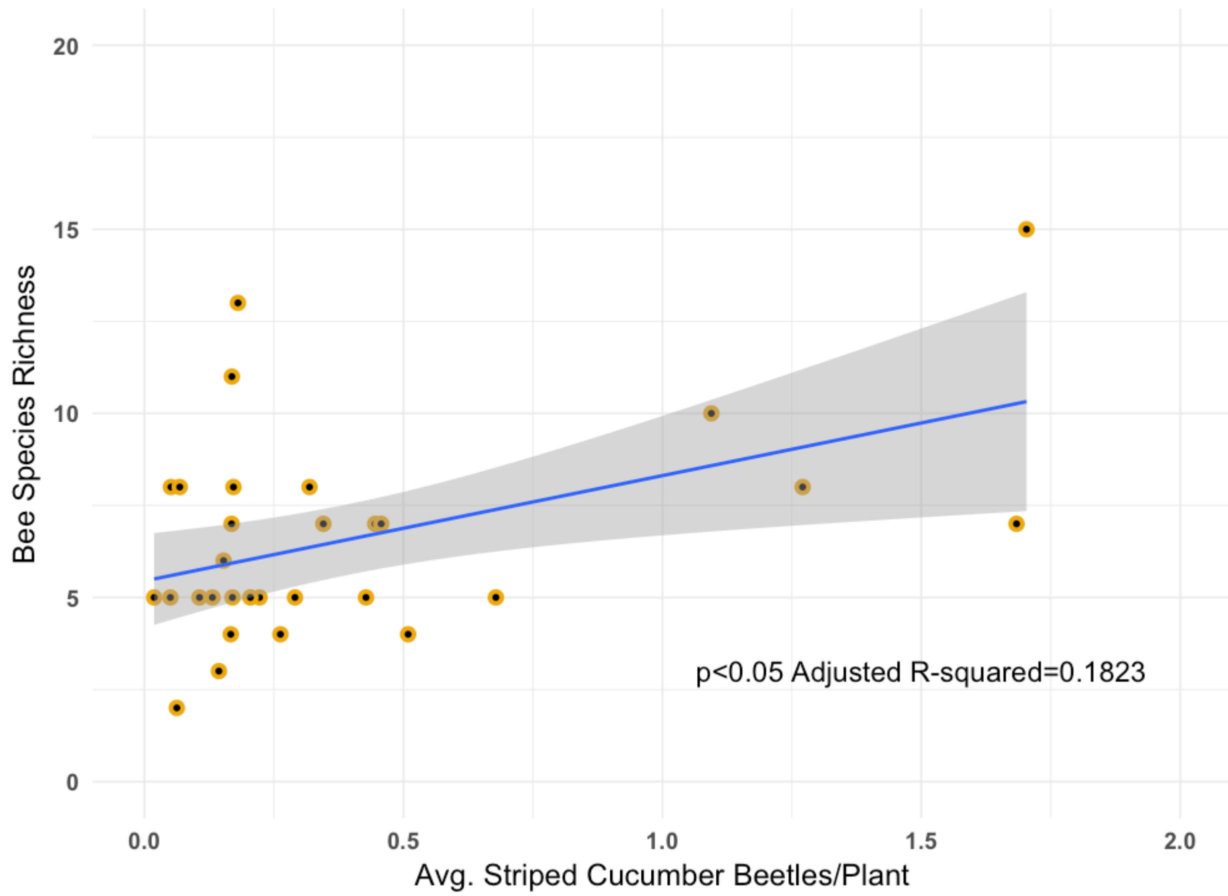

Figure 10: Linear regression plot showing the significant positive relationship between the average number of SCB per plant and bee species richness in commercial watermelon fields. The 95% confidence interval is indicated by the grey shaded area surrounding the blue line.

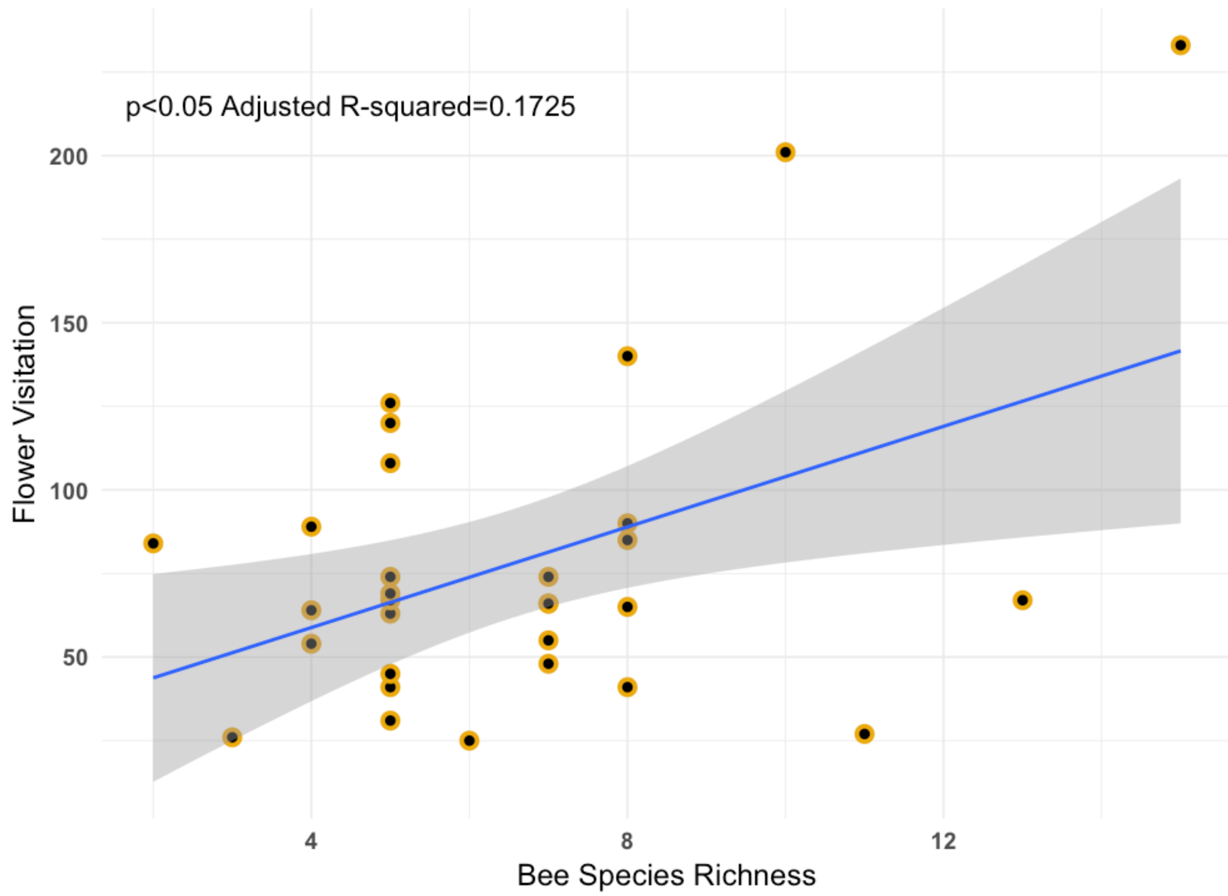

Figure 11: Linear regression plot showing the significant positive relationship between bee species richness in a field and the flower visitation rate of that field. This relationship can be interpreted as fields which have a greater number of pollinator species are likely to experience better pollination. The 95% confidence interval is indicated by the grey shaded area surrounding the blue line.

REFERENCES

Adamowicz, W., Louviere, J., & Swait, J. (1998). Introduction to attribute-based stated choice methods. *Report to NOAA Resource Valuation Branch, Damage Assessment Centre*, (January). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.119.6910&rep=rep1&type=pdf

Adlerz, W. C. (1966). Honey bee visit numbers and watermelon pollination. *Journal of Economic Entomology*, *59*(1), 28–30. https://doi.org/10.1093/jee/59.1.28

Anastassiades, M., Lehotay, S. J., Štajnbaher, D., & Schenck, F. J. (2003). Fast and easy multiresidue method employing acetonitrile extraction/partitioning and "dispersive solid-phase extraction" for the determination of pesticide residues in produce. *Journal of AOAC International*, *86*, 412–431. https://doi.org/10.2478/s11687-011-0011-9

Artz, D. R., & Nault, B. A. (2011). Performance of Apis mellifera, Bombus impatiens, and Peponapis pruinosa (Hymenoptera: Apidae) as pollinators of pumpkin. *Journal of Economic Entomology*, *104*(4), 1153–1161. https://doi.org/10.1603/ec10431

Atallah, S. S., Gómez, M. I., & Conrad, J. M. (2017). Specification of spatial-dynamic externalities and implications for strategic behavior in disease control. *Land Economics*, *93*(2), 209–229. https://doi.org/10.3368/le.93.2.209

Austin, Z., Penic, M., Raffaelli, D. G., & White, P. C. L. (2015). Stakeholder perceptions of the effectiveness and efficiency of agri-environment schemes in enhancing pollinators on farmland. *Land Use Policy*, *47*, 156–162. https://doi.org/10.1016/j.landusepol.2015.04.003

Bass, C., Denholm, I., Williamson, M. S., & Nauen, R. (2015). The global status of insect resistance to neonicotinoid insecticides. *Pesticide Biochemistry and Physiology*, *121*, 78–87. https://doi.org/10.1016/j.pestbp.2015.04.004

Baumgart-Getz, A., Prokopy, L. S., & Floress, K. (2012). Why farmers adopt best management practice in the United States: A meta-analysis of the adoption literature. *Journal of Environmental Management*, *96*(1), 17–25. https://doi.org/10.1016/j.jenvman.2011.10.006

Benjamin, F. E., & Winfree, R. (2014). Lack of pollinators limits fruit production in commercial blueberry (*Vaccinium corymbosum*). *Environmental Entomology*, *43*(6), 1574–1583. https://doi.org/10.1603/en13314

Biddinger, D. J., & Rajotte, E. G. (2015). Integrated pest and pollinator management - adding a new dimension to an accepted paradigm. *Current Opinion in Insect Science*, *10*, 204–209. https://doi.org/10.1016/j.cois.2015.05.012

Blacquière, T., Smagghe, G., Van Gestel, C. A. M., & Mommaerts, V. (2012). Neonicotinoids in bees: a review on concentrations, side-effects and risk assessment. *Ecotoxicology*, *21*(4), 973–992. https://doi.org/10.1007/s10646-012-0863-x

Bonmatin, J. M., Giorio, C., Girolami, V., Goulson, D., Kreutzweiser, D. P., Krupke, C., … Tapparo, A. (2015). Environmental fate and exposure; neonicotinoids and fipronil. *Environmental Science and Pollution Research*, *22*(1), 35–67. https://doi.org/10.1007/s11356-014-3332-7

Brittain, C. A., Vighi, M., Bommarco, R., Settele, J., & Potts, S. G. (2010). Impacts of a pesticide on pollinator species richness at different spatial scales. *Basic and Applied Ecology*, *11*(2), 106–115. https://doi.org/10.1016/j.baae.2009.11.007

Brittain, C., Bommarco, R., Vighi, M., Barmaz, S., Settele, J., & Potts, S. G. (2010). The impact of an insecticide on insect flower visitation and pollination in an agricultural landscape. *Agricultural and Forest Entomology*, *12*(3), 259–266. https://doi.org/10.1111/j.1461-9563.2010.00485.x

Brittain, C., & Potts, S. G. (2011). The potential impacts of insecticides on the life-history traits of bees and the consequences for pollination. *Basic and Applied Ecology*, *12*(4), 321–331. https://doi.org/10.1016/j.baae.2010.12.004

Brust, G. E., & Foster, R. E. (1999). New economic threshold for striped cucumber beetle (Coleoptera: Chrysomelidae) in cantaloupe in the Midwest. *Journal of Economic Entomology*, *92*(4), 936–940. https://doi.org/10.1093/jee/92.4.936

Brust, G. E. (1997). Seasonal variation in percentage of striped cucumber beetles (Coleoptera: Chrysomelidae) that vector *Erwinia tracheiphila*. *Environmental Entomology*, *26*(3), 580–584. https://doi.org/10.1093/ee/26.3.580

Brust, G. E., Foster, R. E., & Buhler, W. (2015). Effect of rye incorporation, planting date, and soil temperature on damage to muskmelon transplants by seedcorn maggot (Diptera: Anthomyiidae). *Environmental Entomology*, *26*(6), 1323–1326. https://doi.org/10.1093/ee/26.6.1323

Brust, G. E., Foster, R. E., & Buhler, W. G. (1996). Comparison of insecticide use programs for managing the striped cucumber beetle in muskmelon. *Horticultural Entomology*, *89*(4), 981–986.

Campbell, J. W., Kimmel, C. B., Bammer, M., Stanley-Stahr, C., Daniels, J. C., & Ellis, J. D. (2018). Managed and wild bee flower visitors and their potential contribution to pollination services of low-chill highbush blueberry (*Vaccinium corymbosum* L.; Ericales: Ericaceae). *Journal of Economic Entomology*, *111*(5), 2011–2016. https://doi.org/10.1093/jee/toy215

Chagnon, M., Kreutzweiser, D., Mitchell, E. A. D., Morrissey, C. A., Noome, D. A., & Van Der Sluijs, J. P. (2015). Risks of large-scale use of systemic insecticides to ecosystem functioning and services. *Environmental Science and Pollution Research*, *22*(1), 119–134. https://doi.org/10.1007/s11356-014-3277-x

Chouinard, H. H., Paterson, T., Wandschneider, P. R., & Ohler, A. M. (2015). Will farmers trade profits for stewardship? Heterogeneous motivations for farm practice selection. *Land Economics*, *84*(1), 66–82. https://doi.org/10.3368/le.84.1.66

Croft, B., & Brown, A. W. A. (1975). Responses of arthropod natural enemies to insecticides. *Annual Review of Entomology*, *20*(December 1973), 285–335.

Cutler, G. C., Scott-Dupree, C. D., Sultan, M., McFarlane, A. D., & Brewer, L. (2014). A large-scale field study examining effects of exposure to clothianidin seed-treated canola on honey bee colony health, development, and overwintering success. *PeerJ*, *2*, e652. https://doi.org/10.7717/peerj.652

Daberkow, S. G., & Mcbride, W. D. (2003). Farm and operator characteristics affecting the awareness and adoption of precision agriculture technologies in the US. In *Precision Agriculture, 4* (Vol. 163, pp. 163–177). Retrieved from https://link-springer-com.ezp.lib.cam.ac.uk/content/pdf/10.1023%2FA%3A1024557205871.pdf

David, A., Botías, C., Abdul-Sada, A., Nicholls, E., Rotheray, E. L., Hill, E. M., & Goulson, D. (2016). Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. *Environment International*, *88*, 169–178. https://doi.org/10.1016/j.envint.2015.12.011

Desneux, N., Decourtye, A., & Depuech, J.-M. (2007). The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, *52*, 81–106.

Di Prisco, G., Cavaliere, V., Annoscia, D., Varricchio, P., Caprio, E., Nazzi, F., … Pennacchio, F. (2013). Neonicotinoid clothianidin adversely affects insect immunity and promotes replication of a viral pathogen in honey bees. *Proceedings of the National Academy of Sciences*, *110*(46), 18466–18471. https://doi.org/10.1073/pnas.1314923110

Dively, G. P., & Kamel, A. (2012). Insecticide residues in pollen and nectar of a cucurbit crop and their potential exposure to pollinators. *Journal of Agricultural and Food Chemistry*, *60*(18), 4449–4456. https://doi.org/10.1021/jf205393x

Douglas, M. R., Rohr, J. R., & Tooker, J. F. (2015). Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield. *Journal of Applied Ecology*, *52*(1), 250–260. https://doi.org/10.1111/1365-2664.12372

Douglas, M. R., & Tooker, J. F. (2015). Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in U.S. field crops. *Environmental Science and Technology*, *49*(8), 5088–5097. https://doi.org/10.1021/es506141g

Douglas, M. R., & Tooker, J. F. (2016). Meta-analysis reveals that seed-applied neonicotinoids and pyrethroids have similar negative effects on abundance of arthropod natural enemies. *PeerJ*, *4*, e2776. https://doi.org/10.7717/peerj.2776

Eshenaur, B., Grant, J., Kovach, J., Petzoldt, C., Degni, J., & Tette, J. (2017). *Environmental Impact Quotient: "A method to measure the environmental impact of pesticides."* Retrieved from www.nysipm.cornell.edu/publications/EIQ

European Commission. (2013). Commission implementing regulations (EU) No 485/2013. *Official Journal of the European Union*, *L139*, 12–26.

Ferguson, A. W., Klukowski, Z., Walczak, B., Clark, S. J., Mugglestone, M. A., Perry, J. N., & Williams, I. H. (2003). Spatial distribution of pest insects in oilseed rape: implications for integrated pest management. *Agriculture, Ecosystems and Environment*, *95*(2–3), 509–521. https://doi.org/10.1089/met.2017.0023

Foster, R. E., & Brust, G. E. (1995). Effects of insecticides applied to control cucumber beetles (Coleoptera: Chrysomelidae) on watermelon yields. *Crop Protection*, *14*(8), 619–624. https://doi.org/10.1016/0261-2194(95)00071-2

Foster, R. E., & Flood, B. R. (2005). *Vegetable Insect Management*. Willoghby, OH: Meister Media Worldwide.

Foster, R. E. (2016). Managing Striped Cucumber Beetle Populations on Cantaloupe and Watermelon. *Purdue E-Pubs*, *E-95-W*.

Foster, R. E. (2017). Cucurbit insect management. *Purdue Extension*, *E-30-W*, 1–6.

Foster, R. E. (1986). Monitoring populations of *Liriomyza trifolii* (Diptera: Agromyzidae) in celery with pupal counts. *Florida Entomologist*, *69*(2), 292–298.

Gallai, N., Salles, J. M., Settele, J., & Vaissière, B. E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*, *68*(3), 810–821. https://doi.org/10.1016/j.ecolecon.2008.06.014

Garibaldi, L. A., Aizen, M. A., Klein, A. M., Cunningham, S. A., & Harder, L. D. (2011). Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences*, *108*(14), 5909–5914. https://doi.org/10.1073/pnas.1012431108

Garibaldi, L. A., Steffan-dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., … Dudenhoffer, J. H. (2013). Wild pollinators enhance fruit set of crops regardless of honey bee abundance. In *Science* (Vol. 339).

Garibaldi, L. A., Carvalheiro, L. G., Leonhardt, S. D., Aizen, M. A., Blaauw, B. R., Isaacs, R., … Winfree, R. (2014). From research to action: Enhancing crop yield through wild pollinators. *Frontiers in Ecology and the Environment*, *12*(8), 439–447. https://doi.org/10.1890/130330

Geier, P. W. (1966). Management of insect pests. *Annual Review of Entomology*, *11*(1), 471–490. https://doi.org/10.1146/annurev.en.11.010166.002351

Gibbs, J. (2011). Revision of the metallic *Lasioglossum* (Dialictus) of eastern North America (Hymenoptera: Halictidae: Halictini). In *Zootaxa* (Vol. 216).

Gibbs, J., Ascher, J. S., Rightmyer, M. G., & Isaacs, R. (2017). The bees of Michigan (Hymenoptera: Apoidea: Anthophila), with notes on distribution, taxonomy, pollination, and natural history. In *Zootaxa* (Vol. 4352). https://doi.org/10.11646/zootaxa.4352.1.1

Goodell, K., & Thomson, J. D. (2007). Influence of bee species (Hymenoptera: Apiformes) with contrasting behaviors on pollen movement in a mustard, *Brassica rapa* (Brassicaceae) and the muskmelon *Cucumis melo* (Cucurbitaceae). *Entomologia Generalis*, *29*(2–4), 237–252. https://doi.org/10.1127/entom.gen/29/2007/237

Gould, G. E. (1944). Insect pests of cucurbit crops in Indiana. *Zoology*, 165–171.

Goulson, D. (2013). An overview of the environmental risks posed by neonicotinoid insecticides. *Journal of Applied Ecology*, *50*(4), 977–987. https://doi.org/10.1111/1365-2664.12111

Goulson, D., Fox, R., Gilburn, A. S., Bunnefeld, N., Brereton, T. M., Botham, M. S., & Wilson, J. M. (2015). Are neonicotinoid insecticides driving declines of widespread butterflies? *PeerJ*, *3*, e1402. https://doi.org/10.7717/peerj.1402

Goulson, D., Nicholls, E., Botías, C., & Rotheray, E. L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, *347*(6229). https://doi.org/10.1126/science.1255957

Goulson, D. (2003). *Bumblebees: their behaviour and ecology*. Oxford University Press.

Hajek, A. E., & Jørgen, E. (2018). *Natural enemies: an introduction to biological control*. Cambridge University Press.

Hanley, N., Breeze, T. D., Ellis, C., & Goulson, D. (2015). Measuring the economic value of pollination services: Principles, evidence and knowledge gaps. *Ecosystem Services*, *14*, 124–132. https://doi.org/10.1016/j.ecoser.2014.09.013

Hatfield, R., Jepsen, S., Thorp, R., Richardson, L., Colla, S., Foltz Jordan, S., & Evans, E. &. (2015). *Bombus affinis*. In *The IUCN Red List of Threatened Species* (Vol. 8235). https://doi.org/10.2305/IUCN.UK.2015-2.RLTS.T44937399A46440196.en

Higley, L. G., & Wintersteen, W. K. (1996). *Thresholds and environmental quality*. Lincoln: University of Nebraska Press.

Hladik, M. L., Kolpin, D. W., & Kuivila, K. M. (2014). Widespread occurrence of neonicotinoid insecticides in streams in a high corn and soybean producing region, USA. *Environmental Pollution*, *193*, 189–196. https://doi.org/10.1016/j.envpol.2014.06.033

Hladik, M. L., Vandever, M., & Smalling, K. L. (2016). Exposure of native bees foraging in an agricultural landscape to current-use pesticides. *Science of the Total Environment*, *542*, 469–477. https://doi.org/10.1016/j.scitotenv.2015.10.077

Holt, A. R., Alix, A., Thompson, A., & Maltby, L. (2016). Food production, ecosystem services and biodiversity: We can't have it all everywhere. *Science of the Total Environment*, *573*, 1422–1429. https://doi.org/10.1016/j.scitotenv.2016.07.139

Hopwood, J., Black, S. H., Vaughn, M., & Lee-Mader, E. (2013). *Beyond the birds and the bees: Effects of neonicotinoid insecticides on agriculturally important beneficial invertebrates*.

Hopwood, J., Code, A., Vaughan, M., Biddinger, D., Shepherd, M., Hoffman Black, S., … Mazzacano, C. (2016). How neonicotinoids can kill bees. In *The Xerces Society for Invertebrate Conservations*. https://doi.org/10.1016/0038-1101(73)90126-3

Iwao, S. (1968). A new regression method for analyzing the aggregation pattern of animal populations. *Researches on Population Ecology*, *10*, 1–20.

Jabbour, R., Gallandt, E. R., Zwickle, S., Wilson, R. S., & Doohan, D. (2014). Organic farmer knowledge and perceptions are associated with on-farm weed seedbank densities in northern New England. *Weed Science*, *62*(02), 338–349. https://doi.org/10.1614/ws-d-13-00098.1

Kessler, S. C., Tiedeken, E. J., Simcock, K. L., Derveau, S., Mitchell, J., Softley, S., … Wright, G. A. (2015). Bees prefer foods containing neonicotinoid pesticides. *Nature*, *521*(7550), 74–76. https://doi.org/10.1038/nature14414

Kleijn, D., & Raemakers, I. (2008). A retrospective analysis of pollen host plant use by stable and declining bumble bee species. *Ecology*, *89*(7), 1811–1823.

Klein, S., Cabirol, A., Devaud, J. M., Barron, A. B., & Lihoreau, M. (2017). Why bees are so vulnerable to environmental stressors. *Trends in Ecology and Evolution*, *32*(4), 268–278. https://doi.org/10.1016/j.tree.2016.12.009

Knodel, J. J., Beauzay, P., Boetel, M., Prochaska, T., & Lubenow, L. (2018). *North Dakota field crop insect management guide*. https://doi.org/E-1143

Koontz, T. M. (2001). Money talks? But to whom? Financial versus nonmonetary motivations in land use decisions. *Society and Natural Resources*, *14*(1), 51–65. https://doi.org/10.1080/08941920117246

Kovach, J., Petzoldt, C., Degni, J., & Tette, J. (1992). A method to measure the environmental impact of pesticides. *New York's Food and Life Sciences Bulletin*, *139*, 1–8.

Kremen, C. (2018). The value of pollinator species diversity. *Science*, *359*(6377), 741–742. https://doi.org/10.1126/science.aar7614

Kremen, C., Williams, N. M., & Thorp, R. W. (2002). Crop pollination from native bees at risk from agricultural intensification. *Proceedings of the National Academy of Sciences*, *99*(26), 16812–16816. https://doi.org/10.1073/pnas.262413599

Krupke, C. H., Hunt, G. J., Eitzer, B. D., Andino, G., & Given, K. (2012). Multiple routes of pesticide exposure for honey bees living near agricultural fields. *PLoS ONE*, *7*(1). https://doi.org/10.1371/journal.pone.0029268

Krupke, C. H., & Long, E. Y. (2015). Intersections between neonicotinoid seed treatments and honey bees. *Current Opinion in Insect Science*, *10*, 8–13. https://doi.org/10.1016/j.cois.2015.04.005

Lawrence, T. J., Culbert, E. M., Felsot, A. S., Hebert, V. R., & Sheppard, W. S. (2016). Survey and risk assessment of apis mellifera (Hymenoptera: Apidae) exposure to neonicotinoid pesticides in urban, rural, and agricultural settings. *Journal of Economic Entomology*, *109*(2), 520–528. https://doi.org/10.1093/jee/tov397

Lloyd, M. (1967). Mean crowding. *Journal of Animal Ecology*, *36*(1), 1–30.

Long, E. Y., & Krupke, C. H. (2016). Non-cultivated plants present a season-long route of pesticide exposure for honey bees. *Nature Communications*, *7*(May), 1–12. https://doi.org/10.1038/ncomms11629

Mallinger, R. E., & Gratton, C. (2015). Species richness of wild bees, but not the use of managed honeybees, increases fruit set of a pollinator-dependent crop. *Journal of Applied Ecology*, *52*(2), 323–330. https://doi.org/10.1111/1365-2664.12377

Mallinger, R. E., Werts, P., & Gratton, C. (2015). Pesticide use within a pollinator-dependent crop has negative effects on the abundance and species richness of sweat bees, *Lasioglossum* spp., and on bumble bee colony growth. *Journal of Insect Conservation*, *19*(5), 999–1010. https://doi.org/10.1007/s10841-015-9816-z

Matteson, K. C., & Langellotto, G. A. (2009). Cities and the environment bumble bee abundance in New York City agriculture. *Cities and the Environment*, *2*(1), 1–12.

Maynard, D. N., & Elmstrom, G. W. (1992). Triploid watermelon production practices and varieties. *Acta Hortic.*, *318*, 169–178.

Michener, C. D., McGinley, R. J., & Danforth, B. N. (1994). *The bee genera of North and Central America*.

Morandin, L. A., Winston, M. L., Franklin, M. T., & Abbott, V. A. (2005). Lethal and sub-lethal effects of spinosad on bumble bees (*Bombus impatiens* Cresson). *Pest Management Science*, *61*(7), 619–626. https://doi.org/10.1002/ps.1058

Morse, R., & Calderone, N. (2000). The value of honey bees as pollinators of U.S. crops in 2000. *Bee Culture*, *128*(3), 1–15.

National Research Council. (2007). Status of pollinators in North America. *National Academies Press*.

Nauen, R., Ebbinghaus-Kintscher, U., Salgado, V. L., & Kaussmann, M. (2003). Thiamethoxam is a neonicotinoid precursor converted to clothianidin in insects and plants. *Pesticide Biochemistry and Physiology*, *76*(2), 55–69. https://doi.org/10.1016/S0048-3575(03)00065-8

NeSmith, D. S., & Duval, J. R. (2001). Fruit set of triploid watermelons as a function of distance from a diploid pollinizer. *HortScience*, *36*(1), 60–61.

Nixon, K. L. (2014). Potential impact of neonicotinoid insecticides on honey bees (*Apis mellifera*) In muskmelon production. *Purdue E-Pubs*, 1–71.

Packer, L. (2008). The bee genera of eastern Canada. *Canadian Journal of Arthropod Identification*, *3*(3), 1–32. https://doi.org/10.3752/cjai.2007.03

Pecenka, J. R., & Lundgren, J. G. (2015). Non-target effects of clothianidin on monarch butterflies. *Science of Nature*, *102*(3–4). https://doi.org/10.1007/s00114-015-1270-y

Pedigo, L. P. (1989). *Entomology and pest management*. New York, NY: Macmillan Publishing Company.

Peterson, R. K. D., Higley, L. G., & Pedigo, L. P. (2018). Whatever happened to IPM? *American Entomologist*, *64*(3), 146–150.

Pisa, L. W., Amaral-Rogers, V., Belzunces, L. P., Bonmatin, J. M., Downs, C. A., Goulson, D., … Wiemers, M. (2014). Effects of neonicotinoids and fipronil on non-target invertebrates. *Environmental Science and Pollution Research*, *22*(1), 68–102. https://doi.org/10.1007/s11356-014-3471-x

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: Trends, impacts and drivers. *Trends in Ecology and Evolution*, *25*(6), 345–353. https://doi.org/10.1016/j.tree.2010.01.007

Rader, R., Reilly, J., Bartomeus, I., & Winfree, R. (2013). Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. *Global Change Biology*, *19*(10), 3103–3110. https://doi.org/10.1111/gcb.12264

Raimets, R., Karise, R., Mänd, M., Kaart, T., Ponting, S., Song, J., & Cresswell, J. E. (2018). Synergistic interactions between a variety of insecticides and an ergosterol biosynthesis inhibitor fungicide in dietary exposures of bumble bees (Bombus terrestris L.). *Pest Management Science*, *74*(3), 541–546. https://doi.org/10.1002/ps.4756

Robert, J. (2000). Fitness impacts of herbivory through indirect effects on plant-pollinator interactions in *Oenothera macrocarpa*. *Ecology*, *81*(1), 30–40.

Ruesink, W. G. (1980). *Introduction to sampling theory*. New York, NY: Springer.

Rundlöf, M., Andersson, G. K. S., Bommarco, R., Fries, I., Hederström, V., Herbertsson, L., … Smith, H. G. (2015). Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature*, *521*(7550), 77–80. https://doi.org/10.1038/nature14420

Sgolastra, F., Hinarejos, S., Pitts-Singer, T. L., Boyle, N. K., Joseph, T., Luckmann, J., … Bosch, J. (2019). Pesticide exposure assessment paradigm for solitary bees. *Environmental Entomology*, *48*(1), 22–35. https://doi.org/10.1093/ee/nvy105

Sheffield, C. S., Frier, S. D., & Dumesh, S. (2014). The bees (Hymenoptera: Apoidea, Apiformes) of the Prairies Ecozone, with comparisons to other grasslands of Canada. In *Arthropods of Canadian Grasslands* (Vol. 4). https://doi.org/10.1111/j.1439-0310.1989.tb00735.x

Slone, J. D., & Burrack, H. J. (2016). Integrated pest management practices reduce insecticide applications, preserve beneficial insects, and decrease pesticide residues in flue-cured tobacco production. *Journal of Economic Entomology*, *109*(6), 2397–2404. https://doi.org/10.1093/jee/tow191

Smith, R. F. (1962). Integration of biological and chemical control: Introduction and principles. *Bulletin of the Entomological Society of America*, *8*(4), 188–189. https://doi.org/10.1093/besa/8.4.188

Sparks, T. C. (2013). Insecticide discovery: an evaluation and analysis. *Pesticide Biochemistry and Physiology*, *107*(1), 8–17. https://doi.org/10.1016/j.pestbp.2013.05.012

Stanghellini, M. S., Ambrose, J. T., & Schulthcis, J. R. (1998). Using commercial bumble bee colonies as backup pollinators for honey bees to produce cucumbers and watermelons. *HortTechnology*, Vol. 8, pp. 588–590. https://doi.org/10.1145/2660267.2660334

Stanley, D. A., Garratt, M. P. D., Wickens, J. B., Wickens, V. J., Potts, S. G., & Raine, N. E. (2015). Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. *Nature*, *528*(7583), 548–550. https://doi.org/10.1038/nature16167

Stanley, D. A., & Raine, N. E. (2016). Chronic exposure to a neonicotinoid pesticide alters the interactions between bumblebees and wild plants. *Functional Ecology*, *30*(7), 1132–1139. https://doi.org/10.1111/1365-2435.12644

Stern, V. M., Smith, R. F., van den Bosch, R., & Hagen, K. S. (1959). The integration of chemical and biological control of the spotted alfalfa aphid. *Hilgardia*, *29*, 81–101.

Stoner, K. A., & Eitzer, B. D. (2012). Movement of soil-applied imidacloprid and thiamethoxam into nectar and pollen of squash (*Cucurbita pepo*). *PLoS ONE*, *7*(6), 1–5. https://doi.org/10.1371/journal.pone.0039114

Stubbs, C. S., & Drummond, F. A. (2001). *Bombus impatiens* (Hymenoptera: Apidae): an alternative to *Apis mellifera* (Hymenoptera: Apidae) for lowbush blueberry pollination. *America*, *94*(3), 609–616.

Taylor, L. R. (1961). Aggregation, variance and the mean. *Nature*, *189*(4766), 732.

Thomas, B. (2001). Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, *25*(0169), 245–260.

USDA-NASS. (2018). *Farm labor*.

USDA-NASS. (2017). *Census of agriculture*.

Vaughan, M., Bommarco, R., Isaacs, R., Pitts-Singer, T. L., Ellis, J., & Williams, N. (2017). Integrated crop pollination: Combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic and Applied Ecology*, *22*, 44–60. https://doi.org/10.1016/j.baae.2017.07.003

Walters, S. A. (2005). Honey bee pollination requirements for triploid watermelon. *HortScience*, *40*(5), 1268–1270.

Whitehorn, P. R., O'Connor, S., Wackers, F. L., & Goulson, D. (2012). Neonicotinoid pesticide reduces bumble bee colony growth and queen production. *Science*, *336*(6079), 351–352. https://doi.org/10.1126/science.1215025

Whitfield, C. W., Behura, S. K., Berlocher, S. H., Clark, A. G., Johnston, J. S., Sheppard, W. S., … Tsutsui, N. D. (2006). Thrice out of Africa: ancient and recent expansions of the honey bee, *Apis mellifera*. *Science*, *314*(October), 642–645. https://doi.org/10.1126/science.1132772

Williams, N. M., Crone, E. E., Roulston, T. H., Minckley, R. L., Packer, L., & Potts, S. G. (2010). Ecological and life-history traits predict bee species responses to environmental disturbances. *Biological Conservation*, *143*(10), 2280–2291. https://doi.org/10.1016/j.biocon.2010.03.024

Winfree, R., Reilly, J. R., Bartomeus, I., Cariveau, D. P., Williams, N. M., & Gibbs, J. (2018). Species turnover promotes the importance of bee diversity for crop pollination at regional scales. *Science*, *359*(6377), 791–793. https://doi.org/10.1126/science.aao2117

Winfree, R., Williams, N. M., Dushoff, J., & Kremen, C. (2007). Native bees provide insurance against ongoing honey bee losses. *Ecology Letters*, *10*(11), 1105–1113. https://doi.org/10.1111/j.1461-0248.2007.01110.x

Winfree, R., Williams, N. M., Gaines, H., Ascher, J. S., & Kremen, C. (2008). Wild bee pollinators provide the majority of crop visitation across land-use gradients in New Jersey and Pennsylvania, USA. *Journal of Applied Ecology*, *45*(3), 793–802. https://doi.org/10.1111/j.1365-2664.2007.01418.x

Winston, M. L. (1991). *The biology of the honey bee*. Harvard University Press.

Wiseman, B. R. (1959). Resistance of selected varieties of cucurbits to the spotted cucumber beetle, *Diabrotica undecimpunctata* howardi Barber, and the striped cucumber beetle, *Acalymma vittata* (Fabricius).