

Food webs and phenology models: evaluating the efficacy of ecologically-based insect pest management in different agroecosystems

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Abstract

Integrated pest management (IPM) is defined as an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. Integrated pest management programs use current, comprehensive information on the life cycles of pests and their interactions with host plants and the environment. This information, in combination with available pest control methods, is used to manage pest populations by the most economical means, and with the least possible hazard to people, property, and the environment. True IPM takes advantage of all appropriate pest management options including, as appropriate, the judicious use of pesticides. It is currently estimated the IPM in its full capacity is being practiced on less than ten percent of the agricultural land in the U.S.

The primary objective of this research was to evaluate land management decisions and create new tools to promote a true IPM approach and encourage growers to reevaluate their method of insect control. To accomplish this I developed new predictive tools to reduce or eliminate unnecessary insecticide application intended to target cereal leaf beetle in wheat, and assessed a conservation biological control technique, farmscaping, to determine its true impact on lepidopteran pest suppression in collards.

Dedication

I dedicate this work to my daughters Penelope and Haylee.

It is all too easy to get dragged down in the "to dos" of the day to day, so much so that at times we forget why we are here, what got us excited about what we do, what got us here in the first place. By sharing this world with them, I am reminded of these things every day. There is nothing like seeing the world through their eyes, and in doing so, I am reminded everyday why I do what I do, and how much I love my job.

“If a child is to keep alive his inborn sense of wonder, he needs the companionship of at least one adult who can share it, rediscovering with him the joy, excitement and mystery of the world we live in.”

— Rachel Carson

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Table of Contents

Introduction.....	1
Objective 1	3
Objective 2	4
References Cited.....	6
Chapter One	10
Fifty years of cereal leaf beetle: an update on its biology, management and current research	10
Abstract.....	10
Introduction	11
Pest Status.....	11
Description of Life Stages and Life History.....	12
Historical Control Effort.....	13
Host plant resistance.....	13
Biological control.	14
Current management	14
Current research.....	15
References Cited.....	18
Tables and Figures.....	21
Chapter Two.....	27
Using degree-days to predict cereal leaf beetle (Coleoptera: Chrysomelidae) egg and larval population peaks	27
Abstract.....	27
Introduction	28
Materials and Methods	30
Results	32
Discussion.....	33
References Cited.....	35
Tables and Figures.....	38
Chapter Three	45
Understanding the risks and benefits of plant provided resources in pest management. .	45
Abstract.....	45
Introduction	46
Using plant-provided resources to improve biological control	47
Farmscape plants	52
Does farmscaping work?	55
Future research	56
References Cited.....	58

Tables and Figures.....	67
Chapter Four.....	68
Effect of flowering buckwheat (<i>Fagopyrum esculentum</i>) on lepidopteran pest management in collards.....	68
Abstract.....	68
Introduction.....	69
Objectives.....	70
Results.....	72
Discussion.....	73
References Cited.....	77
Tables and Figures.....	81
Chapter Five.....	87
Conclusion.....	87
References Cited.....	90

List of Figures

Fig. 1.1. Cereal leaf beetle larval feeding damage to wheat, damaged area in the foreground, green protected area in the background.....	22
Fig. 1.2. Adult cereal leaf beetle.....	23
Fig. 1.3. Cereal leaf beetle eggs.....	24
Fig. 1.4. Cereal leaf beetle larva with no mucus or fecal material.....	25
Fig. 1.5. Cereal leaf beetle larva covered with mucus and fecal material.....	26
Fig 2.1. Population dynamics of a single population (Exmore, VA) of cereal leaf beetle including the dates when the most eggs (egg peak) and larvae (larval peak) were observed in 2010.....	41
Fig 2.2. Interpolation map of when regions of Virginia and North Carolina will reach predicted cereal leaf beetle egg peak (182 degree-days with base development temperature of 8°C) based on thirty-year normal temperature data (1981 - 2010) from over 324 weather stations in Virginia and neighboring states at a resolution of 1km x 1km cells. Maps also includes population survey field locations used to validate the map in 2010 and 2011	42
Fig 2.3. Frequency histogram of the residuals of predicted egg peak and observed egg peak from 60 field sites in 2010 and 65 sites in 2011 throughout Virginia and North Carolina.....	43
Fig. 2.4. Linear regression of cereal leaf beetle eggs and larvae A) data from previous field studies (Ihrig1998); B) data from all monitored populations in 2010 and 2011.....	44
Fig 4.1. Mean lepidopteran larval abundance by distance and year in collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.....	84
Fig 4.2. Mean lepidopteran larval abundance by distance and year in collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.....	85
Fig 4.3. Mean parasitism of imported cabbageworm by distance and year in collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.....	86

List of Tables

Table 1.1 Development time (days) of immature cereal leaf beetle by temperature, data from Guppy and Harcourt 1978.	21
Table 2.1. Cereal leaf beetle population study site locations in 2010 and 2011	38
Table 2.2. Predicted and observed egg peaks of cereal leaf beetle, observed degree-day of egg peak, date of peak larvae, and the time (days) between egg peak and larval peak at four locations in 2010. Degree-days were calculated using two degree-day predictions (182 degree-days and 253 degree-days) at three lower development thresholds (7, 8, 10°C) with an upper development threshold of 25°C.....	39
Table 2.3. Predicted and observed egg peaks of cereal leaf beetle, observed degree-day of egg peak, date of peak larvae, and the time (days) between egg peak and larval peak at four locations in 2010 and six locations in 2011. Degree-days were calculated using degree-day prediction of 182 degree-days with a lower development threshold of 8°C and an upper development threshold of 25°C.....	40
Table 3.1. List of plants known to attract natural enemies.....	67
Table 4.1. Lepidopteran larvae found on collards at the Virginia Tech Kentland Research Farm near Blacksburg, Virginia.....	81
Table 4.2. Predator and parasitoid abundance collected in vacuum sample of flowering buckwheat adjacent to collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.....	82
Table 4.3. Pest abundance collected in vacuum samples of flowering buckwheat adjacent to collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.....	83

Introduction

Integrated pest management (IPM) is defined as an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices. Integrated pest management programs use current, comprehensive information on the life cycles of pests and their interactions with host plants and the environment. This information, in combination with available pest control methods, is used to manage pest populations by the most economical means, and with the least possible hazard to people, property, and the environment. True IPM takes advantage of all appropriate pest management options including, as appropriate, the judicious use of pesticides. It is currently estimated the IPM in its full capacity is being practiced on less than ten percent of the agricultural land in the U.S.

Although numerous advances have been made in IPM over the last fifty years, many growers continue to use calendar-based spray programs. This type of management is generally viewed as an insurance policy that may or may not work in controlling target pests. These management tactics are now widely used across the southeastern U.S. resulting in hundreds of thousands of acres receiving insecticide applications that are probably unnecessary, exacerbating other issues such as the destruction of beneficial organisms and insecticide resistance. For example, these management programs have led to numerous pests, such as spider mites, *Tetranychus spp.*, diamondback moth, *Plutella xylostella* (L.), green peach aphid, *Myzus persicae* (Sulzer) and Colorado potato beetle, *Leptinotarsa decemlineata* (Say), and many others developing resistance to numerous classes of insecticides. Since the early 1940s, the primary means of pest control for most crop producers has been synthetic pesticides. Recently there has been a movement away from quick insecticide applications to a threshold-based approach. In terms of IPM, this is a step in the right direction, although pesticide use continues to grow and most producers are still relying on insecticides as their primary means of pest control.

Currently, most crops in the United States are grown in simple, single plant systems because specialization of equipment used in planting and harvesting has resulted in decreased production costs (Norris 1986, Buttel 1990). These simple systems can produce high yields, but also require increased inputs. Agrichemicals, such as herbicides and insecticides, are commonly used to control biotic elements that interfere with crop production. Although the application of pesticides can be effective in the short-term, their use has a tendency to alter the natural

ecological balance in these systems, and once this balance has been disrupted, these systems must be closely monitored to ensure maximum production (Gliessman 1990).

Despite their effectiveness in many cases, the current dependency on insecticides in simple systems has several disadvantages. From an ecological perspective, modification of the agricultural environment with insecticides can cause pest population outbreaks because of disruption of natural control elements (Pimentel 1961). Insect pests also develop resistance to insecticides, requiring more frequent, but less effective, applications or a reliance on older and often more toxic chemistries (Croft 1992), both of which mean additional expenses for growers (van Emdem 1990). In addition to the ecological impact in these systems, long-term safety concerns surrounding the excessive use and concomitant environmental impacts of pesticides has led to many countries adopting more stringent insecticide regulations. As more insecticide chemistries are lost to legislation, and social pressure for reducing pesticide use increases, finding alternative pest management strategies has become a top priority.

As human populations continue to increase, the challenge facing growers in the coming years is to produce more food with fewer resources. The only way to accomplish this is to develop methods that efficiently use natural resources that also minimally disturb the environment. Conservation agriculture is a series of practices aiming to achieve sustained or improved crop production and profitable agriculture while simultaneously conserving natural resources and protecting the environment. Conservation agriculture emphasizes proactive, multi-tactic practices in contrast to the “single approach” reactive methods generally used in conventional systems. A technique common in conservation agriculture is farmscaping.

Farmscaping refers to the arrangement or configuration of insect-attracting plants that promotes biological pest management by attracting and sustaining beneficial organisms, with an emphasis on beneficial insects. Ideal farmscape plantings provide a habitat for beneficial insects, suppress weeds, and grow in close proximity to the cash crop without competing for light, water, and nutrients. The configuration of crop plants and insect-attracting plants has a substantial impact on the suite of arthropod pests and natural enemies present in the field (Barbosa 1998, Bugg and Pickett 1998). These practices can have numerous benefits including the potential to enhance the activity of arthropod natural enemies and improve biological control, but they might also exacerbate pest populations (Landis et al. 1987, Turnock et al. 1993, Renner 2000, Wäckers

et al. 2007, Winkler et al. 2010). Therefore, the true impact of farmscaping on pest management remains unclear.

The primary objective of this research was to promote a true IPM approach and encourage growers to reevaluate their methods of insect control in two different agricultural systems. To accomplish this, I: 1) developed a new predictive tool to reduce or eliminate unnecessary insecticide application targeting cereal leaf beetle in wheat, and 2) evaluated the current conservation biological control technique of farmscaping with buckwheat, *Fagopyrum esculentum* (Moench), to determine its true impact on lepidopteran pest suppression in collards.

Objective 1

Cereal leaf beetle has one generation per year, and adults overwinter in areas adjacent to the previous season's grain fields. Adults emerge from overwintering in the early spring when daytime high temperatures consistently exceed 14°C (Helgesen and Haynes 1972, Gutierrez et al. 1974), and move into small grains to lay eggs (Helgesen and Haynes 1972).

Virginia and North Carolina currently recommend an economic threshold of 25 eggs or small larvae per 100 tillers (Herbert 2009, Herbert and Van Duyn 1999). Nevertheless, there is a growing trend for producers to spray for cereal leaf beetle independent of scouting and thresholds. Insecticides are typically tank-mixed with liquid fertilizers. Given the limited residual activity of these insecticides, these early insecticide applications are often too early in relation to cereal leaf beetle population phenology and are ineffective for control. This management tactic is now widely used in North Carolina and Virginia resulting in hundreds of thousands of acres of wheat receiving an insecticide application that essentially serves no purpose.

The seasonal biology of cereal leaf beetle is strongly influenced by temperature (Guppy and Harcourt 1978, Grant and Patrick 1993). Cereal leaf beetle emergence from overwintering and the rates of development are largely determined by spring temperatures. If correlations with temperature and population dynamics can be developed, it should be possible to make accurate predictions of cereal leaf beetle infestations. Determining if degree-days can accurately predict when peak egg and larval densities occur is an important step in this process. Degree-day accumulation has been widely used to accurately predict population arrivals or peaks for a number of pests, including other chrysomelid beetles and other pests of small grains (Harding et al. 2002, Pedigo and Rice 2008). Currently, no degree-day predictions exist for cereal leaf beetle

and scouting is often done from late March to June, which is extremely inefficient. By building on existing cereal leaf beetle temperature development data (Guppy and Harcourt 1978), I determined when peak egg populations occur and correlated these egg densities to current thresholds. The ability to accurately predict when to scout fields for cereal leaf beetle may encourage growers to reevaluate their method of springtime insect control in wheat, and consider re-adoption of an economic threshold-based approach, thereby reducing or eliminating unnecessary insecticide applications.

Objective 2

At least one lepidopteran pest attacks every major crop grown in the U.S. Because there is a large caterpillar pest complex, and they are the most damaging insect group feeding on cruciferous crops in the Southeastern U.S. I chose this system. The most common and damaging caterpillars of Virginia crucifers are diamondback moth, *Plutella xylostella* (L.), cabbage looper, *Trichoplusia ni* (Hübner), and imported cabbageworm, *Pieris rapae* (L.) (Wallingford et al. 2012). In addition, several other lepidopteran species feed on crops in the southeast. Collards, a staple crucifer crop in the south, are particularly vulnerable to economic losses from these pests as some species strongly prefer collards to other crucifers, and because the leaves, which are fed upon by pests, are the marketable portion of the crop. Historically, control measures for lepidopteran pests in commercial cabbage, broccoli, and collards in Virginia has involved multiple insecticide applications applied on a 7-10 day schedule, with little regard for pest population levels (Lasota and Kok 1986, Cordero and Kuhar 2007). Several of these pests are now highly resistant to numerous classes of insecticides. To develop new sustainable programs that effectively manage lepidopteran pests, a firm understanding of what roles natural enemies play in regulating caterpillar pest populations is needed.

Conservation of natural enemies involves manipulation of the environment to favor native natural enemies, either by eliminating adverse factors or by providing improved conditions for colonization (DeBach and Rosen 1991, Greathead 1995). In addition to acting as a reservoir for natural enemies (Altieri and Whitcomb 1979, Altieri and Letourneau 1982), the use of farmscapes may increase alternative prey or insect hosts when other food resources are scarce (Bugg 1992, Phatak 1992). Therefore, we must reassess current agricultural production from an ecological perspective. This approach builds on characteristics of an agroecosystem and

integrates the ecological principles of a natural ecosystem such as predator/prey interactions, competition, and energy flow through trophic levels, with the human inputs of agriculture production (Hecht 1987, Gleissman 1990, Reijntjes et al. 1992).

Numerous studies have shown that habitat diversity in agricultural landscapes has the potential to decrease pest pressure or increase natural control (Bianchi et al. 2006, Gardiner et al. 2009, Power et al. 2009, O'Rourke et al. 2011). The mechanisms behind this are not well understood, and recent research indicates the scale and arrangement may be important (Lee and Heimpel 2005, O'Rourke et al. 2011). However, it is believed that increasing the plant diversity in these systems provides essential elements that natural enemies need to survive and reproduce (Sarhou et al. 2005, Landis et al. 2000). In addition, diverse landscapes may make it more difficult for pests to locate hosts requiring more of their energy, reducing the time and energy available for reproduction (Fahrig and Paloheimo 1988, Schneider 1999, den Belder et al. 2002, O'Rourke et al. 2011). By gaining a better understanding of the population dynamics in cruciferous crop ecosystems, we can develop sound IPM programs for lepidopteran pests in crucifers as well as in other systems.

Integrated pest management is ready to enter a new stage of development. Agroecosystems are comprised of various components including animal and plant communities, physical environments, as well as human inputs and their interactions (Reijntjes et al. 1992). It is important to remember that the primary objective in any agroecosystem is crop production, and that these crops are susceptible to, but also reliant on, the same processes and interactions found in other natural ecosystems (Hecht 1987). What differentiates agroecosystems from natural ecosystems is the degree of human input (Gliessman 1990), and the ephemeral nature of these systems. Thinking of these systems from an ecological perspective can lead to a better understanding of the interactions in these systems, thereby leading to improved crop production. From a pest management perspective, a closer examination of the management decisions and how they impact insect communities, as well as how these communities interact within these systems has tremendous potential to improve natural pest control.

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Chapter One

Fifty years of cereal leaf beetle: an update on its biology, management and current research

(Philips et al. 2011. Journal of Integrated Pest Management. 2: C1-C5.)

Abstract

Cereal leaf beetle, *Oulema melanopus* L., is an introduced insect pest of small grains first recorded in the United States in the early 1960's. Since its introduction from Europe or Asia into Michigan, cereal leaf beetle has rapidly spread and can now be found in most states. Cereal leaf beetle feeds on numerous species of grasses and is considered a major pest of oats, barley, and wheat. Although several studies have investigated cereal leaf beetle biology and population dynamics, numerous gaps remain in understanding the mechanisms that influence its spread and distribution, which makes predicting pest outbreaks difficult. Because of the difficulty in predicting when and where pest outbreaks will occur many growers in the Southeast apply insecticides on a calendar basis rather than using a threshold-based IPM approach. Our challenge is to develop new information and procedures that will encourage growers to reevaluate the way they are approaching spring-time insect control in wheat, and consider adoption of the IPM approach. This article is a review of cereal leaf beetle biology, past and present management practices, and current research being conducted.

Introduction

Cereal leaf beetle, *Oulema melanopus* L. (Coleoptera: Chrysomelidae), is native to Europe and Asia where it is a pest of small grains. The first record of cereal leaf beetle in the United States was in southern Michigan in the early 1960's (Castro et al. 1965, Hanes and Gage 1981). After its initial discovery, programs were initiated in an attempt to eradicate this pest. As those began to fail emphasis was placed on programs attempting to control CLB. Most of these programs had limited success; nevertheless the pest status of cereal leaf beetle has decreased over time. In recent years however outbreaks have become more common, and while numerous studies have attempted to quantify the mortality factors associated with cereal leaf beetle in North America, the population dynamics remain unclear as populations continue to rise and spread (Hanes and Gage 1981). Early studies set thresholds of cereal leaf beetle at one larvae per stem (Webster et al. 1972, Haynes and Gage 1981), but more recent research has shown that substantial losses can occur when populations reach that level (Ihrig et al. 2001, Buntin et al. 2004). From those studies a scouting and management plan is well established in both Virginia and North Carolina (Herbert and Van Duyn 1999, Herbert 2009), but recently growers have been moving away from a threshold approach and adopting a calendar-based spraying program. These sprays are timed with plant phenology to correspond to the best time for application of nitrogen and not for the management of cereal leaf beetle. Growers will often incorporate a fungicide at this time, in addition to an insecticide, independent of scouting and thresholds. In order to continue to effectively manage this pest it is imperative that we understand the population dynamics, as well as how and why populations fluctuate both spatially and temporally. This article is an overview of cereal leaf beetle biology as well as a description of management practices through time, and glimpse at current research being conducted.

Pest Status

Cereal leaf beetle is considered a major pest in its native range as well as in the United States. Since its introduction, it has rapidly spread east and is now found in all states east of the Dakotas, south to Oklahoma, as well as in Montana, Idaho, Utah, Wyoming, Nevada, Oregon and Washington (Herbert et al. 2007). It feeds on numerous species of wild and cultivated grasses including oats, barley, and wheat, although preferences are shown for certain species, possibly due to increases in survival and development time (Wilson and Shade 1966). Although

adults will feed on young small grain plants, their feeding generally does not affect the plant's performance. Larvae however, will eat long strips of parenchyma tissue skeletonizing the leaf giving it a “frosted” appearance, which decreases the plant’s ability to photosynthesize (Grant and Patrick 1993, Buntin et al. 2004; Fig. 1.1). This loss of photosynthetic ability can cause significant losses in yield or grain quality (Wilson et al. 1964, Koval 1966, Merrit and Apple 1969, Webster and Smith 1983, Grant and Patrick 1993). Losses are highly variable, and will depend on infestation levels as well as the crop and the region, with maximum losses of approximately 40% (Buntin et al. 2004). In Virginia, however, commercial fields that suffer from cereal leaf beetle infestations average about 15% yield loss. One possible reason for these dense populations is poor establishment of introduced biological control agents leading to limited or no control (Herbert et al. 2007). Poor establishment has been attributed to several other factors, including land management practices such as later planting or low seeding rate, with a key reason being the unnecessary and poorly timed use of pesticides.

A tremendous amount of research has been done on cereal leaf beetle population dynamics and control. Nevertheless, the underlying mechanisms that determine its spread and distribution remain unresolved (Hanes and Gage 1981). Because so much remains unknown about this insect pest’s life history and population and community ecology, predicting outbreaks is extremely difficult.

Description of Life Stages and Life History

Cereal leaf beetle has one generation per year, although McPherson (1983b) did report a small second generation in Virginia. The entire life cycle can take 10 to almost 90 days depending on temperature, but generally requires 45 to 47 days at average spring time temperatures for the Midwest and mid-Atlantic United State (Guppy and Harcourt 1978, Metcalf and Metcalf 1993).

Adult. The adult is a small elongated chrysomelid beetle about 5 mm long with a metallic, bluish-black head and wing covers (elytra) and rust red to burgundy legs and thorax (Fig. 1.2). Adults overwinter in debris in or near wooded areas often adjacent to the previous season’s grain fields. Adults emerge from overwintering in the early spring when daytime temperatures consistently exceed 14°C (Helgesen and Haynes 1972, Gutierrez et al. 1974), and move into small grains and begin to lay eggs.

Eggs. Female cereal leaf beetles deposit eggs individually or in short chains along the midvein, on the upper surface of leaves (Helgesen and Haynes 1972). A single mated female can deposit up to 50 eggs in her lifetime. Eggs are elongate, yellowish orange in color and are about 1 mm long (Fig. 1.3). Eggs darken as they develop. A minimum temperature requirement for immature cereal leaf beetle development is about 9°C. Development time decreases with increasing temperature until about a maximum of about 25°C (Yun 1967, Helgesen 1969, Guppy and Harcourt 1978; Table 1.1). At optimal temperatures (between 22-32°C), eggs complete their development in about five days (Guppy and Harcourt 1978, Herbert et al. 2007).

Larva. Newly-hatched larvae are slug-like and have grayish yellow bodies with heads and legs that are brownish-black (Fig. 1.4). However, body coloration is usually obscured by a black globule of mucus and fecal matter held on the body, giving them a shiny black, wet appearance, especially in later instars (Fig. 1.5). Larvae pass through four instars and typically develop in 10-14 days at optimal temperatures between 22-32°C, with the time divided equally between the four instars (Guppy and Harcourt 1978, Herbert et al. 2007). Upon reaching full size (~ 5 mm), larvae drop to the soil surface and burrow down to about 2 inches (5 cm) and pupate.

Pupa. This life stage is rarely encountered in the field, as pupae are small (~5mm) and enclosed in earthen cells. Pupae are exarate, yellow and darken with time. Adults emerge after 17 to 25 days based on soil temperature.

Historical Control Effort

Quarantine. Shortly after its discovery in the United States, large-scale quarantine and eradication efforts were implemented. Large areas of Michigan and Indiana were placed under quarantine and small grains had to be treated before transportation (Haynes and Gage 1981). In spite of these efforts, the pest continued to spread. It was later discovered that the likely culprit was overwintering adults on conifers sold as Christmas trees (Hess 1971). Along with these quarantine efforts were large-scale attempts to eradicate cereal leaf beetle using pesticides (Castro and Guyer 1963, Haynes and Gage 1981). During this time hundreds of thousands of acres were sprayed across Michigan, Indiana, and Illinois, cereal leaf beetle still continued to spread. By 1970 the decision was made to discontinue the cereal leaf beetle eradication program and attention was turned to other methods of control.

Host plant resistance. Resistance to cereal leaf beetle has been found in wheat, and is associated with the trichome density and length associated with plant leaves (Wellso 1973, Hoxie

et al. 1975, Webster et al. 1975, Haynes and Gage 1981). It appears the primary mechanism for control with pubescence is oviposition preference with resistance reducing egg populations by 90% or more (Gallun et al. 1973). However, because of the generalist feeding habits of cereal leaf beetle, using host plant resistance alone is likely not a long term solution, but when used in conjunction with other control methods, it may prove to be a useful tool in the integrated pest management (IPM) toolbox for cereal leaf beetle (Haynes and Gage 1981).

Biological control. Classical biological control efforts in the United States were also explored in the 1960s. From 1963 to 1967, five parasitoids were released in an attempt to control cereal leaf beetle, four of which have been reported as well-established (Hanes and Gage 1981). Several of these parasitoids have been cultivated and released at various locations throughout the Midwest and mid-Atlantic states (Buntin et al. 2004). The two that appeared to be the most successful in control were the larval parasitoid *Tetrastichus julis* (Walker) (Hymenoptera: Eulophidae) and the egg parasitoid *Anaphes flavipes* (Förster) (Hymenoptera: Mymaridae). Numerous studies have illustrated that these parasitoids have become well established in the Midwest with parasitism rates as high as 90% (Stehr 1970, Maltby et al. 1971, Gage 1974, Hanes and Gage 1981); however, little work has been done in recent years to evaluate the impact of these parasitoids on cereal leaf beetle. In 2010 the authors conducted surveys in Virginia and North Carolina, and no parasitoids were recovered from eggs or larvae. These parasitoids may be poorly established in these areas and likely doing little to control cereal leaf beetle.

Current management

Because cereal leaf beetle is a pest that can usually be managed with sound cultural practices (the application of thresholds and, when needed, well-timed insecticide applications) it has not been the focus of much research in recent years. In areas where Hessian fly *Mayetiola destructor* (Say) (Diptera: Cecidomyiidae) has not been a problem, cultural controls include avoiding late plantings and managing for early stands of thick-tillered wheat. If insecticides are needed, there are several pesticides registered for small grains that work well in controlling cereal leaf beetle if applied at the appropriate time. Currently, pyrethroids are typically used by growers because of their relatively low cost and effectiveness.

Treatment thresholds vary by state and region, but in recent years, an IPM program for cereal leaf beetle in wheat has become well-established in both Virginia and North Carolina with

an economic threshold of 25 eggs or small larvae per 100 tillers (Herbert 2009, Herbert and Van Duyn 1999). Nevertheless, numerous growers are beginning to spray for cereal leaf beetle independently of scouting and thresholds. This approach is similar to the blanket sprays of the 1960's that did little to control cereal leaf beetle. The success of insecticide applications is heavily dependent on the timing in relation to cereal leaf beetle phenology; therefore, for effective management, we must improve our understanding of the biology and population dynamics and develop effective and accurate predictive tools that will allow for well-timed scouting and insecticide applications.

Current research

To illustrate the importance of timing of insecticide applications, small plot studies were conducted to investigate the possibility that residual activity of insecticides, when applied to correspond with plant phenology in terms of nitrogen applications, was likely too early, in relation to the cereal leaf beetle population phenology. Therefore, it would be ineffective for control. In 2010 and 2011 studies, Reisig (unpublished data) applied several pyrethroids, a spinosyn, and an organophosphate insecticide to coincide with nitrogen application approximately 30 days before cereal leaf beetle reached threshold levels. In one location (Plymouth, NC 2010) the cereal leaf beetle population greatly exceeded threshold (30 days after application). However, beetle abundances were not significantly different among the treatments or the untreated control. In another location (Lumberton, NC) and in Plymouth NC, 2011, cereal leaf beetle populations never developed in either the treated or untreated wheat. Results in these studies were indicative of many cases where automatic insecticide applications are applied, either too early to be effective, or where cereal leaf beetle populations would never develop due to regional distribution patterns.

In addition to timing of insecticide applications, movement patterns and plant preferences of adult cereal leaf beetle after spring emergence are likely to play an important role in where beetles will be found, and these details have yet to be determined. Prior to experimental investigation, it was thought that emerging adults followed a succession pattern of host plants from wild grasses to cultivated grains (Ihrig 1998). However, Helgesen (1969) found that when grains were available they were the preferred host, and later studies illustrated clear preferences for wheat and oats over other potential hosts (Ruesink 1972, Gage 1974, Casagrande et al. 1977).

While cereal leaf beetle may exhibit some level of host plant preference, the extent to which they prefer one host plant over another, remains unclear. Cereal leaf beetle infestations can be sporadic and highly variable. According to some observations, the pest appears to prefer late-planted, thinly-sown wheat or in areas where there are conditions that lead to poor growth (McPherson 1983a, Grant and Patrick 1993). In contrast, Honek (1991) found that cereal leaf beetles prefer dense stands. Simulation models suggest that field edge, size, and habitat surroundings are the leading factors contributing to cereal leaf beetle infestations (Sawyer and Haynes 1986). What regulates when and where cereal leaf beetle infestations occur has yet to be determined.

To begin to understand when and where cereal leaf beetle outbreaks might occur, the interaction of various factors and populations within wheat fields must be considered. The main variables in the ecology of cereal leaf beetle are likely to be the interactions between temperature and field dynamics, such as host plant quality, and natural enemy populations. It is believed that the seasonal biology of cereal leaf beetle is driven by temperature. If the temperature correlation with population dynamics can be disentangled, it will make it much easier to predict cereal leaf beetle infestations. This may also lead to an understanding of what influences cereal leaf beetle distribution. Although data are sparse, some wheat fields have specific characteristics that may make them more susceptible to cereal leaf beetle infestations. These characteristics include planting date, stand thickness, soil characteristics, field size, and surrounding vegetation but adult beetles also appear to seek out less mature plants (Hanes and Gage 1981, McPherson 1983a). This may indicate that anything that limits plant stand and growth also increases the likelihood of cereal leaf beetle infestations.

To improve the ability to predict cereal leaf beetle infestations, cereal leaf beetle distribution should be described; an understanding should be gained regarding why these infestations occur, and gaps should be filled in what we know about this insect's biology. Research is underway to evaluate all of these needs and preliminary results are promising. Recent studies in the southeastern United States show that cereal leaf beetle populations are spatially aggregated on a field, farm, and regional level (D.D.R. and D.A.H, *unpublished data*, Reay-Jones 2010), but the main contributing factors leading to this distribution remain unknown. Knowledge of these factors is needed to explain the spatial distribution of this pest.

Because cereal leaf beetle emergence from overwintering and the rates of egg and larval development are largely determined by spring temperatures, determining if degree days can accurately predict when peak egg and larval densities occur may improve scouting efficiency and could encourage more growers to adopt an IPM approach. By building on an existing predictive degree day model (Guppy and Harcourt 1978), I hope to determine when peak egg populations occur and correlate these egg densities to current thresholds. In 2010 I used this model to estimate the dates of peak egg populations of cereal leaf beetle in Virginia and North Carolina. With a lower development threshold of 8°C and upper development threshold of 25°C a prediction for egg peak was made at 182 degree days. Four wheat fields, three in Virginia and one in North Carolina were sampled weekly from the first emergence of adults, through the egg and larval stages, until second generation adults began emerging. Population peaks were plotted against calculated degree-days to evaluate population trends and to predict population peaks. Observed cereal leaf beetle egg population peaks occurred between 6 and 12 April at all four locations with an average of 8 April. This model predicted the calendar date of peak eggs within two days of the average, 10 April. Data are also being collecting on peak larval populations. These data together will be used to determine if a model can be developed to predict peak larval numbers based on the peak number of eggs. Similar studies are planned in the future to provide additional data to further develop these models. When perfected, these model should provide growers with a 'heads-up' as to when to expect to see cereal leaf beetle stages in their fields, thus limiting the need to scout to those important days and thereby saving growers time and money.

All of this collaborative research, when integrated, should allow us to predict what fields are at the greatest risk to cereal leaf beetle infestation, when they are at risk, and why. Better knowledge of when, why and where outbreaks will occur could improve sampling efficiency and accuracy reducing the number of unnecessary insecticide applications. Our challenge is to develop new information and procedures that will encourage growers to re-evaluate the way they are approaching spring-time insect control in wheat, and reconsider adoption of the IPM approach.

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Tables and Figures

Table 1.1. Development time (days) of immature cereal leaf beetle by temperature, data from Guppy and Harcourt 1978.

Stage	Temperature °C										
	8	10	12	14	18	22	25	28	30	32	34
Egg	41.3	38.5	25.3	17.9	10.1	6.1	4.5	3.8	3.7	3.9	
Instar 1	11.1	9.3	7.2	5.9	4	2.8	2.2	1.8	1.7	1.5	1.5
Instar 2	13.2	11.8	7.8	5.8	3.4	2.3	1.8	1.5	1.3	1.3	1.5
Instar 3	11.5	12.3	9	6.5	4.1	2.7	2.1	1.8	1.6	1.8	2.6
Instar 4	11.3	12.7	9.3	6.9	4.2	3	2.4	2.1	2	2.2	
Total larval	47.5	46.2	32.5	25.2	15.7	10.8	8.5	7	6.4	6.6	



Fig. 1.1 Cereal leaf beetle larval feeding damage to wheat, damaged area in the foreground, green protected area in the background. Photo by D.A. Herbert



Fig. 1.2. Adult cereal leaf beetle. Photo by D.D. Reising



Fig. 1.3. Cereal leaf beetle eggs. Photo by D.D. Reising



Fig. 1.4. Cereal leaf beetle larva with no mucus or fecal material. Photo by D.A. Herbert



Fig. 1.5. Cereal leaf beetle larva covered with mucus and fecal material. Photo by D.D. Reising

Chapter Two

Using degree-days to predict cereal leaf beetle (Coleoptera: Chrysomelidae) egg and larval population peaks

(Philips et al. 2012. Environmental Entomology. 41: 761-767.)

Abstract

To improve cereal leaf beetle scouting efficiency and encourage the use of thresholds, temperature-based degree-day models were developed and tested to determine their accuracy to predict the date of egg and larval peaks. Previously published cereal leaf beetle temperature development data were used to create the degree-day model. This model of 182 degree-days using a base development temperature of 8°C was validated using cereal leaf beetle sampling data from four locations in Virginia and North Carolina in 2010, and six locations in 2011. In both years, the degree-day model predicted the average egg peak within 3 days of the observed calendar date. There was also a consistent period between egg and larval peaks averaging 17.5 days. Given the accuracy of this model, historical high and low temperature data were used to create a predictive map of the calendar week that different areas of Virginia and North Carolina would exceed 182 degree-days, and was validated using survey data from 60 field sites in 2010 and 65 sites in 2011 throughout Virginia and North Carolina. Finally, correlation and linear regression analyses were performed using data from all cereal leaf beetle study populations in 2010 and 2011, as well as previously collected data to determine if the number of eggs at peak could be used to predict larval peak numbers. There was a significant positive linear relationship between egg peak density and larval peak density explaining 94% of the variation seen in larval peaks, indicating that egg peaks could reliably predict larval infestation levels.

Introduction

Cereal leaf beetle, *Oulema melanopus* L. (Coleoptera: Chrysomelidae), is an introduced insect pest of small grains first recorded in the United States in the early 1960's (Philips et al. 2011). Since its introduction from Europe or Asia into Michigan, cereal leaf beetle has rapidly spread and is now found throughout much of North America. Cereal leaf beetle feeds on numerous species of grasses and is a major pest of oats, barley, and wheat. Helgesen (1969) found that cereal grains were the preferred host when they were available; additionally, later studies illustrated clear preferences for wheat and oats over other potential hosts (Ruesink 1972, Gage 1974, Casagrande et al. 1977). Although adults feed on small grain plants, their feeding generally does not seriously affect the plant. Larvae, however, skeletonize the leaf giving it a "frosted" appearance and decreasing plant photosynthesis (Grant and Patrick 1993, Buntin et al. 2004). This loss of photosynthetic ability can cause significant losses in yield and grain quality (Wilson et al. 1964, Koval 1966, Merrit and Apple 1969, Webster and Smith 1983, Grant and Patrick 1993). Yield loss from cereal leaf beetle is highly variable, with maximum losses of approximately 40% (Buntin et al. 2004).

Cereal leaf beetle has one generation per year; although a second generation has been reported in Virginia (McPherson 1983). Adults overwinter in debris or wooded areas adjacent to the previous season's grain fields. Adults emerge from overwintering in the early spring when daytime high temperatures consistently exceed 14°C (Helgesen and Haynes 1972, Gutierrez et al. 1974), and move into small grains to lay eggs (Helgesen and Haynes 1972). Female cereal leaf beetles deposit eggs individually or in short chains along the midvein, on the upper surface of leaves (Helgesen and Haynes 1972). A single mated female can deposit up to 50 eggs in her lifetime (Philips et al. 2011).

Larvae are slug-like, have grayish yellow bodies with heads and legs that are brownish-black. Larvae pass through four instars and typically develop in 10-14 days at optimal temperatures between 22-32°C, with the time divided equally between the four instars (Guppy and Harcourt 1978, Herbert et al. 2007). Upon reaching full size (~ 5 mm), 4th instars drop to the soil surface, burrow down about 5 cm and pupate. Adults emerge in 17 to 25 days based on soil temperature (Philips et al. 2011).

Their life cycle can span from 10 to 90 d depending on temperature, but generally requires an average of 46 days at typical spring temperatures for the Midwest and mid-Atlantic

United States (Guppy and Harcourt 1978, Metcalf and Metcalf 1993). Although research has been done on cereal leaf beetle population dynamics and control (Battenfield et al. 1982), the underlying mechanisms that determine its spread and distribution remain unresolved (Haynes and Gage 1981). Because so much remains unknown about this insect pest's life history, predicting outbreaks is extremely difficult.

Early studies set action thresholds for cereal leaf beetle at one larvae per stem (Webster et al. 1972, Haynes and Gage 1981), but more recent research suggests that the economic threshold should be lower (Ihrig et al. 2001, Buntin et al. 2004). Virginia and North Carolina currently recommend an economic threshold of 25 eggs or small larvae per 100 tillers (Herbert 2009, Herbert and Van Duyn 1999). Nevertheless, there is a growing trend for producers to spray for cereal leaf beetle independent of scouting and thresholds. Insecticides are typically tank-mixed with liquid fertilizers applied at small grain growth stage (GS) 30 (Zadoks et al. 1974). This GS 30 insecticide application was designed to suppress aphids and control barley yellow dwarf virus infection in the southern U.S., where it works well in achieving these goals. In the mid-Atlantic region, however, feeding by cereal leaf beetle larvae generally does not peak until GS 45, approximately 30-40 days after this GS 30 nitrogen application. Given the limited residual activity of these insecticides, applications at GS 30 are often too early in relation to cereal leaf beetle population phenology and are ineffective for control. In addition, recent surveys have shown that in many cases, these insecticide applications are not needed, as the small grain acreage treated far exceeds the percentage of acres actually infested by cereal leaf beetle (Reisig et al. 2012).

Also in the southeastern United States, preventive cereal leaf beetle spray applications are often tank-mixed with a foliar fungicide application for leaf rust (*Puccinia sp.*). This combination is usually applied at boot stage to early head emergence (GS45-50), which at more southern latitudes, corresponds fairly well with cereal leaf beetle phenology. Thus, this timing is effective in controlling cereal leaf beetle in fields with a history of infestation. Over time, this management tactic has slowly moved northward and is now widely used in North Carolina and Virginia resulting in hundreds of thousands of acres of wheat receiving an insecticide application that essentially serves no purpose. To reverse this trend we must develop new decision-making strategies that reduce the time or cost required by the user.

The seasonal biology of cereal leaf beetle is strongly influenced by temperature (Guppy and Harcourt 1978, Grant and Patrick 1993). Cereal leaf beetle emergence from overwintering and the rates of egg and larval development are largely determined by spring temperatures. If correlations with temperature and population dynamics can be developed, it should be possible to make accurate predictions of cereal leaf beetle infestations. Determining if degree-days can accurately predict when peak egg and larval densities occur is an important step in this process (Fig 2.1). Degree-day accumulation has been widely used to accurately predict population arrivals or peaks for a number of pests, including other chrysomelid beetles and other pests of small grains (Harding et al. 2002, Pedigo and Rice 2008). Currently, no degree-day predictions exist for cereal leaf beetle and scouting is often done from late March and to June as to not miss population peaks, which is extremely inefficient. By building on existing cereal leaf beetle temperature development data (Guppy and Harcourt 1978), I hope to determine when peak egg populations occur and correlate these egg densities to current thresholds. The ability to accurately predict when to scout fields for cereal leaf beetle may encourage growers to reevaluate their method of springtime insect control in wheat, and consider re-adoption of the economic threshold-based approach.

Materials and Methods

Degree-day calculations and monitoring. Cereal leaf beetle temperature development data from previously published studies (Gutierrez et al. 1974, Guppy and Harcourt 1978, Blodgett et al. 2004) were used to create a predictive degree-day model to estimate the dates of peak egg and larval populations. This model was validated using cereal leaf beetle population data from four wheat fields in Virginia and North Carolina in 2010, and six fields in 2011 (Table 2.1). Degree-days were calculated using weather data from the VAES Weather Mesonet website (VAES Weather MESONET 2011) using daily max-min temperature data for two degree-day predictions (182 and 253 (Blodgett et al. 2004)), an upper development threshold of 25°C (Guppy and Harcourt 1978), and three lower development thresholds 7 (Blodgett et al. 2004), 8 (Guppy and Harcourt 1978), and 10°C (Gutierrez et al. 1974). Degree-days were calculated using a January 1 bio fix and standard degree-day calculations $((\text{maximum} + \text{minimum temperature})/2 - \text{lower threshold})$ to determine the calendar date of 182 and 253 degree-days at each of the three lower development thresholds.

In 2010, cereal leaf beetle populations were monitored weekly at each study site. All populations developed on either wheat or barley. Fields were monitored from the first adult appearance through egg deposition and larval development until emergence of second-generation adults. At each field study site, all eggs and larvae were counted on all tillers in eight randomly-selected 0.305-m sections of row. Degree-days for each site were calculated using weather data obtained from the nearest available weather station. Cereal leaf beetle population peaks were plotted against calculated degree-days to evaluate population trends and to predict egg and larval peaks.

In 2011, populations were monitored at six different locations and degree-days were calculated using the most accurate degree-day and lower threshold model from 2010. All populations were monitored twice weekly and all other methods remained the same (Table 2.1).

Predictive map. Using a lower development threshold of 8°C a predictive map for Virginia and North Carolina was created using BioSIM 10, a seasonal pest biology forecasting system (Régnière and Saint-Amant 2008) and ArcGIS. Thirty-year normal temperature data (1981 - 2010) from over 489 weather stations in Virginia and neighboring states were used to generate a map of the calendar day of 182 degree-day threshold at a resolution of 1km x 1km cells.

Validating predictive map. Predictive maps were validated using survey data from 60 field sites in 2010 and 65 sites in 2011 throughout Virginia and North Carolina (Fig 2.2). Cereal leaf beetle population densities were monitored weekly from 1 April until emergence of second-generation adults by recording total numbers of eggs and larvae per 100 randomly selected tillers in each field.

Eggs to predict larvae. To determine if the number of cereal leaf beetle eggs present at peak could be used to accurately predict the likelihood of a field exceeding threshold, the relationship between peak egg numbers and peak larval numbers was examined using correlation and linear regression in JMP 8.0 (SAS Institute 2011). Variables for this analysis consisted of observed peak egg densities and observed peak larval densities. Analysis were performed on collected data from 10 populations monitored in 2010 and 2011, as well as on data collected in previous studies (Ihrig1998).

Results

Population peaks and degree-days. The mean date of egg peak was accurately predicted with the lower degree-day model (182), but not the higher degree-day model (253). Based on the four locations in 2010, the 182 degree-day model predicted the calendar date within 3 days with a lower development threshold of 8°C (Table 2.2). The higher degree-day prediction model (253) was much more variable in predicting peak dates (Table 2.2). Based on these data, the most accurate model was the 182 degree-day prediction with a lower development threshold of 8°C therefore this model was used for the remainder of the data presented here. Cereal leaf beetle egg peaks occurred between 6 and 12 April with an average peak date of 8 April. The model predicted egg peak for each population within 3 days and predicted the average (8 April) perfectly. Larval peaks occurred between 19 and 29 April and averaged 17.7 days after egg peak.

In 2011, egg peaks occurred between 28 March and 25 April with an average peak of 11 April (Table 2.3). The model predicted egg peak for each population, but results were much more variable than 2010 with a maximum difference of 15 days. Larval peaks were observed between 22 April and 3 May, and occurred on average 17.3 days after egg peak (Table 2.3).

To determine if degree-days could be used to accurately predict the time between egg and larval peaks the number of degree-days between peaks was calculated for field-collected data. Trends were observed in 2010 they did not hold in 2011, therefore it does not appear that accumulated degree-days are a reliable predictor of time between peaks (Table 2.3).

Over the two years of the study, the model of 182 degree-days with a lower development threshold of 8°C predicted observed average egg peak within 3 days with a range of 0 to 16 days and average larval peak occurring 17.5 days later with a range of 7 to 35 days (Table 2.3).

Validating predictive map. Given the accuracy of 182 degree-days in predicting egg peaks, historical high and low temperature data were used to create a predictive map of the calendar week that different areas of Virginia and North Carolina would exceed 182 degree-days (Fig 2.2). In 2010, the map was accurate at all sites within 11 days, with an average difference between predicted and observed of 3 days. The map accurately predicted 88% of fields within one week and predicted >98% of fields within 10 days. In 2011, variation in prediction ranged from 0 to 11 days with an average difference of 4 days. The map accurately predicted 77% of the fields within 7 days and >98% of the fields within 10 days. Over the two years of the study, the map predicted all sites within 11 days with 81% of fields predicted within 7 days and 98% within

10 days. The difference between predicted and observed for all populations was 4 days, with only two sites outside of 10 days (Fig 2.3).

Eggs density predicting larval density. A significant correlation was detected between egg and larval peaks for all populations in 2010 and 2011 ($F = 135.13$; $df = 1, 8$; $P < 0.0001$) as well as for previously collected data ($F = 147.09$; $df = 1, 13$; $P < 0.0001$). Using data from all study populations in 2010 and 2011 this correlation and linear regression model indicates a strong significant positive correlation ($r = 0.97$) between egg and larval peaks explaining 94% of the variation seen in larval peaks ($R^2 = 0.94$; $P < 0.0001$). This trend held true when the same analysis was performed on data collected in a previous study ($r = 0.96$; $R^2 = 0.92$; $P < 0.0001$) (Fig. 2.4).

Discussion

Using the temperature-based developmental work of Guppy and Harcourt (1978), I was able to determine that degree-days are going to be a useful tool in predicting cereal leaf beetle population peaks. This study validated the degree-day prediction for cereal leaf beetle egg peaks at 182 degree-days. In addition, the predictive model allowed me to create a map that accurately indicated when various locations throughout Virginia and North Carolina would exceed 182 degree-days. I was also able to determine that there appears to be a consistent period between egg and larval peaks regardless of degree-day accumulation, and that the number of eggs observed during peak can be used as an indicator of when larval populations will peak.

The results of this study indicate that the date of cereal leaf beetle egg peaks in small grains can be accurately predicted using degree-days in the mid-Atlantic and southeast United States, but there are several caveats to be noted. The first is that this model is highly accurate at predicting population peaks in a typical weather year. It is important to keep in mind that extremely hot or cold years may influence the accuracy of the model. Both years in this study were typical for Virginia and North Carolina, although degree-days did start to accumulate about a month sooner in 2011. This may explain some of the variability observed in population data for that year. In addition, in 2011, there were egg peaks that appeared to occur much later than predicted. This is likely due to the true egg peak occurring prior to the beginning of sampling nevertheless, I was able to determine larval peak at all sites. In addition, because I found that in both years, the average between peaks was about 17.5 days, I was able to use this interval and

use larval peaks to predict egg peaks. To test this assumption, I took the date of larval peak and subtracted 17.5 days to get what would be an estimate of egg peak date. The model accurately predicted egg peak within 3 days at all locations.

These models provide several valuable pieces of information that can improve the efficiency of cereal leaf beetle management by predicting a calendar date to begin field scouting. Given the correlation between temperature and development (Yun 1967, Helgesen 1969, Guppy and Harcourt 1978, Metcalf and Metcalf 1993, Herbert et al. 2007), it is not surprising that a weather-based model can accurately predict egg peaks. This model predicted dates of egg peaks accurately, and over time, as more data are added to this model, its overall accuracy will be improved. In addition, given the significant positive relationship and high level of correlations, it is likely that the number of eggs found at peak will consistently be an accurate predictor of larval population peaks. Combine this with the consistent time between egg and larval peaks, and this becomes a very powerful tool for improving management of cereal leaf beetle. With these predictive tools, the scouting process will become much more efficient, which could minimize the use of automatic insecticide applications.

In summary, these data show that a model based on temperature can accurately predict the date of cereal leaf beetle egg peak in Virginia and North Carolina, and that peak larval densities occur approximately 17.5 days after egg peak. These data also indicate that cereal leaf beetle egg density can be used as a predictor of larval peak density, and concomitant likelihood of a field exceeding the economic threshold. These data can improve the efficiency of cereal leaf beetle management by predicting a calendar date to begin scouting, narrowing this window from several weeks to a few days. This eliminates the need for long-term, labor-intensive scouting programs and reduces the scouting to one or two days. More data are needed, but these new tools will be invaluable in assisting growers in making decisions on how to manage cereal leaf beetle.

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Tables and Figures

Table 2.1. Cereal leaf beetle population study site locations in 2010 and 2011.

2010			2011		
Location	Latitude	Longitude	Location	Latitude	Longitude
Exmore, VA 1	37.71527	-75.93694	Petersburg, VA	37.22911	-77.43904
Exmore, VA 2	37.59333	-76.03555	Yale, VA	36.87682	-77.30483
Suffolk, VA	36.68512	-76.76669	Plymouth, NC	35.85167	-76.65368
Plymouth, NC	35.85167	-76.65368	Mechanicsville, VA	37.65483	-77.22515
			Richmond, VA	37.40342	-77.34620
			Montross, VA	38.01858	-76.71725

Table 2.2. Predicted and observed egg peaks of cereal leaf beetle, observed degree-day of egg peak, date of peak larvae, and the time (days) between egg peak and larval peak at four locations in 2010. Degree-days were calculated using two degree-day predictions (182 degree-days and 253 degree-days) at three lower development thresholds (7, 8, 10°C) with an upper development threshold of 25°C.

Life Stage									
Model		Egg Peak		Larval Peak		Between Peaks			
Field Location	Lower Threshold	Predicted (182°D)	Predicted (253°D)	Observed	Observed degree-day	Observed	Observed degree-day	Degree-days	Days
Exmore, VA 1	7°C	8-Apr	20-Apr	12-Apr	210.85	29-Apr	321.37	110.52	17
Exmore, VA 2	7°C	8-Apr	20-Apr	8-Apr	186.43	29-Apr	321.37	134.94	21
Suffolk, VA	7°C	3-Apr	8-Apr	9-Apr	258.67	27-Apr	397.39	138.72	18
Plymouth, NC	7°C	2-Apr	7-Apr	6-Apr	238.11	19-Apr	357.67	119.56	13
Field Location	Lower Threshold	Predicted (182°D)	Predicted (253°D)	Observed	Observed degree-day	Observed	Observed degree-day	Degree-days	Days
Exmore, VA 1	8°C	11-Apr	28-Apr	12-Apr	177.51	29-Apr	271.45	93.94	17
Exmore, VA 2	8°C	11-Apr	28-Apr	8-Apr	157.09	29-Apr	271.45	114.36	21
Suffolk, VA	8°C	7-Apr	15-Apr	9-Apr	220.35	27-Apr	341.07	120.72	18
Plymouth, NC	8°C	5-Apr	13-Apr	6-Apr	199.61	19-Apr	306.17	106.56	13
Field Location	Lower Threshold	Predicted (182°D)	Predicted (253°D)	Observed	Observed degree-day	Observed	Observed degree-day	Degree-days	Days
Exmore, VA 1	10°C	30-Apr	5-May	12-Apr	111.16	29-Apr	175.72	64.56	17
Exmore, VA 2	10°C	30-Apr	5-May	8-Apr	98.73	29-Apr	175.72	76.98	21
Suffolk, VA	10°C	15-Apr	27-Apr	9-Apr	151.05	27-Apr	235.77	84.72	18
Plymouth, NC	10°C	11-Apr	23-Apr	6-Apr	132.78	19-Apr	213.33	80.56	13

Table 2.3. Predicted and observed egg peaks of cereal leaf beetle, observed degree-day of egg peak, date of peak larvae, and the time (days) between egg peak and larval peak at four locations in 2010 and six locations in 2011. Degree-days were calculated using degree-day prediction of 182 degree-days with a lower development threshold of 8°C and an upper development threshold of 25°C.

		Life Stage						
2010	Model		Egg Peak		Larval Peak		Between Peaks	
Field Location	Lower Threshold	Predicted (182°D)	Observed	Observed degree-day	Observed	Observed degree-day	Degree-days	Days
Exmore, VA 1	8°C	11-Apr	12-Apr	177.51	29-Apr	271.45	93.94	17
Exmore, VA 2	8°C	11-Apr	8-Apr	157.09	29-Apr	271.45	114.36	21
Suffolk, VA	8°C	7-Apr	9-Apr	220.35	27-Apr	341.07	120.72	18
Plymouth, NC	8°C	5-Apr	6-Apr	199.61	19-Apr	306.17	106.56	13
2011								
Petersburg, VA	8°C	23-Mar	28-Mar	136.04	2-May	439.5	303.46	35
Yale, VA	8°C	18-Apr	6-Apr	169.82	28-Apr	400.63	230.81	22
Plymouth, NC	8°C	22-Mar	7-Apr	177.33	22-Apr	309.37	132.04	15
Mechanicsville, VA	8°C	11-Apr	20-Apr	215.13	3-May	350.86	135.73	13
Richmond, VA	8°C	11-Apr	11-Apr	149.08	25-Apr	271.31	122.23	14
Montross, VA	8°C	12-Apr	25-Apr	271.31	2-May	343.94	72.63	7

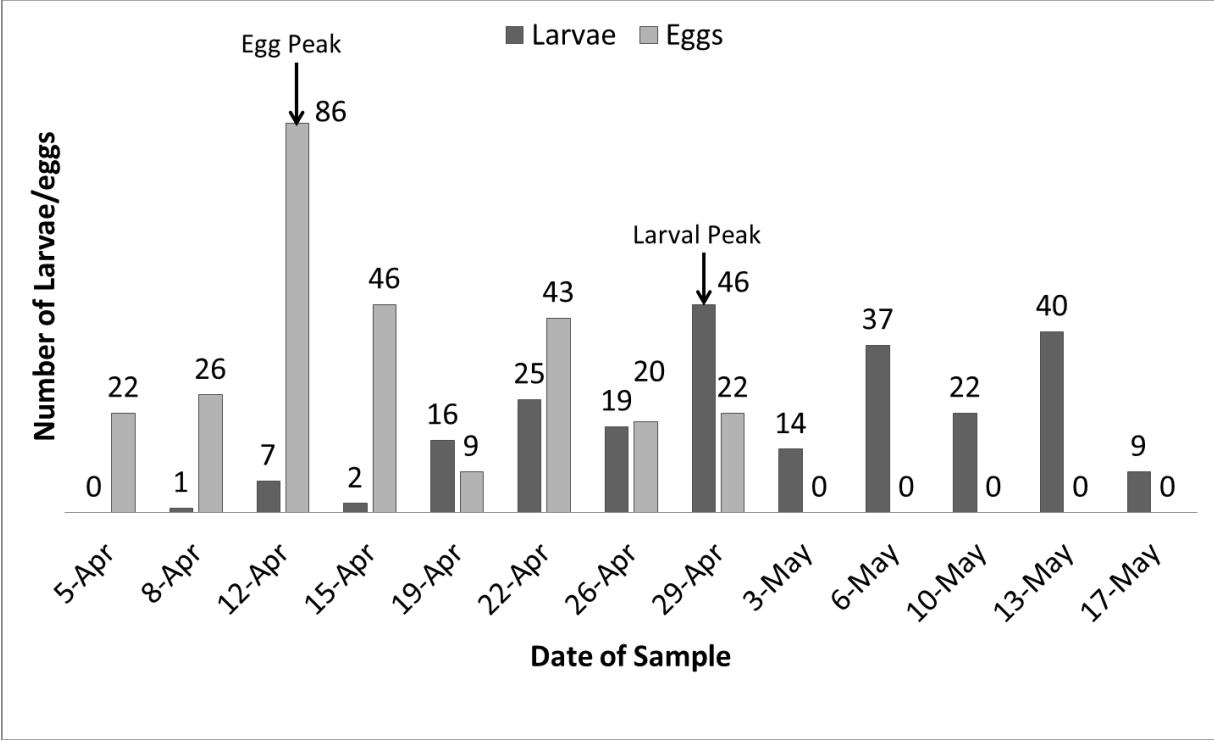


Fig 2.1. Population dynamics of a single population (Exmore, VA) of cereal leaf beetle including the dates when the most eggs (egg peak) and larvae (larval peak) were observed in 2010.

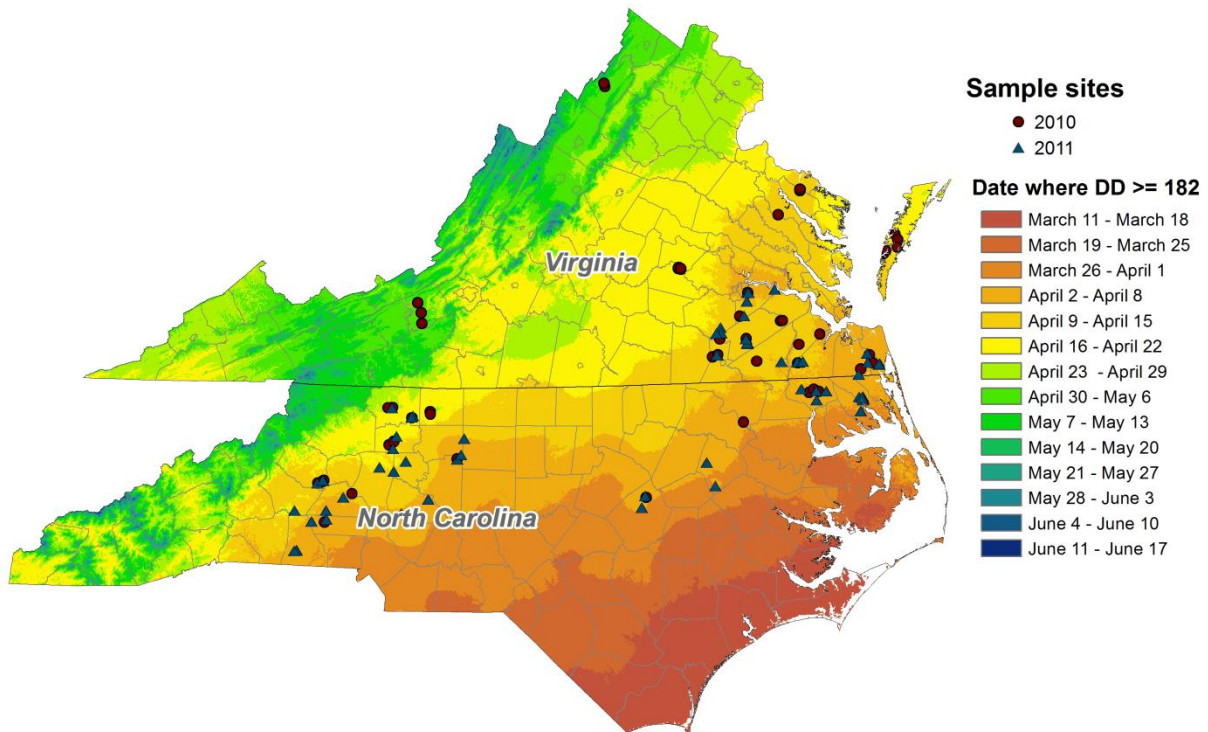


Fig 2.2. Interpolation map of when regions of Virginia and North Carolina will reach predicted cereal leaf beetle egg peak (182 degree-days with base development temperature of 8°C) based on thirty-year normal temperature data (1981 - 2010) from over 324 weather stations in Virginia and neighboring states at a resolution of 1km x 1km cells. Maps also includes population survey field locations used to validate the map in 2010 and 2011.

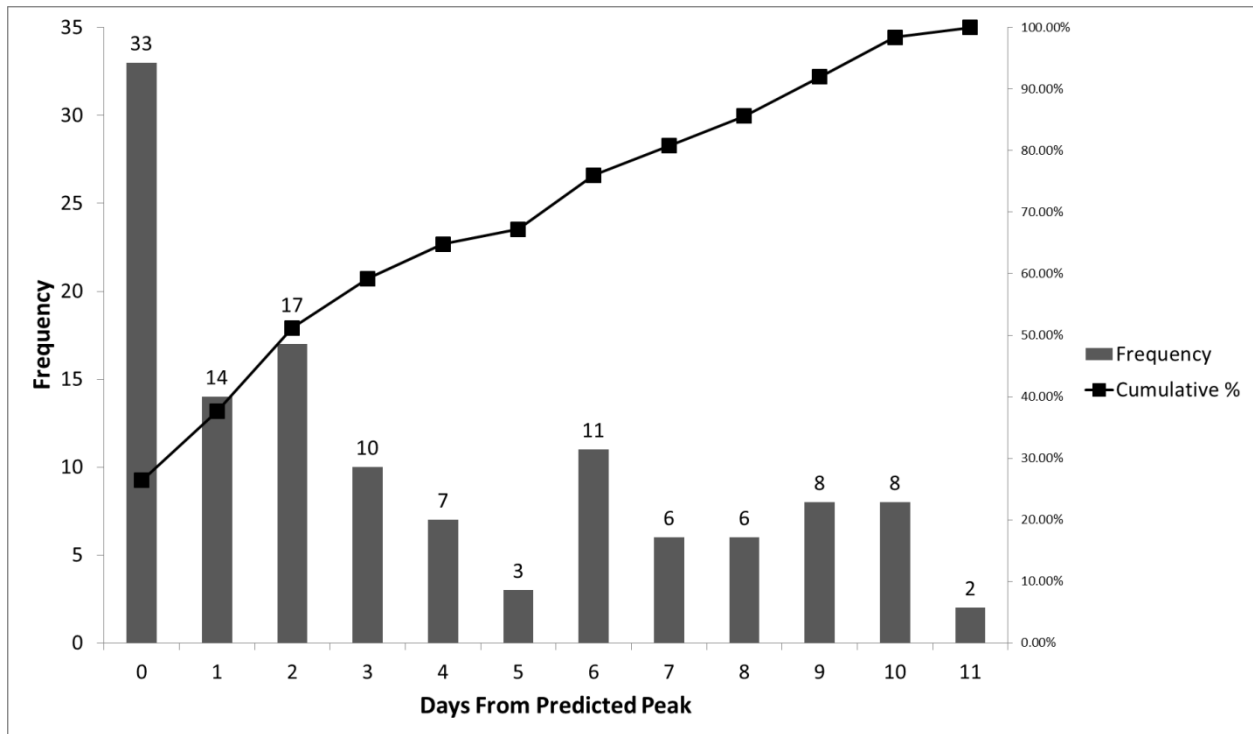


Fig 2.3. Frequency histogram of the residuals of predicted egg peak and observed egg peak from 60 field sites in 2010 and 65 sites in 2011 throughout Virginia and North Carolina.

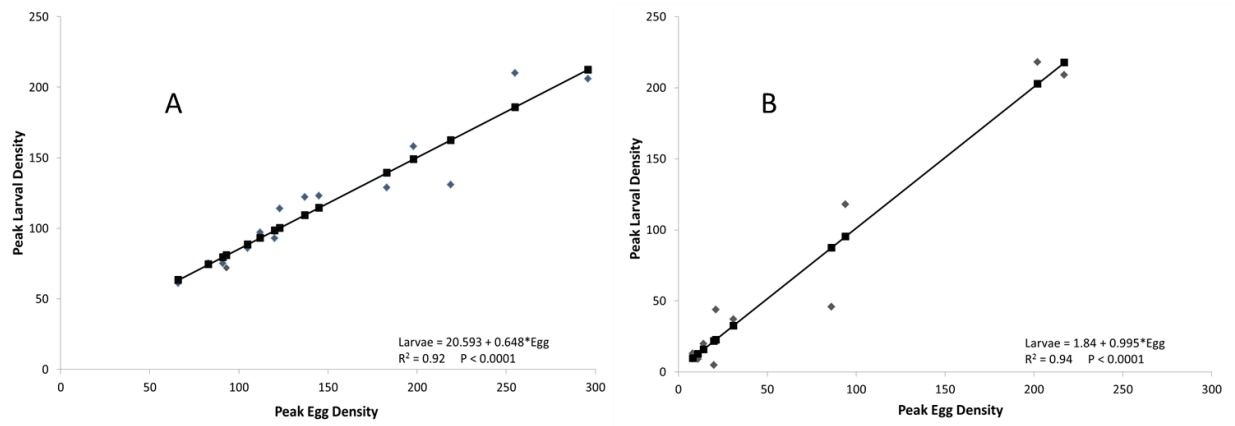


Fig 2.4. Linear regression of cereal leaf beetle eggs and larvae A) data from previous field studies (Ihrig1998); B) data from all monitored populations in 2010 and 2011.

Chapter Three

Understanding the risks and benefits of plant provided resources in pest management.

Abstract

Farmscaping is a technique used in conservation agriculture that refers to the arrangement or configuration of insect-attracting plants that promotes biological pest management by attracting and sustaining beneficial organisms. Ideal farmscape plantings provide a habitat for beneficial insects, suppress weeds, and grow in close proximity to the primary (or cash) crop without competing for light, water and nutrients. The configuration of crop plants and insect-attracting plants can impact the suite of arthropod pests and natural enemies present in the field, and specifically the primary, or cash crop of interest. In this chapter, I review the theory behind farmscaping, discuss some commonly-used farmscaping plants, and discuss what studies have been conducted to evaluate the impact of companion planting on pests.

Introduction

As human populations continue to increase, the challenge facing growers in the coming years is to produce more food with fewer resources. To accomplish this, it is necessary to develop methods that efficiently use natural resources that, at the same time, minimally disturb the environment. Currently, most crops in the United States are grown in simple, monoculture systems because of the efficiency in planting and harvesting (Norris 1986, Buttel 1990). These simple systems can produce high yields, but also frequently require increased inputs of synthetic chemicals. In these systems, pesticides are commonly used to control pests that interfere with crop production. Although the application of pesticides can be effective in the short-term, its use alters the ecological balance in these systems. Once this balance has been disrupted, these systems must be closely monitored to ensure maximum production and additional inputs are often required (Gliessman 1990).

Conservation agriculture is a series of practices aiming to achieve sustained or improved crop production and profitable agriculture, while simultaneously conserving natural resources and protecting the environment. Conservation agriculture emphasizes proactive, multi-tactic practices in contrast to the “single approach” reactive methods generally used in conventional systems. A technique common in conservation agriculture is farmscaping. Farmscaping refers to the arrangement or configuration of plants that promotes biological pest management by attracting and sustaining beneficial organisms (Bugg and Pickett 1998). Recently, the term farmscaping has been broadened to incorporate other types of companion plantings. Farmscape plantings can be arranged in one or in a combination of designs and at different locations throughout the farm sites: (1) as living mulches or trap crops near cash crops; (2) in fence rows or borders; (3) as island patches within rows or occupying entire rows spaced at regular intervals within the field; or (4) as herb/flower cash crops intercropped with vegetable/fruit crops.

Ideal farmscape plantings provide a habitat for beneficial insects, suppress weeds, and grow in close proximity to the cash crop without competing for light, water and nutrients. The configuration of crop plants and insect-attracting plants can impact the suite of arthropod pests and natural enemies present in the field (Barbosa 1998, Bugg and Pickett 1998). These practices can have numerous benefits including the potential to enhance the activity of arthropod natural enemies, and improve biological control, but they might also exacerbate pest populations (Landis et al. 1987, Turnock et al. 1993, Renner, 2000, Wäckers et al. 2007, Winkler et al. 2010). In this

chapter, I review the theory behind farmscaping, as a means to attract beneficials and discuss some commonly used farmscaping plants, as well as what studies have been conducted to evaluate the impact of companion plantings on pests.

Using plant-provided resources to improve biological control

The agroecosystem: It has been proposed that diversity in the agroecosystem will lead to increased control of insect pests through conservation of habitats for their natural enemies. Central to this concept is the definition of an agroecosystem. An agroecosystem can be thought of as a community of living organisms in conjunction with the nonliving components of their environment, interacting as a system that has been modified by humans to produce food, fiber, or other agricultural products (Waltner-Towes 1996).

The perturbation of natural processes in simplified systems has a tendency to shift the ecological balance to favor pests (Altieri and Letourneau 1982). Therefore, the primary goal of farmscaping should be to shift the ecological balance back towards a more favorable equilibrium to improve pest control (Norris 1986). To accomplish this, it is essential that we begin to think of these systems in ecological terms (Waltner-Towes 1996). Agroecosystems are comprised of various components including animal and plant communities, the physical environment, as well as human inputs and their interactions (Reijntjes et al. 1992). It is important to remember that the primary objective in any agroecosystem is crop production, and that these crops are susceptible to, but also reliant on, the same processes and interactions found in other natural ecosystems such as trophic interactions, predatory/prey dynamics, plant species competition, successional dynamics, and nutrient cycling (Hecht 1987). What differentiates agroecosystems from natural ecosystems is the degree of human input (Gliessman 1990). Thinking of these systems from an ecological perspective can lead to a better understanding of the interactions in these systems leading to improved crop production. From a pest management perspective, a closer examination of the insect communities and how they interact within these agrosystems has tremendous potential to improve pest management.

Agroecosystem communities and diversity

In addition to all the other factors acting on an agroecosystem, there are three interacting communities of insects: plant-feeding pests, natural enemies, and alternative prey hosts. These three communities have close and complex relationships with the vegetation found in an

agroecosystem. Pest insects have been studied intensively because of the immediate problems they pose to agricultural production. For this reason, their biology is better understood, although many questions remain. Moreover, the interactions among vegetation, natural enemies, alternative prey, and pests are not thoroughly understood and more research is needed to understand the complexities of these relationships.

Root (1973) formulated two hypotheses that are central to understanding how diversity may influence insect populations in agroecosystems. The “enemies hypothesis” states that more natural enemies should be found in diverse plantings due to greater availability of alternative food. The “resource concentration hypothesis” explains the susceptibility of less diverse systems to insect pest damage by hypothesizing that these large clusters of resources are easier for pests to locate. Over the past 40 years, these two hypotheses have led to numerous studies investigating the importance of diversity in agroecosystems (Gurr et al. 2012).

In testing the “enemies hypothesis”, Letourneau and Altieri (1983) showed that natural enemies increased colonization rates in more diverse systems and that this increase may be the result of additional nectar and pollen sources, which encourage natural enemy colonization leading to reduced pest population densities. Another test of these hypotheses involves investigating the role of weeds in modifying insect populations. Weeds may also provide alternative food resources as many species of predators and parasitoids are known to feed on plant-provided resources when prey are scarce, but they can also be important resources for pests (van Emdem 1965, Altieri and Whitcomb 1979, van Emdem 1990).

Diverse systems tend to favor a greater diversity of alternative prey and provide additional important resources due to more complex microhabitats, which in turn may lead to increases in survival of natural enemies in these systems (Norris 1986, van Emdem 1990). A recent meta-analysis found that herbivore suppression, enemy enhancement, and decreased crop damage were significantly greater in diverse systems (Letourneau et al 2011). Polycultures provide diversity in agroecosystems, which can result in higher population densities of natural enemies as predicted by the “enemies hypothesis”. This increase in diversity can be managed within an agroecosystem to help conserve populations of natural enemies.

Farmscaping theory

Most crops have pests that are specific to that crop, and associated with those pests are natural enemies. These predator-prey relationships tend to follow specific patterns unless something interferes with the normal dynamics of the system. Low populations of naturally occurring beneficial insects might be attributed to intensive farming operations including growing large monocultures, regular cultivation, and use of insecticides. These practices lower diversity and, at the same time, maintain a high level of disturbance, limiting resources for insect natural enemies (Rabb et al. 1976, Powell 1986, Dutcher 1993, Landis and Menalled 1998). In addition, these conditions favor the rapid colonization and population growth by pests (Price 1981, Letourneau 1998). Farmscaping is a technique designed to add diversity back to the system and minimize disturbance leading to increases in natural enemy populations by providing important food and shelter resources.

Conservation of natural enemies involves manipulation of the environment to favor natural enemies, either by eliminating adverse factors or by providing improved conditions for colonization and survival (DeBach and Rosen 1991, Greathead 1995). In addition to acting as a reservoir for natural enemies (Altieri and Whitcomb 1979, Altieri and Letourneau 1982), the use of farmscapes may increase alternative prey or insect hosts when other food resources are scarce (Bugg 1992, Phatak 1992). Therefore, we must reassess current agricultural production from an ecological perspective. This approach builds on characteristics of an agroecosystem and integrates the ecological principles of a natural ecosystem such as predator/prey interactions, competition, and energy flow through trophic levels, with the human inputs of production agriculture (Hecht 1987, Gleissman 1990, Reijntjes et al. 1992). Species diversity is one of the key characteristics of an agroecosystem (Altieri and Letourneau 1982).

Increasing plant diversity agroecosystems provides essential elements that attract beneficial insects from surrounding areas. These plants provide conditions where natural enemies can thrive and become established densities to increase in sufficient numbers to control pests (Landis et al. 2000, Sarthou et al. 2005). Farmscape plantings can also serve as an overwintering habitat, which is another important component of conservation biological control to ensure carryover of beneficial insects from year to year.

Numerous studies have shown that habitat diversity in agricultural landscapes has the potential to decrease pest pressure or increase natural control (Bianchi et al. 2006, Gardiner et al.

2009, Power et al. 2009, O'Rourke et al. 2011). The mechanisms behind this are not well understood, and recent research indicates the scale and arrangement may be important (Lee and Heimpel 2005, O'Rourke et al. 2011). In addition, diverse landscapes may make it more difficult for pests to locate hosts reducing the time and energy available for reproduction (Fahrig and Paloheimo 1988, Schneider 1999, den Belder et al. 2002, O' Rourke et al. 2011). It is likely that reduced pest pressure in more diverse systems results from a combination of factors. The addition of farmscaping to a management plan may be a major factor and appears to offer a potential to improve pest management.

Predator and parasitoid foraging

Natural enemies have a tremendous capacity to regulate pest populations. Most of the work in this area has been done with parasitoids. Adult parasitoids balance their time between foraging for food and hosts. Over the past several decades, information attained from numerous studies has greatly increased our understanding of parasitoid-host foraging (Vinson 1976, Lewis et al. 1990, Vet and Dicke 1992, Tumlinson et al. 1993, DeMoraes and Lewis 1999). Much less is known about how adult parasitoids forage for food. Therefore, how parasitoids balance their time between these two behaviors is not well understood. Even more ambiguous is the impact farmscaping has on these behaviors and the role predators play in pest control.

Adult predators and parasitoids are known to visit a number of flowering plants and consume nectar and pollen (Al-Doghairi and Cranshaw 1999). Studies have shown that available adult food sources can enhance natural enemy longevity and fecundity and may improve natural control in pests (White et al., 1995; Hickman and Wratten, 1996; Johanowicz and Mitchell 2000, Eubanks and Styrsky 2005, Gurr et al. 2005, Bianchi and Wäckers 2008). Researchers believe that increases in natural enemy abundance will translate to higher levels of pest control; however, this may not always occur. Farmscaping is often credited for reduced pest pressure, but few studies have thoroughly investigated this claim. While there is no doubt that farmscapes attract natural enemies, how these predators and parasitoids interact and move remains unclear. Therefore, natural enemy movement and dispersal from farmscapes into crops needs to be investigated. In addition, the role of omnivorous predators remains largely unknown and warrants further investigation. While several studies have shown that farmscaping attracts numerous predators, the impact that these predators have on pest populations is not known

(Forehand et al. 2006a). Moreover, the interactions of these various predator species may be antagonistic or synergistic. The type, magnitude, and frequency of these interactions may play a major role in the ability of natural enemies to control pests.

Omnivory

Omnivory is generally thought of as feeding on prey and plant food, but a more broad definition would be feeding at more than one trophic level (Pimm and Lawton 1978, Coll and Guershon 2002). Therefore, a predator that feeds on plants, and a predator that feeds on herbivores, but also on other predators would be considered an omnivore. To confound this issue even further, omnivores can be classified as life history, temporal, or permanent depending on how and when these various resources are utilized. Early work in predator – prey relationships predict that food webs should become less stable with omnivory; therefore, omnivory should be rare or weak for it to persist, yet it appears to be widespread (Pimm 1982, Denno and Fagan 2003, Arim and Marquet 2004). Recent research has shown that almost all predators and parasitoids are, to some extent, capable of feeding on plant provided resources, and that these interactions may in fact strengthen some of these food webs (Wäckers and Van Rijn 2005). It is not known if these omnivores preferentially feed on plant or insect prey, although studies suggest that predators will track resources at the lowest trophic level in which they feed (Eubanks and Denno 1999). Nevertheless, the ecological consequences of omnivory are not well understood (Eubanks 2005).

Intraguild predation

A subset of omnivores, known as intraguild predators, feed on prey and the prey of their prey (Polis et al. 1989). As a result, intraguild predators eat other predators, but also compete with them for resources. Intraguild predation appears to be common in nature, with up to 87% of species involved in intraguild predation (Arim and Marquet 2004). Numerous studies have shown that the stability of these interactions should only be possible when intraguild prey are stronger competitors for the shared resource and only at intermediate levels of productivity (Holt and Polis 1997, Borer et al. 2007). However, given the prevalence of intraguild predation in nature, additional mechanisms acting to stabilize these interactions must be present including cannibalism, spatial or temporal refuges, or alternative prey (Briggs and Borer 2005, Amarasekare 2007, Holt and Huxel 2007, Janssen et al. 2007, Rudolf, 2007).

Our efforts at conservation biological control are often conceived under the assumption of simple food chains. They reflect our desire to manage trophic cascades, whereby the abundance of top predators determines the standing crop biomass (Paine 1980, Carpenter et al. 1985, Hunter and Price 1992, Hunter 2001, Hunter, 2009). Omnivory may dampen the effects of trophic cascades reducing herbivore suppression leading to increases in plant damage (Strong 1992, McCann et al. 1998, Finke and Denno 2004, 2005, Denno 2007). Therefore, there is a need to determine to what extent these interactions interfere with natural pest control (Holt and Polis 1997). Research has shown that these interactions may be positive, negative, or neutral, and the strength and form of these interactions appears to determine their impacts on pest suppression (Cardinale et al. 2006, Hunter 2009). In addition, crops with diverse pest and predator communities may suffer less overall damage, even when those predators engage in omnivory (Rosenheim 1998, Sih et al. 1998, Snyder and Ives 2003, Ives et al. 2005). However, Finke and Denno (2005) demonstrated that increasing the diversity of predators that engaged in intraguild predation led to decreased pest suppression and a concomitant reduction in plant biomass.

Adding diversity to these systems may reduce the negative effects of intraguild predation and improve prey suppression. Although habitat heterogeneity does not always result in short-term pest suppression, long-term persistence of a diverse enemy pool may facilitate long-term suppression of pest populations (Langellotto and Denno 2004, Janssen et al. 2007). It is important that we consider how the biology and ecology of predators and prey influence the strength and direction of interactions in omnivorous food webs and the effects of omnivory on pest suppression, especially when thinking about farmscaping (Denno et al. 2003, Gratton and Denno 2003, Rosenheim and Corbett 2003, Singer and Bernays 2003, Denno et al. 2005) and strive to understand how and why these interactions change with context (Straub and Snyder, 2008).

Farmscape plants

Understanding the life history requirements for pests and natural enemies is to the use of farmscaping as a tool to maintain pest densities below thresholds. This type of pest management focuses on conservation of natural enemies through increased understanding of their biology and ecology. One major issue is that most of this information is thoroughly understood for most predators. Nevertheless, since pest control is a numbers game, increasing the productivity of

beneficial insects should theoretically give them the advantage. Therefore, it is important to plan so that the resources required by beneficials are readily available whenever they are needed. Examples include plants with flowers that provide ample nectar and pollen production, plants that sustain beneficial insect populations until they are needed, and plants with flowers with resources accessible to natural enemies, but not pests.

Things to consider when farmscaping

The idea of farmscaping seems straightforward, but it is a complex process. For farmscaping to work as intended, a thorough understanding of how populations interact is needed. The temporal and spatial arrangement of farmscape plantings must be carefully considered to provide resources that will enhance beneficial insect populations, but not pests. By focusing on the nectar and pollen use by beneficial insects, the fact that many herbivores depend on floral resources that can lead to higher pest numbers has received very little attention (Latheef and Irwin 1979, Zhao et al. 1992, McEwen and Liber 1995, Baggen and Gurr 1998, Romeis et al. 2005, Wäckers et al. 2007, Winkler et al. 2010). It has been demonstrated that herbivorous and beneficial insects often differ in their ability to exploit floral resources, and that this variation can be used to identify specific sources that are suitable for predators and parasitoids, but not for pests (Baggen et al. 1999, Wäckers 1999, Wäckers et al. 2007, Winkler et al. 2010). Such selectivity can be based on plant characteristics including floral attraction, nectar accessibility and nutritional suitability allowing for the identification of plants that meet the needs of beneficial insects, while at the same time reduce the risk of pest outbreaks (Wäckers et al. 2005, 2007, Winkler et al. 2010).

Characteristics of the insect-plant interaction in relation to floral use are an important consideration when choosing farmscaping plants. Nevertheless, most plants are selected for other reasons. A basic principle of conservation biological control is that, following the acquisition of resource subsidies, natural enemies will disperse into the adjacent cropping system. The distance over which this dispersal takes place will determine the spatial arrangement and overall quantity of resource subsidies needed (Wratten et al. 2003). Numerous factors must be considered when selecting plants for farmscaping and the selection criteria are complex, ranging from ecological to agronomic (Gurr et al. 2012).

Plant characteristics

Most beneficials feed on nectar and pollen at some point in their life so these two characteristics are essential considerations in farmscaping. Because the accessibility of these resources can vary considerably based on flower and insect morphology, plants must be selected that make these resources accessible to beneficial arthropods (Forhand et al. 2006a). Many plants in the carrot family (*Apiaceae*) make exceptional farmscaping plants because they contain exposed floral nectaries. In addition, many plants in the legume family (*Fabaceae*) contain extra floral nectaries, which are nectar glands not associated with the flower, that make these resources highly accessible. Different plant families provide these resources in different ways, and some, such as buckwheat, have become staples in farmscapes. Fiedler and Landis (2007) found several characteristics that correlate with increase in natural enemy abundance, including corolla size floral area, and peak bloom time, but these characteristics increased the abundance of insect herbivores.

Buckwheat

Although numerous plant species can serve as pollen and nectar sources for natural enemies, buckwheat (*Fagopyrum esculentum* Moench) has been touted as an ideal farmscaping plant, because it provides abundant, easily accessible nectar, has extra-floral nectaries, a long bloom time, suppresses weed growth, is inexpensive, and is easy to manage. In addition, no major crops are closely related to buckwheat and thus it should not attract or harbor additional pests. Buckwheat has been widely used as a companion planting on vegetable farms (Lavandero et al. 2005, Lee and Heimpel 2005), vineyards (Scarratt et al. 2008), and orchards (Stephens et al. 1998) to supply nectar and pollen and encourage arthropod natural enemy populations. Nevertheless, because little is known about the nectar availability requirements for specific natural enemies it may be a good idea to plant a mix of flowering plants from various plant families to ensure that resources are available to the target beneficials at the right time. Numerous organic gardening periodicals have published comprehensive lists of plants recommended for farmscaping such as Rodale's Successful Organic Gardening™ Companion Planting, Rodale Press, 1994. I listed some of the most popular companion plants in Table 1. In addition, there are several commercially-available multiple plant species seed mixes that work well in attacking a wide range of beneficial insects (Forehand et al. 2006b).

Does farmscaping work?

There is no doubt that farmscaping has the potential to offset insecticide use and maintain pest populations below threshold with minimal inputs and minimal disturbance to the agroecology. However, scientific data demonstrating the true biological control benefit of such companion plantings are scarce. To date, only a handful of studies have quantitatively measured the impact of farmscaping on pest suppression. Most of this work has focused on parasitoids. A review by Heimpel and Jervis (2005) comparing parasitism in nectar rich and nectar poor habitats found only 20 cases where adequate studies were conducted. Increases in parasitism were reported in only seven cases, and a concomitant decrease in pest density was only documented in one (Gallego et al. 1983). In this case, however, it is not clear whether plant-provided resources were responsible for changes in population-level patterns. Numerous studies since have documented increases in abundance and fitness in both predators and parasitoids associated with plant-provided resources. However, in almost all of these cases these increases did not translate to increases in predation or parasitism and concomitant decreases in pest densities (Al-Doghairi and Cranshaw 2004, Heimpel and Jervis 2005, Lee and Hempel 2005, Forehand 2006a, 2006b, Pfiffner et al., 2009, Winkler et al. 2010, Woltz et al. 2012). It is clear that there are many unanswered questions remaining about how plant-provided resources influence natural biological control, and the mechanisms that drive these interactions. Although most research to date has focused on insect populations to a single scale of land use, recently there has been an emphasis on scale, both spatial and temporal, as well as farmscape arrangement.

Scale and landscape context

For example, O'Rourke et al. (2011) found that diverse agricultural landscapes support pest management by directly suppressing pests and by enhancing natural enemy populations. Insect densities and land use may be positively related at one scale and negatively related at another, and that landscape–insect relationships at one scale may depend on land use at another. In addition, Lee and Heimpel (2005) suggest that variation in control at various scales may be the result of insufficient separation of experiments and the dispersal capabilities of natural enemies. Nevertheless, pest suppression is likely to be influenced by landscape diversity, and it has been proposed that local land use matters more where the regional landscapes are less

diverse (Tscharntke et al. 2005, Schmidt et al. 2008, Zaller et al. 2008, Gardiner et al. 2009, O'Rourke et al. 2011, Tscharntke et al. 2012). Therefore, the ability of a farmer to manipulate insect populations by farmscaping may depend on the regional land use, but it is important to examine farm-level diversity in the context of regional landscape diversity. This is known as the intermediate landscape-complexity hypothesis, which states that local conservation management will have the greatest impact in structurally simple, rather than extremely simplified or complex landscapes (Tscharntke et al. 2012). Therefore, increasing the spatial scales at which these studies are conducted may lead to better predictions about the effects of diversity on insect populations.

Future research

We have come a long way in our understanding of the ecology in these systems and over the last few decades, our understanding of how plant-provided resources enhance natural enemy activity has greatly increased (Powell 1986, van Emden 1990, Heimpel and Jervis 2005). Nevertheless, insecticide applications remain the predominate tactic used by growers to control pests of vegetable crops. However, in the interest of human and environmental safety, as well as integrated pest management, there has been an increase in the importance for alternative control methods. Understanding how plant-provided resources and increases in plant diversity influence natural enemy abundance, and determining if this translates to an increase in natural enemy movement and pest suppression in adjacent cash crops, may provide alternative control methods, thereby, slowing the rate of insecticide resistance and reducing pesticide exposure to the applicator and surrounding environments.

The literature is replete with evidence that farmscaping with flowering plants attracts numerous beneficial insects. It is also well documented that predators and parasitoids play an important role in regulating many pest populations, even at low numbers. However, comprehensive experiments that combine both and determine the true impact of farmscaping on pest suppression are scant. Such studies will be complex and confounded by the fact that generalist predators may be destabilizing these food webs through omnivory, or they may be playing a more important role in pest suppression than previously thought. Future research will have to be aimed at improving our ability to unambiguously evaluate if, in fact, plant-provided resources lead to improved pest suppression. Critical issues include investigating the biology,

habitat use, and predation impacts of generalist predators, natural enemy and pest dispersal from nectar sources, responses of pests to nectar sources, as well as the impact of plant-provided resources and diversity on intraguild predation and predator-predator interactions. While numerous gaps in our understanding of these systems remain, plant-provided resources and the diversification of agroecosystems may provide growers new biological control options with the potential to reduce insecticide use. With continued efforts and research, the long-term goal of biological pest management through agroecosystem diversification may be feasible (Gurr and Wratten 2000, Wratten et al. 2003, Gurr et al. 2005, Heimpel and Jervis 2005).

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Tables and Figures

Table 3.1. List of plants known to attract natural enemies.

Carrot Family (Apiaceae)		Legumes (Fabaceae)	
Anise	<i>Pimpinella anisum</i>	Alfalfa	<i>Medicago sativa</i>
Blue Lace	<i>Trachymene caerulea</i>	Big flower vetch	<i>Vicia grandiflora</i>
Caraway	<i>Carum caryi</i>	Fava bean	<i>Vicia fava</i>
Chervil	<i>Anthriscus cerefolium</i>	Hairy vetch	<i>Vicia villosa</i>
Coriander/Cilantro	<i>Coriandrum sativum</i>	Sweet clover	<i>Melilotus officinalis</i>
Dill	<i>Anethum graveolens</i>	Red clover	<i>Trifolium pratense</i>
Fennel	<i>Foeniculum vulgare</i>	White clover	<i>Trifolium repens</i>
Lovage	<i>Lovisticum officinale</i>	Cabbage Family (Brassicaceae)	
Bishops Lace	<i>Ammi majus</i>	Yellow rocket	<i>Barbarea vulgaris</i>
Wild Carrot	<i>Daucus carota</i>	Sweet Alyssum	<i>Lobularia maritima</i>
Aster Family (Asteraceae)		Candytuft	<i>Iberis umbellata</i>
Blazing Star	<i>Liatrus pycnostachya</i>	Mustards	<i>Brassica spp.</i>
Chamomile	<i>Anthemis nobilis</i>	Teasel Family (Dipsaceae)	
Cosmos	<i>Cosmos bipinnatus</i>	Cephalaria	<i>Cephalaria gigantea</i>
Coneflower	<i>Echinacea spp.</i>	Dipsacus	<i>Dipsacus spp.</i>
oreopsis	<i>Coreopsis spp.</i>	Pincushion Flower	<i>Scabiosa caucasica</i>
Golden Marguerite	<i>Anthemis tinctoria</i>	Scabiosa	<i>Scabiosa atropurpurea</i>
Goldenrod	<i>Solidago altissima</i>	Mint Family (Lamiaceae)	
Marigold, Signet	<i>Tagetes tenuifolia</i>	Peppermint	<i>Mentha piperata</i>
Mexican Sunflower	<i>Tithonia tagetifolia</i>	Spearmint	<i>Mentha spicata</i>
Sunflower	<i>Helianthus spp.</i>	Thyme	<i>Thymus spp.</i>
Tansy	<i>Tanacetum vulgare</i>	Other Species	
Yarrow, milfoil	<i>Achillea millefolium</i>	Buckwheat	<i>Fagopyrum esculentum</i>
Yarrows	<i>Macrophylla taygetea</i>	Cinquefoil	<i>Potentilla spp.</i>

Chapter Four

Effect of flowering buckwheat (*Fagopyrum esculentum*) on lepidopteran pest management in collards

Abstract

Buckwheat (*Fagopyrum esculentum* Moench) has been widely used as a companion planting on vegetable farms, vineyards, and orchards to supply nectar and pollen and encourage arthropod natural enemy populations. However, scientific data demonstrating the true biological control benefit of such companion plantings are scarce. The primary objective of this project was to determine how predators and parasitoids move in collards (*Brassica oleracea* L. var. *acephala* DC) associated with buckwheat companion plantings and their concomitant effects on key pest populations. Buckwheat farmscape were planted in the center of collard fields and lepidopteran pest abundance, parasitoid abundance and lepidopteran larvae parasitism were compared at 1, 15, 30, 45, and 60 m from the buckwheat farmscapes. This study was conducted twice in 2012 and once in 2013. No differences were detected in lepidopteran pest abundance or parasitism with increasing distance from buckwheat companion plantings. Parasitoid abundance was low in all studies with average parasitism of 68%. Increasing the spatial scales at which these studies are conducted may lead to better predictions about the effects of diversity on insect populations. In addition, several predatory species were collected in high numbers at flowering buckwheat indicating that predators may play a large role in pest management when farmscaping is used.

Introduction

Understanding how buckwheat companion plantings impact natural enemy abundance, and determining if this translates to increases in natural enemy movement and pest suppression in adjacent crops, may provide alternative control methods, thereby slowing the rate of insect resistance to pesticides and reducing pesticide exposure to the applicator and surrounding habitats. Buckwheat (*Fagopyrum esculentum* Moench) has been widely used as a companion planting on vegetable farms (Lavandero et al. 2005, Lee and Heimpel 2005), vineyards (Scarratt et al. 2008) and orchards (Stephens et al. 1998) to supply nectar and pollen and encourage arthropod natural enemy populations. However, scientific data demonstrating the true biological control benefit of such companion plantings are scarce. The purpose of this project was to 1) record the natural enemies and pest populations associated with buckwheat companion plantings, and 2) measure the movement of these natural enemies into a neighboring cash crop collards (*Brassica oleracea* L. var. *acephala* DC), and if there are any effects on lepidopteran pest populations.

I used collards as a model system for this experiment because there are multiple lepidopteran pests, which have been shown to be impacted significantly by natural enemies (Chamberlin and Kok 1986, Lasota and Kok 1986, Lasota and Kok 1989, Gaines and Kok. 1995, Cordero 2005, Cordero et al 2007). The most common and damaging caterpillars in Virginia crucifers are diamondback moth, *Plutella xylostella* (L.), cabbage looper, *Trichoplusia ni* (Hübner), and imported cabbageworm, *Pieris rapae* (L.) (Wallingford et al. 2012). Collards, a staple crucifer crop in the south, are particularly vulnerable to economic losses from these pests as some species prefer collards to other crucifers, and because the leaves, which are fed upon by pests, are the marketable portion of the crop. Historically, control of lepidopteran pests of crucifers in Virginia has involved multiple insecticide applications, with little regard for the pest populations (Lasota and Kok 1986, Cordero and Kuhar 2007). To develop sound IPM programs for lepidopteran pests, a firm understanding of the roles that natural enemies play in regulating these populations is needed. By gaining a better understanding of the population dynamics in this system, we can development sound integrated pest management programs for lepidopteran pests in crucifers as well as other systems.

Natural enemies have a tremendous capacity to regulate lepidopteran pest populations, and over the past several decades, data from numerous studies have greatly increased our

understanding of how parasitoids forage for hosts (Vinson 1976, Lewis et al. 1990, Vet and Dicke 1992, Tumlinson et al. 1993, DeMoraes and Lewis 1999, Wäckers et al. 2007, Winkler et al. 2010). However, the availability of adult food sources can also have major impacts on parasitoids, and how they balance their time between these two behaviors is not well understood. Even more ambiguous is the impact farmscaping has on these behaviors and the role predators play in lepidopteran pest control. Studies have shown that floral resources increase abundance, longevity and fecundity of adult predators and parasitoids (Wratten et al. 2003, Eubanks and Styrsky 2005, Woltz et al. 2012). Because *Cotesia glomerata* (L.), the primary parasitoid of imported cabbageworm in Virginia (Herlihy et al. 2012), is synovigenic, adult feeding is necessary to meet the nutritional requirements necessary for females to produce eggs and successfully reproduce (Harvey et al. 2003). Adults are commonly observed feeding on flowers, but because females must continue to feed to produce eggs, how they move from these resources is largely unknown (Wäckers 2005, Winkler et al. 2010). Moreover, additional studies have shown that nectar producing plants increased the abundance of *Diadegma insulare* (Cresson) the primary parasitoids of diamondback moth in Virginia, these increases in abundance often did not translate to increased pest suppression (Heimpel and Jervis 2005). It is clear that there are many unanswered questions remaining about how plant-provided resources influence natural biological control, and the mechanisms that drive these interactions.

Objectives

The primary objective of this project was to determine the impact of buckwheat farmscapes on lepidopteran pests and their natural enemies in collards. To accomplish this, I:

- 1) Evaluated lepidopteran pest species abundance in collards associated with buckwheat companion plantings;
- 2) Evaluated parasitoid abundance in collards associated with buckwheat companion plantings using yellow sticky traps;
- 3) Used naturally occurring larvae of imported cabbageworm *Pieris rapae* (L.) to evaluate parasitism rates in collards associated with buckwheat companion plantings; and
- 4) Evaluated predator communities associated with buckwheat companion plantings in collards.

Materials and Methods

All experiments were conducted near Blacksburg, Virginia at the Virginia Tech Kentland Research Farm (80° 25'W, 37° 14'N). Sixteen rows of collards (var. Champion) were direct seeded on 2 May, and 13 August 2012 and 20 rows (6 var. Champion and 14 var. Georgia) were seeded on 23 April, 2013 in four 130 m by 8 m fields (Fig. 4.1). Sixteen 7 m rows of buckwheat were direct-seeded at the same time as the collard in the center of each field leaving 60 m of collards on each side. On 15 May, 2013 collards and buckwheat were reseeded due to poor stand establishment. Fields were separated by a minimum of 150 m and were isolated from other flowering vegetation. All distance sampling occurred at 1, 15, 30, 45, and 60 m from buckwheat farmscape based on previous studies (Lavandero et al. 2005).

Lepidopteran pest abundance. Visual inspections were performed on ten collard plants nearest to sample distance. Inspections were conducted weekly beginning 30 days after planting, and continued until harvest (approximately 30 days). In 2012, visual counts were performed on 4, 11, 18 and 25 June. In 2013, counts were performed on 10, 17, and 24 June and 1 July. All pest species and abundance was recorded.

Parasitoid abundance. Yellow sticky traps (Olson, Medina, OH) were placed in the middle rows in each plot just above the collard canopy at each sample distance. Sampling began 30 days after planting, and traps were replaced weekly until harvest (approximately 30 days). In 2012, traps were collected on 11, 18 and 25 June. In 2013, traps were collected on 17, and 24 June and 1 July. Sticky traps were evaluated under stereomicroscope and all parasitoids were counted, and where possible, identified to the lowest taxonomic group. In addition, analysis of variance was used to determine if parasitoid abundance changed with distance from buckwheat companion plantings.

Parasitism. Natural occurring larvae of *P. rapae* were collected from each plot on 11 and 28 June, 2012 and 20 June, 2013. Five larvae were collected at each distance in both directions from the buckwheat for a total of 50 per plot. The number of larvae collected varied because of low populations. Larvae were returned to the lab and evaluated daily for parasitism. Parasitism was assessed by year using analysis of variance, and correlations between distance from companion planting and parasitism was analyzed using linear regression.

Predator communities. A single 10-second vacuum sample was collected on eight rows of buckwheat (2 in each plot) bloom on 5 June and 25 Sept, 2012, and 12 and 24 June, 2013 using a motorized suction sampler (Craftsman™ 200 mph leaf blower-vac) fitted with a fine

mesh 5 gallon paint strainer bag on a 12-cm diameter intake tube. In 2013, both samples were collected in June because there was not a fall collard planting. Samples were returned to the lab, placed in a freezer for 24 hours, and insects were sorted and identified to lowest taxonomic group possible. Abundance of all collected predators was recorded.

Data analysis. Data from all experiments were analyzed in JMP (JMP 2013) using analysis of variance to determine changes with distance from buckwheat companion plantings. If significant differences were detected, data were analyzed using correlation and linear regression.

Results

Lepidopteran pest abundance. Overall, no significant difference in pest abundance with distance from nectar sources was detected ($F = 0.56$, $df = 4,455$, $p=0.96$) (Fig 4.2). In 2012, 364 lepidopteran larvae were observed with *P. rapae* being the most abundant (Table 4.1). The other five larvae observed were cross-striped cabbageworm *Evergestis rimosalis* (Guenee). All larvae detected were found in the spring planting and no significant differences were detected in abundance with distance from nectar ($F=2.88$, $df=2,275$, $p=0.60$) (Fig 4.2). In 2013, 353 larvae were observed with *P. rapae* again being the most abundant throughout sampling, and again no significant differences were detected ($F= 3.18$, $df= 4,195$, $p=0.23$) (Fig 4.2).

Parasitoid abundance. In all sample periods, parasitoid numbers were very low on yellow sticky traps. Only 37 parasitoids were collected, 13 in 2012 and 24 in 2013. This suggests that yellow sticky traps may not be an adequate tool for monitoring parasitoids in collards.

Parasitism. Over the three collection dates, 431 larvae were collected with an average parasitism 68%. No significant difference in parasitism with distance was detected ($F = 0.14$, $df = 4, 53$, $p = 0.97$) (Fig 4.3). In 2012, two collections were made with parasitism rates of 70 and 65%, and no significant differences were detected with distance from buckwheat ($F = 0.46$, $df = 4, 35$, $p = 0.77$). In 2013, a single collection was made with parasitism rates of 68%, and again no significant difference was detected with distance from buckwheat ($F = 0.51$, $df = 4, 15$, $p = 0.73$) (Fig 4.3).

Predator communities. In 2012 a total of 407 insects were collected, 296 in the spring and 112 in the fall. In the spring sample, 214 predators, 34 parasitoids, and 48 known pests were collected. In the fall, 22 predators, 8 parasitoids and 82 known pests were collected. In 2013, 339

insects were collected 212 predators and parasitoids and 127 pests, almost all of which were tarnished plant bug *Lygus lineolaris* (Palisot de Beauvois).

Over the four sample periods, seven families of insect predators were collected, the most abundant being anthocorids, syrphids and cantharids. Braconids were the most abundant parasitoid, accounting for about half of the total parasitoids collected (Table 4.2). Relatively few significant agricultural pests were found on the buckwheat with the exception of tarnished plant bug, *L. lineolaris*. (Table 4.3).

Discussion

In the current study, parasitism rates of *P. rapae* did not differ with distance from available nectar sources. Abundance of parasitoids did not vary with distance, and while average rates of parasitism were around 70%, parasitoid abundance, based on sticky trap catch, was very low. Overall abundance of pest caterpillars did not vary with distance. This indicates that, in the mid-Atlantic, the nature of the landscape may be such that it provides enough of a natural farmscape making the need to replace crops with additional farmscaping unnecessary.

Farmscaping with flowering plants attracts numerous beneficial insects, and has the potential to maintain pest populations below threshold with minimal inputs and minimal disturbance to the agroecology. However, scientific data demonstrating the true biological control benefits of such companion plantings are scarce. To date, only a handful of studies have quantitatively measured the impact of farmscaping on pest suppression in neighboring cash crops. While the current recommendations for organic growers consist of allowing about 15 percent of land space to farmscaping, the results of my experiment with buckwheat and collards showed that an area as small as 5 percent of the land space may be enough to provide adequate protection from certain pests. This may be due to the agriculture layout at larger spatial scales. Agriculture in the mid-Atlantic is notably diverse and the number of smaller local/organic farms is increasing. For example, in Virginia, the number of farms growing fresh market vegetables has increased to 1,616 growing on 27,887 acres, and more than half of these farms operate on less than 15 acres (USDA 2007). In addition, these farms are separated by grassland, shrubland and deciduous forest. Contrast this to agriculture in California, where the average farm size is over 300 acres, and is adjacent to additional agricultural land.

Although most research to date has focused on insect populations to a single scale of land use, recently there has been an emphasis on scale, both spatial and temporal, as well as farmscape arrangement. For example, recent research has shown that pest suppression is likely to be influenced by landscape diversity, and that local land use may be more important where regional landscapes are less diverse (Tscharntke et al. 2005, Schmidt et al. 2008, Zaller et al. 2008, Gardiner et al. 2009, O'Rourke et al. 2011, Tscharntke et al. 2012). Therefore, the ability of a farmer to manipulate insect populations by farmscaping may depend on the regional landscape structure, so it is important to examine farm-level diversity in the context of regional landscape diversity. This is known as the intermediate landscape-complexity hypothesis, which states that local conservation management will have the greatest impact in structurally simple, rather than extremely simplified or complex landscapes (Tscharntke et al. 2012). Increasing the spatial scales at which these studies are conducted may lead to better predictions about the effects of diversity on insect populations.

There is no doubt that parasitoids play an important role in the regulation of lepidopteran pest populations, even at low numbers. Although parasitoid catch was consistently low in all of my studies, there are several reasons this may be the case. The use of colored sticky cards often works well as a passive sampling technique to collect flower-visiting insects. Trap color is particularly important and attraction of insects to a particular color determines its effectiveness. These differences in preference may influence what species are collected in these samples (Brødsgaard 1989, Leong and Thorp 1999, Cho et al. 2011, Vrdoljak and Samways 2012). It is unknown if the primary parasitoids of lepidopteran pests in collards demonstrate color preferences, but if they do this could be a reason why parasitoid abundance on yellow sticky cards was low.

In addition to color preferences, another reason for low trap catch could be that once parasitoids reached the nectar sources in the study plots they were not moving far from these resources, or these parasitoids were not food foraging as nectar and pollen were not a limiting factor. In addition, it has been demonstrated that the parasitoids *D. insulare* and *C. glomerata* are not likely to be nectar limited in the field (Heimpel and Jervis 2005).

The results of the current experiment also indicate that pest densities are extremely low in the fall as no larvae were detected in my fall 2012 experiment, but there are several caveats to be aware of in interpreting these results. In the spring of 2012 over 99% of the lepidopteran pests

present was imported cabbageworm. Previous studies conducted in Virginia have shown that the largest population peaks for *P. rapae* larvae occur in late July or early August (Chamberlin and Kok 1986, Lasota and Kok 1989, Gaines and Kok 1995). In 2012, *P. rapae* densities were very high in the spring collards. However, rather than have a season-long planting, or overlapping planting, all plots were mowed and tilled the first week of August. Because this corresponds to the largest larval population peak of this pest, it is likely that this method destroyed the remaining pest population and any parasitoids leading to the low lepidopteran pest population observed in the fall.

One question that remains unanswered is the role that generalist predators play in pest suppression. Because certain generalist predators were highly abundant on the flowering buckwheat in my experiments, they may be playing a larger role in pest management where farmscaping is used than previously believed. For example, cantharid adults were one of the most abundant predators found on buckwheat; however, very little is known about the biology and ecology of these predators. Future research will need to include investigating the biology, habitat use, and predation impacts of generalist predators, as well as the impact of plant-provided resources and diversity on intraguild predation and predator-predator interactions.

While there may be benefits to buckwheat companion planting, these plants can also attract pests. In my experiments, high densities of *L. lineolaris* were found on buckwheat. The temporal and spatial arrangement of farmscape plantings must be carefully considered to provide resources that will enhance beneficial insect populations, but not pests, as many herbivores have been shown to utilize these plant-provided resources as well (Latheef and Irwin 1979, Zhao et al. 1992, McEwen and Liber 1995, Baggen and Gurr 1998, Romeis et al. 2005, Wäckers et al. 2007, Winkler et al. 2010). This should also be a focus area of future research.

We have come a long way in our understanding of the ecology in these systems and over the last few decades, greatly increasing our knowledge of how plant-provided resources enhance natural enemy activity (Powell 1986, Van Emden 1990, Heimpel and Jervis 2005). Nevertheless, insecticide applications remain the predominate strategy used by growers to control pests of vegetable crops. Future research will have to be aimed at improving our ability to unambiguously evaluate if, in fact, plant-provided resources lead to improved pest suppression. Integrated pest management is a sustainable approach to managing pests that promotes the use of a variety of tactics that minimize the disturbance to balanced agroecosystems, the environment,

and human health. It is a dynamic field-by-field approach built on a philosophy of pest management rather than a set of standard automatic control practices. There is no single, best way to control pests, and over-reliance on any method generally has undesirable economic or ecological results leading to perturbations of natural processes shifting the ecological balance to favor pests. Therefore, our primary goal in IPM should be to shift this balance back towards a more favorable equilibrium to improve natural pest control. Thinking of these systems in ecological terms will facilitate a better understanding of the interactions in these systems leading to improved crop production. From a pest management perspective, a closer examination of insect communities, and how they interact within these ecosystems, has tremendous potential to improve pest management programs. Although these interactions are not thoroughly understood with continued efforts and research, the long-term goal of biological pest management through agroecosystem diversification may be feasible (Gurr and Wratten 2000, Wratten et al. 2003, Gurr et al. 2005, Heimpel and Jervis 2005).

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Tables and Figures

Table 4.1. Lepidopteran larvae found on collards at the Virginia Tech Kentland Research Farm near Blacksburg, Virginia.

Year	Period	Total number of larvae observed			
		ICW	DBM	CSCW	CL
2012	Spring	359	0	5	0
2012	Fall	0	0	0	0
2013	Spring	290	62	1	0

ICW = *Pieris rapae*; DBM = *Plutella xylostella*; CSCW = *Evergestis rimosalis*; CL = *Trichoplusia ni*

Table 4.2. Predator and parasitoid abundance collected in vacuum sample of flowering buckwheat adjacent to collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.

Predators and Parasitoids														
Month	Day	Year	Period	Brac	OHP	Syr	Coc	Can	Aran	Chr	Anth	Geo	Red	Total
6	5	2012	Spring	17	34	49	13	35	13	1	82	3	1	248
9	25	2012	Fall	4	8	0	6	0	5	1	4	1	1	30
6	12	2013	Spring	12	20	22	2	32	2	0	24	0	3	117
6	24	2013	Spring	0	4	12	4	32	4	1	36	2	0	95
Total				33	66	83	25	99	24	3	146	6	5	490

Brac = Braconidae; OHP = Other Hymenopteran Parasitoids; Syr = Syrphidae; Coc = Coccinellidae; Can = Cantharidae; Aran = Araneae; Chr = Chrysopidae; Anth = Anthocoridae; Goe = Geocoridae; Red = Reduviidae

Table 4.3. Pest abundance collected in vacuum samples of flowering buckwheat adjacent to collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.

Month	Day	Year	Period	Pests			Total
				<i>Lygus Spp.</i>	<i>Diabrotica undecimpunctata howardii</i>	<i>Pieris Rapae</i>	
6	5	2012	Spring	45	1	2	49
9	25	2012	Fall	78	2	1	84
6	12	2013	Spring	63	0	0	63
6	24	2013	Spring	63	1	0	64
Total				249	4	3	260

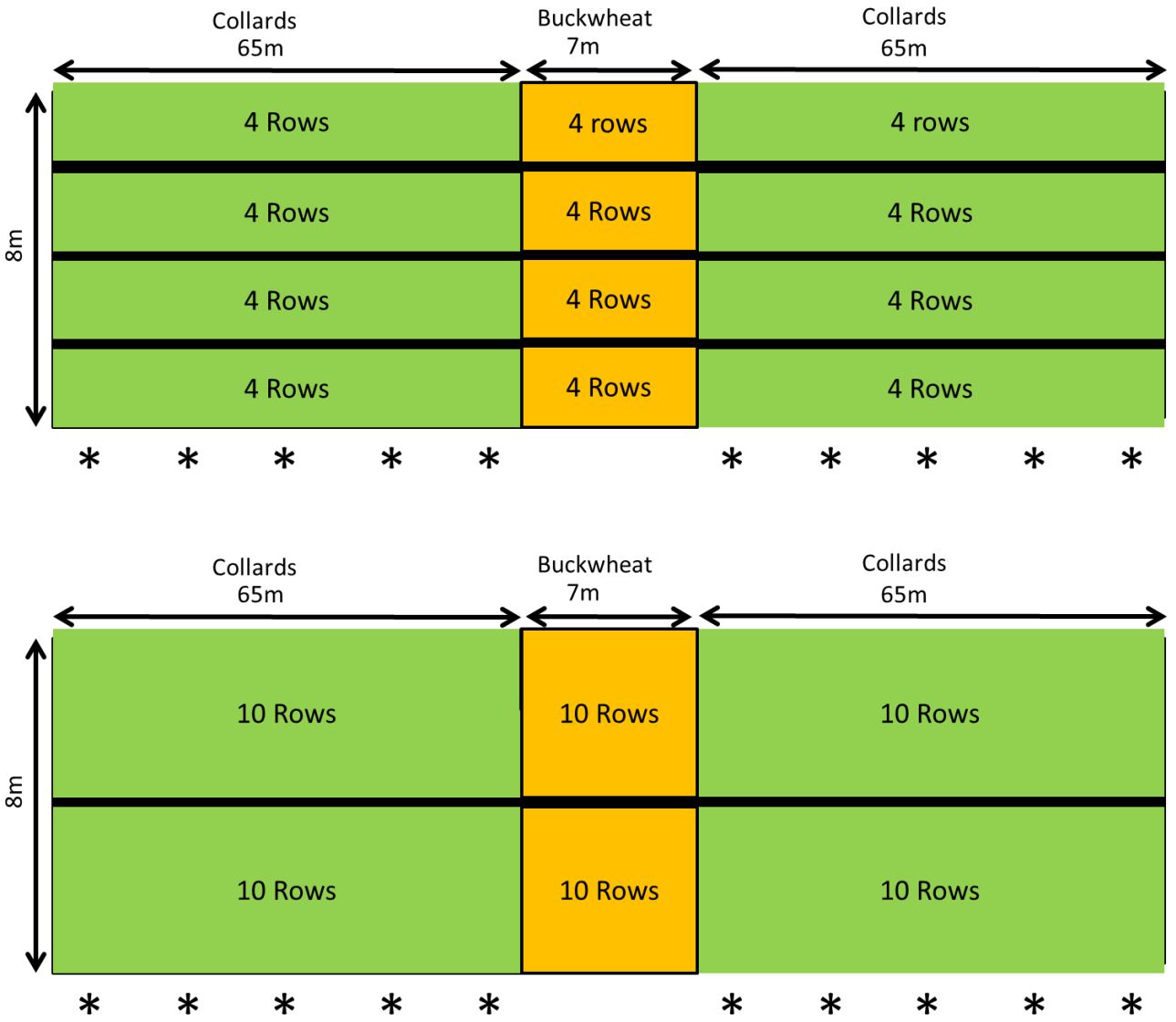


Fig 4.1. Diagram of collard plot from 2012 (top) and 2013 (bottom). Sample distances of 1, 15, 30, 45 and 60 m and denoted by *.

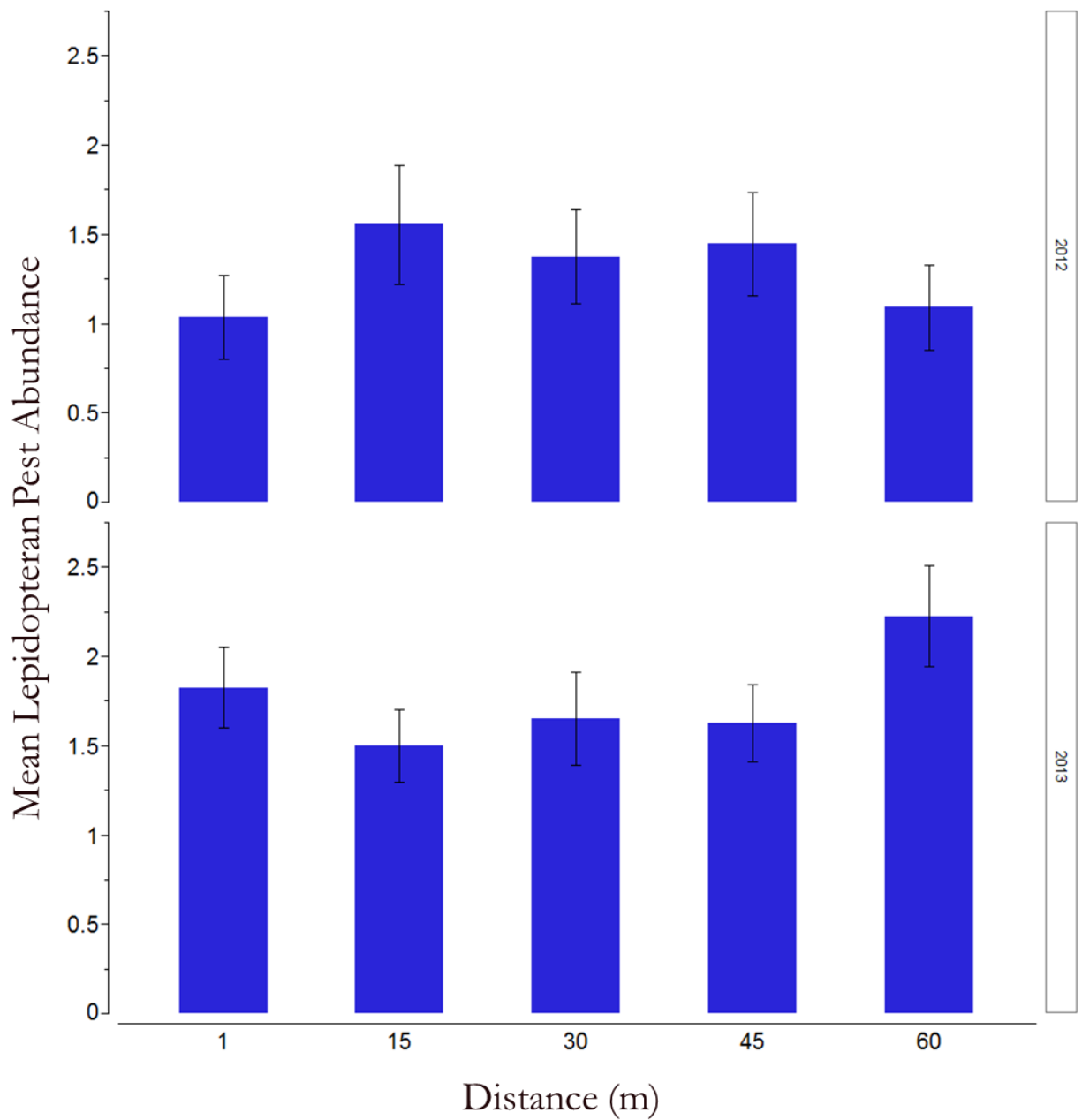


Fig 4.2. Mean lepidopteran larval abundance by distance and year in collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.

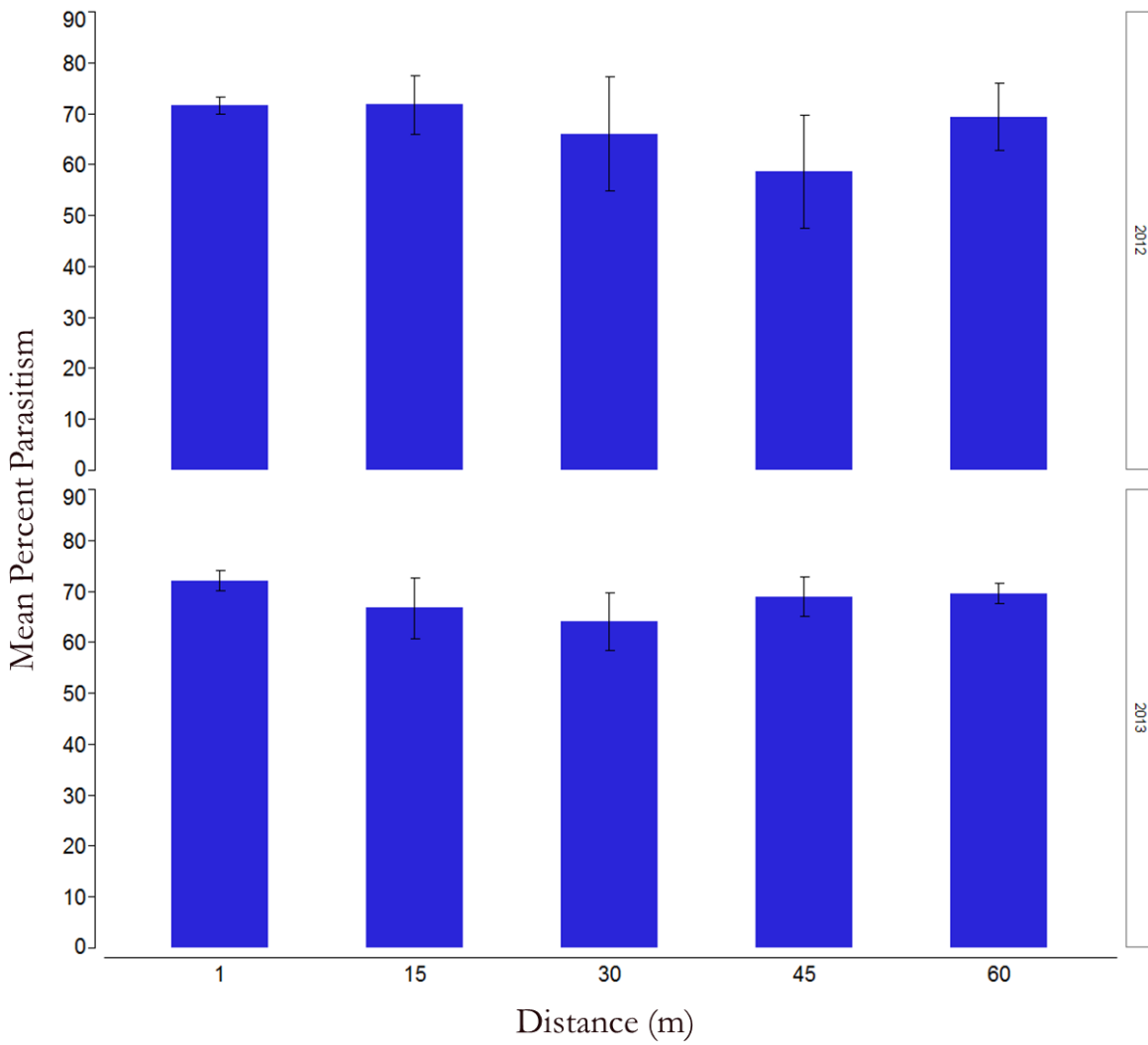


Fig 4.3. Mean parasitism of imported cabbageworm by distance and year in collard at the Virginia Tech Kentland Research Farm in Blacksburg, Virginia.

Chapter Five

Conclusion

Integrated pest management programs should utilize a variety of tactics that minimize the disturbance to agroecosystems, the environment, and human health. It is a dynamic field-by-field approach built on a philosophy of pest management rather than a set of standard automatic control practices. Because pest management systems are subject to constant change, and must respond accordingly, IPM specialists must strive to implement practices and tools into programs that work synergistically to achieve desired outcomes while posing the least risks to people, property, and the environment. There is no single, best way to control pests, and over-reliance on any method generally has undesirable economic or ecological results leading to perturbations of natural processes that shift the ecological balance to favor pests. Therefore, our primary goal in IPM should be to shift this balance back towards a more favorable equilibrium to improve natural pest control. Thinking of these systems in ecological terms will lead to a better understanding of the interactions in these systems leading to improved crop production. From a pest management perspective, a closer examination of insect communities, and how they interact within these ecosystems, has tremendous potential to improve pest management programs.

Changing the way growers approach pest control in their fields can be a hard problem to solve. While chemical insecticides have been a staple in American agriculture since the 1940's, I believe it is possible to change the way producers approach pest management. Several approaches can be utilized to gather information needed to encourage these changes. One is to conduct research experiments that will help us understand and predict when and where pest outbreaks will occur. The other approach is to evaluate the true impact of alternative management practices on pest populations. To address these two approaches, I developed a temperature-based predictive tool to reduce unnecessary insecticide applications for cereal leaf beetle in wheat, and assessed the current conservation biological control technique of farmscaping with buckwheat to determine its true impact on lepidopteran pest suppression in collards.

To encourage growers to reevaluate their method of springtime insect control in wheat and consider re-adoption of the economic threshold-based approach, a degree-day model was developed and tested. This model of 182 degree-days accurately predicted cereal leaf beetle egg peaks within 10 days at all sites over two years. This new tool will provide wheat growers in

Virginia and North Carolina a narrow window of when scouting should be done, and based on what is found at that time they will know if that field should be treated. This tool should make cereal leaf beetle scouting more efficient and much less costly, potentially eliminating unnecessary insecticide applications.

Many growers, pest management professionals, and researchers have already taken notice of this new tool. In addition to being published in *Environmental Entomology* (Philips et al. 2011, 2012), this work was recognized by a Southern Region IPM center article, *The Southeast Farm Press*, as well as in the journal *International Pest Control*. Now the goal is to get this tool into the hands of the people that need it most. Therefore, the next step will be the creation of a mobile delivery system to send real-time updates and alerts to growers and crop consultants of impending pest problems and scouting dates. As more data are collected and incorporated into this model, its accuracy should improve. Once these tools are complete, this model has the potential to revolutionize springtime insect control in wheat as well as other crops.

Conservation biological control and agroecosystem diversity have received an increasing amount of attention in recent years. Nevertheless, there is a tremendous amount we still do not know about the true impact of these practices on pest suppression. Farmscaping is common in organic agriculture, and receives a tremendous amount of credit for reducing pest populations, and most of this credit is given to parasitoids. While there is no doubt that plant-provided resources attract beneficial insects, it is difficult to find studies that illustrate that these practices lead to increased pest suppression in adjacent crops. This project was not designed to compare communities on fields with and without farmscapes; it was intended to illustrate what level of protection may be provided by a farmscape and how farmscapes influence lepidopteran pests using collards as a model system.

No differences were detected in pest abundance or parasitism in collards with distance from buckwheat farmscapes and although only 37 parasitoids were collected throughout the duration of this project, parasitism rates were consistently high, around 70%. There are several possible reasons for this; however, it could simply be that a small number of parasitoids are capable of parasitizing a large number of caterpillars. It is also important to note that pest suppression is likely to be influenced by landscape diversity, and that techniques such as farmscaping may be more important where regional landscapes are less diverse (Tschardt et al. 2005, Schmidt et al. 2008, Zaller et al. 2008, Gardiner et al. 2009, O'Rourke et al. 2011,

Tscharntke et al. 2012). Farmscaping began and gained fame in California. In the agricultural areas of California, fields can stretch for miles and are adjacent to other fields that stretch for miles. In this type of landscape techniques such as farmscaping become increasingly important. However, in the mid-Atlantic, this is not the case, and the nature of the landscape may be such that it provides enough of a natural farmscape making the need to replace crops with additional farmscapes unnecessary.

Another important thing to note is the large number of generalist predators collected from the buckwheat samples. Not only were they the most abundant insects collected but some of these insect families, such as cantharids, have unknown life histories. Therefore, how these predators are interacting with each other, and their predation effects remain unknown. In addition, because the number of these generalist predators were so high in such a concentrated area, intraguild predation and cannibalism may also interfere with the functional response.

As we move into a new era of pest management, a better understanding on the population dynamics and ecology of these systems is essential. This will allow for the development of new predictive tools and land management techniques that will provide producers with the best option for what is happening on their farms. These two projects provide new information and tools that can be incorporated into current management programs in order to reduce the amount of unnecessary insecticide application and the amount of land space being devoted to farmscaping, both of which will save growers time and money. There are numerous questions that remain, but with continued efforts, the long-term goal of reducing insecticide reliance and increasing the adoption of IPM approaches is feasible.

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