TRAP CROP SYSTEMS FOR STRIPED CUCUMBER BEETLE CONTROL IN WINTER SQUASH

A Thesis Presented

By

ANDREW F. CAVANAGH

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE
September 2008

Graduate Program in Entomology

TRAP CROP SYSTEMS FOR STRIPED CUCUMBER BEETLE CONTROL IN WINTER SQUASH

A Thesis Presented

by

Andrew F. Cavanagh

Approved as to style and content by:

____
Lynn S. Adler, Chair

____
Ruth Hazzard, Co-Chair

____
Rob Wick, Member

____
Steve Rich,
Entomology Graduate Program Director

DEDICATION

To my Wife and my Son, Kathie Mae Crivelli & Samuel Owen Cavanagh.

ACKNOWLEDGMENTS

I would like to thank my advisors, Lynn S. Adler and Ruth Hazzard, for their patience, guidance, and support. Thanks also to Dr. Rob Wick, for serving on my committee and providing advice and opportunities through the years.

I want to thank Northeast SARE, USDA/CSREES Northeast IPM, and the New England Vegetable and Berry Growers Association for funding and supporting my research

I would like to thank Jude Boucher, who was instrumental in establishing this project. I wish to express my gratitude to all the individuals who participated in and contributed to this work: Neal Woodard, Amanda Brown, Tim Andematten, Wes Autio, Sorrel Hatch, Amber O'Reilly, John Boisvert, Wally Czjakowski, Edwin Matuszko, Al and Bill Mckinstry, Ray Rex, Ken Santos, Len Shuzdak, Jim Ward, Tim Wheeler, John & Jamie Bagdon, Jeff Bober, Tom Calabrese, Joe Czjakowski, Gary Gardner, Paul & Kevin Jekanowski, Mike Kosinski, Skip Peppin, Al Sandersen, Mike Wisserman, and Jodi Zgrodnick.

ABSTRACT

TRAP CROP SYSTEMS FOR STRIPED CUCUMBER BEETLE CONTROL IN WINTER SQUASH

SEPTEMBER 2008

ANDREW F. CAVANAGH

Directed by: Assistant Professor Lynn S. Adler & Ruth Hazzard

ABSTRACT CHAPTER 1

Striped cucumber beetle, *Acalymma vittatum* F., is the primary insect pest of cucurbit crops in the Northeastern United States. Adult beetles colonize squash crops from field borders, causing feeding damage at the seedling stage and transmitting the bacteria *Erwinia tracheiphila* Hauben et al. Conventional control methods rely on insecticide applications to the entire field, but surrounding main crops with a more attractive perimeter could reduce reliance on insecticides. *Acalymma vittatum* demonstrates a marked preference for Blue Hubbard squash (*Cucurbita maxima* Duchesne) over butternut squash (*C. moschata* Duchesne). Given this preference, Blue Hubbard squash has the potential to be an effective perimeter trap crop. We evaluated this system in commercial butternut fields in 2003 and 2004, comparing fields using perimeter trap cropping with Blue Hubbard to conventionally managed fields. In 2003 we used a foliar insecticide to control beetles in the trap crop borders, and in 2004 we compared systemic and foliar insecticide treatments for the trap crop borders. We found that using a trap crop system reduced or eliminated the need to spray the main crop area, reducing insecticide use by up to 94% compared to conventional control methods, with no increase in herbivory or beetle numbers. We also surveyed the growers who participated in these experiments and found a high level of satisfaction with the effectiveness and simplicity of the system. These results suggest that this method of pest control is both effective and simple enough in its implementation to have high potential for adoption amongst growers.

ABSTRACT CHAPTER 2

Winter squash is a vital agricultural commodity in many parts of the world. In the Northeastern United States, the primary insect pest of these crops is the striped cucumber beetle, *Acalymma vittatum* F, which has traditionally been controlled with multiple full field pesticide applications. Recent studies have indicated that using a Blue Hubbard squash perimeter trap crop system (PTC hereafter) can reduce insecticide use by >90% in butternut squash, the primary winter squash grown in this region. This method involves dedicating a portion of the field to the trap crop. Despite the savings in insecticide costs, growers may be reluctant to give up field space for Blue Hubbard squash, which has a limited market. Finding a more marketable trap crop than Blue Hubbard would lower the barrier for adoption of this system. We tested eight varieties of three species of cucurbits for attractiveness to beetles relative to Blue Hubbard and butternut squash, and chose buttercup squash as the most promising replacement for Blue Hubbard. We compared the effect of a buttercup border, Blue Hubbard border, or control (no border) on beetle numbers, herbivory, and insecticide use. We found that buttercup squash performed equally well as Blue Hubbard as a trap crop, with up to 97% reduction in the total field area requiring insecticide compared to control fields.

This study confirms the effectiveness of PTC systems and offers growers a more marketable trap crop.

TABLE OF CONTENTS

Page

1. USING TRAP CROPS FOR CONTROL OF ACALYMMA VITTATUM (COLEOPTERA:CHRYSOMELIDAE) REDUCES INSECTICIDE USE IN BUTTERNUT SQUASH

2. BUTTERCUP SQUASH PROVIDES A MARKETABLE ALTERNATIVE TO BLUE HUBBARD AS A TRAP CROP FOR CONTROL OF STRIPED CUCUMBER BEETLE (COLEOPTERA CHRYSOMELIDAE)

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

USING TRAP CROPS FOR CONTROL OF *ACALYMMA VITTATUM* (COLEOPTERA:CHRYSOMELIDAE) REDUCES INSECTICIDE USE IN BUTTERNUT SQUASH

1.1 Introduction

Vegetable crops are an important commodity in the United States, valued at $12.7 billion in 2002 (USDA, 2002 Census of Agriculture). Northeastern states have a high proportion of their vegetable crop industry invested in cucurbit crops, including squash, melons, cucumbers, and pumpkins; in Massachusetts, 40% of the vegetable-crop acreage is devoted to cucurbit crops (USDA, 2002). The value of winter squash has been estimated at greater than $5 million for the state (Hollingsworth, Mordhurst, Hazzard, & Howell, 1998). Butternut squash (*C. moschata* Duchesne) is the primary winter squash crop in MA, representing 54% of all winter squash harvested in the state (Clifton, 2007). The main insect pest of butternut squash is the striped cucumber beetle (*Acalymma vittatum* F.), which also serves as the vector for *Erwinia tracheiphila* Hauben et al, a bacterium which causes a lethal wilt disease in cucurbits. The current chemical control strategies for this pest face issues related to rising costs, environmental concerns, and the potential for developing pesticide resistance. Growers often implement integrated pest management strategies to mitigate spraying, but this generally entails spraying based on economic thresholds rather than reducing the amount of the crop that is sprayed. Perimeter trap cropping represents a strategy that can potentially reduce the proportion of the field that requires insecticides. Blue Hubbard (*Cucurbita* *maxima* Duchesne), due to its attractiveness to striped cucumber beetles, has strong potential as a trap crop in a perimeter trap cropping system (PTC hereafter). Our experiments tested a Blue Hubbard PTC system over two years in commercial butternut fields.

Striped cucumber beetles are ranked as the most important insect pest in cucurbit crops in the Northeastern US, and are the primary target of insecticide applications used by growers. The Northeast Vegetable IPM Working Group ranked the cucumber beetle and bacterial wilt complex as a region-wide problem that causes significant reduction in yield and results in high insecticide use (IPM Priorities for Vegetables in the Northeast: http://northeastipm.org/work_vegepriority.cfm). In New England, cucumber beetles overwinter as adults in the woods and brush borders surrounding fields, colonize cucurbit fields from the edges inward in early to mid-June, and can completely destroy newly germinated plants. Damage to leaves and early flowers takes place over a month-long period in New England, followed by a period of inactivity aboveground after adults have laid eggs in the soil and died. New adults emerge in mid to late summer and continue to feed, damaging leaves, flowers, and fruit, before leaving the fields for overwintering sites. Relatively low amounts of herbivory (20% by the 3-leaf stage) can significantly reduce yield in winter squash (Hoffmann et al, 2000). Additional yield losses are caused by cucumber beetle transmission of *E. tracheiphila*, the causal organism of bacterial wilt disease in cucurbits. Infection rates among beetle populations may be as high as 78% (Fleischer et al, 1999). Cucurbits suffer the greatest yield loss from bacterial wilt when they are infected as young plants, making early season protection from beetles critical for bringing a crop to harvest (Yao et al, 1996; Brust, 1997). Yield losses from bacterial wilt in winter squash and pumpkins have increased in the past decade (McGrath, 2004), necessitating the development of control methods that reduce transmission of wilt during the most susceptible stages of plant development.

There are many issues associated with insecticide use, including time and financial costs, human health, environmental concerns, the potential for evolution of insect resistance, and damage to non-target organisms. Conventional pest management for many cucurbit crops requires two to eight applications of insecticides such as carbaryl, other carbamates, or synthetic pyrethroids (Brust & Rane, 1995; Brust & Foster, 1999). It is possible that full field insecticide applications of insecticides can reduce yield by deterring or harming pollinators (e.g., Brust & Foster, 1995), and insecticides can also have deleterious effects on natural enemy populations, leading to pest resurgence and secondary pest outbreaks. Growers in the Northeast have recently adopted the use of systemic insecticides (e.g., imidacloprid) in the furrow at planting, which protects cucurbit crops from early feeding damage. This has the advantage of eliminating the need for precise timing with foliar applications and potentially lowering overall pesticide use. However, the insecticide cost is higher than with foliar applications, and widespread adoption of systemic insecticides may lead to the evolution of insect resistance more quickly than foliar treatments. Imidacloprid has caused enough concern among beekeepers that it has been banned in France, though research has thus far not supported these concerns (Maus et al 2007). Therefore, developing methods for controlling cucumber beetles with limited reliance on insecticides could have the advantages of delaying insecticide resistance, reducing environmental impacts, and preserving pollinators and natural enemies.

Perimeter trap cropping uses insect preference for certain hosts to concentrate pest insects in the crop border, away from the main crop. The more attractive crop is planted around the outer edge of the entire main crop (Hokkanen, 1991; Boucher et al, 2003; Boucher & Durgy, 2004). Similar strategies have been used successfully in collards, summer squash, peppers, and papaya (Aluja et al, 1997; Mitchell et al, 2000; Boucher et al., 2003; Boucher, T. J., & Durgy, R. 2004). Striped cucumber beetles overwinter in the woods surrounding fields, and move into a crop from the edges. This makes them a good candidate for control via PTC, as they will encounter the attractive border before they come into contact with the main crop. The beetles concentrate in the borders before dispersing into the field, allowing insecticides to be applied to a much smaller area. If the border is treated with a systemic insecticide at planting, the crop may be protected throughout the critical early growth period. Reducing the field area sprayed with insecticides may also provide a refuge for beetles that are susceptible to chemical controls, potentially delaying the evolution of resistance (Liu & Tabashnik, 1997; Zhao et al, 2000; Tang et al, 2001).

Blue Hubbard squash is highly attractive to striped cucumber beetles in comparison with butternut squash (*C. moschata* Poir) and has low susceptibility to bacterial wilt (McGrath & Shishkoff, 2000; Cavanagh , Adler, and Hazzard, unpublished data). It has been used as an effective perimeter trap crop in summer squash and cantaloupe, allowing for adequate beetle control with greatly reduced applications of insecticides (Pair 1997, Boucher & Durgy, 2004). Blue Hubbard is similar to butternut squash in terms of its days to maturity, temperature and spacing requirements. These factors make it a promising perimeter trap crop for butternut squash.

The goal of this research was to test the effectiveness of a perimeter trap crop system in reducing the amount of insecticide needed to effectively control the primary pest of butternut. We performed trials for two years in commercial fields to determine whether a PTC system would allow growers to reduce insecticide use without increasing herbivory or beetle numbers in the main crop. We compared measures of herbivory and insecticide use between fields with a PTC system or conventional full field insecticide applications. We also surveyed participating growers about their experience and satisfaction with the system. When evaluating an experimental system that is designed to be ultimately adopted by growers, it is vitally important to evaluate the participating growers' opinions of the effectiveness of the system. This type of evidence, while anecdotal, often carries more weight in the target community than more objective forms of measurement.

1.2 Materials and Methods

1.2.1 Experimental Design

To assess the effectiveness of PTC systems in commercial agriculture, we assigned treatments to 13 commercial butternut squash fields in MA. Seven fields were planted and managed using a PTC system. The other six used conventional chemical control practices. Fields were as similar as possible in terms of size, management practices, and soil types. Fields ranged in size from 0.20 hectares to 10.05 hectares. Borders comprised an estimated 3-14% of the total field. Similar experiments were conducted in 2003 and in 2004. All growers planted their fields as they normally would, except for the inclusion of the border in the PTC fields. Cultivation and nutrient management were performed by the grower, as per the needs of the field and standard management practices. The threshold over which we recommended spraying in the main crop was an average of one beetle per plant up to the five leaf stage and two beetles per plant thereafter until flowering.

All PTC fields used a Blue Hubbard border as the trap crop. During 2003, this border was treated with a foliar application of carbaryl (Sevin XLR Plus, Bayer CropScience, Research Triangle Park, NC) at the first sign of beetles and at roughly 10 day intervals thereafter. The main crop in PTC systems was left untreated. Conventional fields received full field applications of insecticide according to the normal practices of the growers, which were dictated by beetle pressure. Fields were monitored at weekly intervals from 3 June to 14 July (peak beetle season that year). During each census, 25 plants were randomly selected and scouted in the field borders to determine beetle numbers and the level of herbivory. Another 25 were randomly selected and scouted from a row half way between the border and the center of the field to determine beetle numbers and the level of herbivory in the main crop. Plants were scouted for number of live and dead beetles, presence of cotyledon damage, and overall defoliation of the plant. We rated defoliation on a 0-5 scale in 20% increments, with 0 for no damage. We also recorded insecticide use as the number of times borders and/or main crops were sprayed.

The experimental design in 2004 was very similar to that of 2003, except that we also examined the effects of treating the border with the systemic insecticide imidacloprid (Admire 2F, Bayer CropScience, Research Triangle Park, NC) using a furrow drench applied at planting to the Hubbard borders of the PTC fields and to the whole field in the conventional fields. This was done after consulting with several growers, as the use of a systemic seemed likely to alleviate difficulties in timing the initial spray correctly. The design was adapted to include two levels of insecticide: systemic (Admire) and foliar (Sevin), crossed in a 2x2 factorial design with system (PTC or conventional), for a total of four treatment combinations. We initially had three fields per treatment combination, for a total of 12 fields. One of our PTC systemic fields failed to emerge due to wet weather, leaving only two fields in that category. Fields were scouted for beetles and herbivory at weekly intervals between 4 June and 6 July following the 2003 protocol. The number of sprays required for adequate beetle control was recorded for each field. At the end of the season in 2004, growers were given a survey in which they were asked to quantify their satisfaction with different aspects of the system, including its effectiveness, usability, cost relative to conventional methods, and impact on yield relative to their past experiences with more traditional methods.

1.2.2 Data analysis

We asked how PTC *vs*. conventional management affected herbivory and beetle numbers in the border and main crop, and what proportion of the field was treated with insecticide. All data were analyzed using PROC GLM in SAS V. 9.1 (SAS-Institute, 2004). We evaluated the impact of a PTC system on herbivory and beetle numbers in the main crop using MANOVA with system (PTC or conventional) and insecticide type (foliar or systemic, 2004 only) as the independent factors. We used the same model for beetle numbers and damage in field borders to determine whether borders of PTC fields had more beetles than conventional fields. Beetle numbers, defoliation, and cotyledon damage were averaged over censuses to provide one measure per response for analysis. Analyzing data from the first four censuses alone, when beetle damage may have the highest impact on plant health, provided qualitatively the same results as averaging over the whole season (data not shown). Beetle numbers were square root transformed to meet assumptions of normality; other data were normal without transformation. Cotyledon damage was not recorded in one field with early cultivation, and so was analyzed separately in both years since MANOVA will exclude replicate fields with any missing responses.

Insecticide use was analyzed as total proportion of field with insecticides applied. As fields were of uneven size and shape, proportion of field with insecticides applied was a more universal measurement than area treated, amount of insecticide used, or other absolute measures of insecticide use. Because fields were of uneven shape the border area was estimated as if the fields were rectangular with length to width proportions of 1:2. For example, a two hectare field of irregular proportions would be standardized as a rectangular 2 hectare field with a width of 100 m and a length of 200 m. Assuming that the PTC borders were 1.8 m wide, this would give us an estimated border area of 1092 m^2. Standardizing the fields in this way allowed us to quantify and compare pesticide use between fields of different size and shape. Exact measurement of the sometimes curved or jagged field edges was not practical. As all fields were roughly rectangular in shape, we believe that this method provides an accurate estimation of border area. The total proportion of fields treated in each system were compared using ANOVA with system (PTC or conventional) as the independent variable in 2003, and system, insecticide type (foliar or systemic), and their interactions as the independent variables in 2004. In both years, the response was normalized with square root transformations. We used square root transformations instead of the arcsine(sqrt(x)) transformation usually used for proportional data because multiple sprays of the entire field resulted in proportions greater than one. Grower satisfaction surveys were summarized but not subject to statistical analysis.

1.3 Results

1.3.1 Herbivory and beetle numbers

In 2003, system (PTC or conventional) did not affect herbivory in the main crop (MANOVA: Wilks' $\lambda = 0.97$, $F_{2, 10} = 0.16$, $P = 0.85$). ANOVA indicated no significant effect of PTC on cotyledon damage ($F_{1, 10} = 0.52$, $P = 0.49$) in the main crop, which was analyzed separately in both years due to missing values for one field. PTC treatment had a significant effect on herbivory in the borders (MANOVA: Wilks' $\lambda = 0.52$, $F_{2, 10} = 4.59$, $P = 0.039$). Subsequent univariate analysis indicated that the Blue Hubbard borders of the PTC fields attracted significantly more beetles than the borders of the conventional fields (Table 1.1; Fig. 1.1), but defoliation ratings and cotyledon damage were not different between PTC and conventional fields (Table 1.1).

In 2004, neither system (PTC or conventional), insecticide treatment (foliar or systemic), nor their interaction significantly affected beetle numbers, defoliation (MANOVA: Wilks' $\lambda > 0.45$, $F_{2, 6} < 3.70$, $P > 0.09$ for all) or cotyledon damage in the main crop (ANOVA: $F_{1, 6} = 0.53$, $P = 0.50$). There were eight times as many beetles in

Blue Hubbard compared to conventional borders (mean + s.e.: PTC: 2.95 +1.50; Conventional: 0.36 + 0.21), although the effects of system, insecticide, and their interaction on herbivory and beetle numbers in the borders were not statistically significant (MANOVA: Wilks' λ >0.54, $F_{2,6} < 0.29$, $P > 0.16$ for all; Fig. 1.1).

1.3.2 Insecticide use

In 2003, the proportion of PTC fields treated with insecticides was half that of the conventional fields, although this difference was not statistically significant ($F_{1,11} = 2.65$, $P = 0.13$; Fig. 1.2).

In 2004, using a PTC system reduced the proportion of the field requiring insecticides by an average of 94% ($F_{1,7} = 111.36$, $P < 0.0001$, Fig. 1.2). Insecticide type (foliar or systemic) had a marginally significant effect on the proportion of the field requiring treatment ($F_{1,7} = 5.23$, $P = 0.056$; mean ± s.e.: systemic: 0.88 ± 0.38; foliar 0.62 ± 0.24). The interaction of system (PTC or conventional) and insecticide (foliar or systemic) was not significant ($F_{1,11} = 1.01$, $P = 0.35$), indicating that PTC effectively reduced insecticide use regardless of the type of insecticide used.

1.3.3 Grower satisfaction

Ten growers who were introduced to PTC in this research were surveyed at the end of the 2004 growing season. All considered the system to be good or excellent overall and were satisfied with the way the system worked for them. Eighty percent of the growers using the system found that it saved them money. All of the growers spent the same or less time on beetle control using a PTC system compared with conventional methods, and all of the growers reduced their insecticide use by implementing the PTC system.

1.4 Discussion

Fields with Blue Hubbard borders required 50% and 94% less insecticide use than conventional fields in 2003 and 2004 respectively, although this effect was only significant in 2004. Beetle pressure was similar in both years (mean beetles per plant in the main crop was 0.28 in 2003 and 0.31 in 2004). Although the PTC fields required less insecticide overall, the PTC system did not eliminate the need for insecticides in the main crop; in 2003 six out of seven PTC fields received one or more full-field sprays. One of the major barriers to effective use of PTC in 2003 was the precise timing required to effectively apply insecticides to the Blue Hubbard border before it was breached by the beetles. Another barrier was grower reluctance to refrain from spraying crops, even though in some cases they were not at risk. Issues with the critical timing of the foliar insecticides were addressed in the 2004 trials with the use of a systemic insecticide at planting and better communication with participating growers. These modifications led to greatly improved effectiveness; in 2004 the main crop of PTC fields did not exceed threshold beetle numbers and no PTC fields required full-field insecticide treatments. There was a marginally significant decrease in the proportion of the field requiring spray in fields treated with a foliar insecticide regardless of system type. This difference is likely due to some of the conventional foliar treated fields requiring multiple applications, while the systemic fields require only one application of insecticide for full season control. It is important to note that the beetle populations and herbivory in the main crop of all fields were very similar (e.g., beetle numbers 2003: Conventional: 0.42 ± 0.13, PTC: 0.35 ±. 0.07; 2004: Conventional: 0.33 ± 0.07, PTC: 0.32 ± 0.23), even though the main crops of the PTC fields were not treated with any insecticide in 2004, while the main crops of the conventional fields all required insecticide treatment. The 50% reduction in insecticide use for PTC fields in 2003, while not statistically significant, would certainly be important to the growers of these crops. These results show that using a PTC system can reduce or eliminate the need for full field insecticide treatments on this crop, leading to higher profit margins for the grower, reduced exposure to potentially dangerous toxins, and potential preservation of pollinators.

The results of the grower survey, while anecdotal, support the empirical evidence in this study. To the agricultural community at large, the opinions and experiences of fellow growers often weigh more heavily than experimental data in their considerations of pest management options. Our objective for this study was to evaluate not only whether or not we could demonstrate that PTC reduced insecticide use, but also to evaluate how it would be accepted by the growers. The positive results of this survey, and our experience in working with the growers who volunteered their fields, showed that PTC has strong potential for adoption.

While a reduction in insecticide use will likely be the most important benefit for the growers who adopt PTC systems, there may be other advantages as well. Using a cropping strategy that provides an unsprayed refuge for susceptible pest individuals can delay the onset of insecticide resistance in insect populations (Liu & Tabashnik, 1997; Zhao et al., October 2000). In addition, it has been shown that increasing the size of the refuge generally slows the development of resistance (Tang et al., 2001). Perimeter trap cropping provides for a large proportion of the field (up to 97% in this study) to act as a refuge for susceptible individuals, and may help preserve the useful life of several important agricultural chemicals. For refuge strategies to work, insect resistance traits must be recessive and associated with a fitness cost in the absence of insecticides (Baker et al., 2007). In *Leptinotarsa decemlineata* Say, a related chrysomelid beetle, resistance to imidicloprid has been documented (Olson et al, April 2000). It has been shown that this resistance is genetic, recessive, and has a fitness cost (Zhao et al., 2000; Baker et al., 2007). Studies are necessary to document whether similar resistance occurs in *A. vittatum*. While directly evaluating the effectiveness of PTC in delaying insecticide resistance is beyond the scope of this study, it is clear that the system meets the basic criteria for an effective refuge strategy.

Some current implementations of IPM have been criticized for being too reliant on chemical controls and under-utilizing tactics which promote the inherent strengths of agricultural ecosystems (Lewis et al 1997; Ehler & Bottrell, 2000). Rather than relying entirely on scout-and-spray approaches, PTC modifies crop layout to take advantage of pest host colonization behavior. Our work shows that PTC significantly reduces insecticide use while potentially providing a refuge to preserve beneficial insects such as pollinators and natural enemies, and may also help delay insecticide resistance. In this sense PTC as an IPM tactic represents a total system approach to pest management.

The basic principles of trap cropping are not new. Many traditional farming systems rely on trap cropping for control of insect pests, and there are examples in the US dating back to 1860 (Hokkanen, 1991). With the advent of modern chemical controls, these methods of pest control have largely fallen out of use. Trap cropping has only recently been adopted in modern commercial agriculture (Hokkanen, 1991; Pair, 1997; Boucher et al., 2003; Boucher & Durgy, 2004; Shelton & Badenes-Perez, 2006).

Traditional chemical control measures face increased pressure from rising costs, environmental concerns, and insecticide resistance, necessitating the development of alternative pest control measures. In his review of trap crop systems, Hokkanen (1991) suggests that at least 35-40 important pest species could likely be controlled with some form of trap cropping, and yet only a handful of trap crop systems are used regularly in commercial agriculture. Exploring the potential of new trap crop systems and developing methods that are acceptable to growers is an important strategy for increasing the economic and environmental sustainability of farms. The results of this study show that PTC with Blue Hubbard is an excellent strategy for control of *A. vittatum* in butternut fields in New England.

Our experiments demonstrated that perimeter trap cropping can provide effective striped cucumber beetle control while greatly reducing insecticide use in commercial butternut squash fields. Most of the growers who participated in this experiment have adopted this system as their own, and were still using it as of this writing. The high level of satisfaction with the system expressed by growers who participated in the experiment indicates that PTC has excellent potential for adoption by growers wishing to reduce their insecticide costs and exposure.

Table 1.1. Effect of system (PTC or conventional) on herbivory in field borders in 2003. ANOVAs are not presented for 2004 since MANOVA results were not significant. Note that cotyledon damage was not included in the initial MANOVA (see text) due to missing values in one field.

	Total Beetles			**Defoliation**			**Cotyledon Damage**		
Source	df	SS	P	df	SS	P	df	SS	P
System	1	1.92	0.01	1	0.09	0.26	1	0.02	0.49
Error	11	2.28		11	0.68		10	0.35	

Fig. 1.1 Beetle numbers in borders of PTC and conventional plots. Error bars represent standard error.

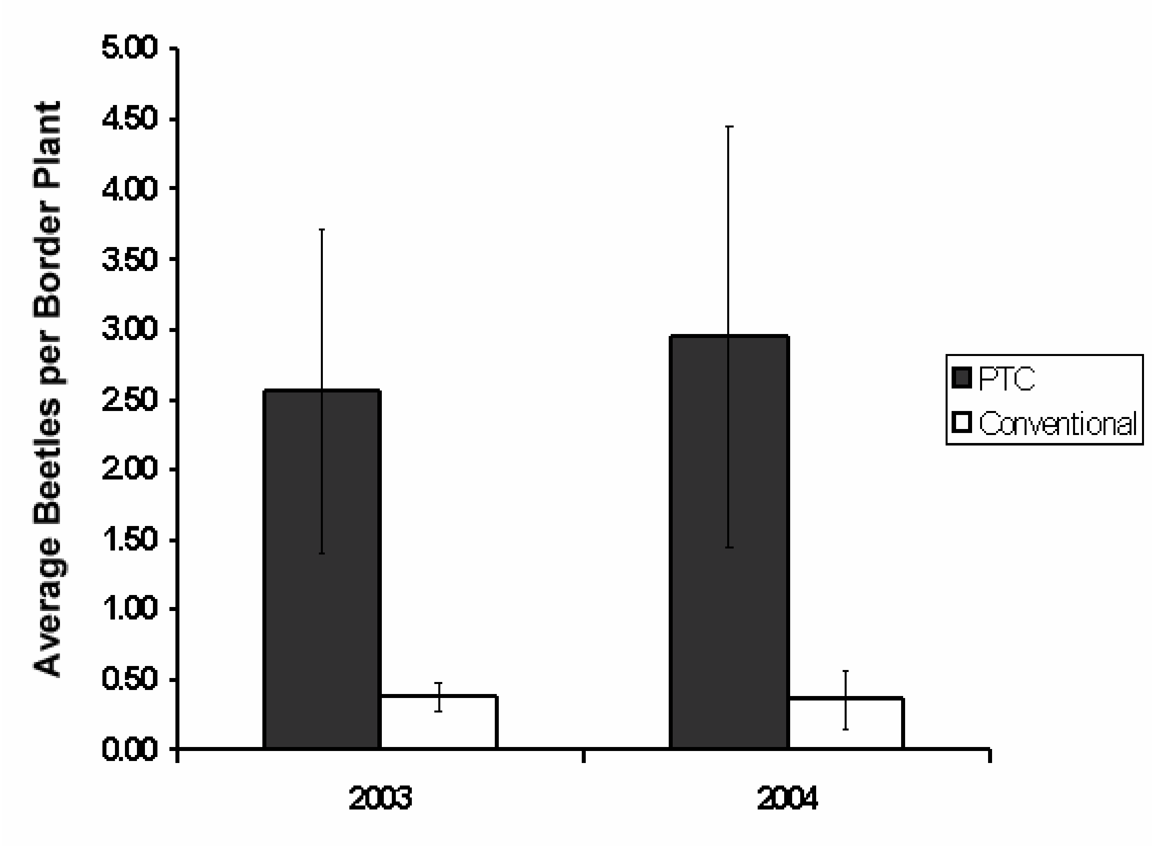
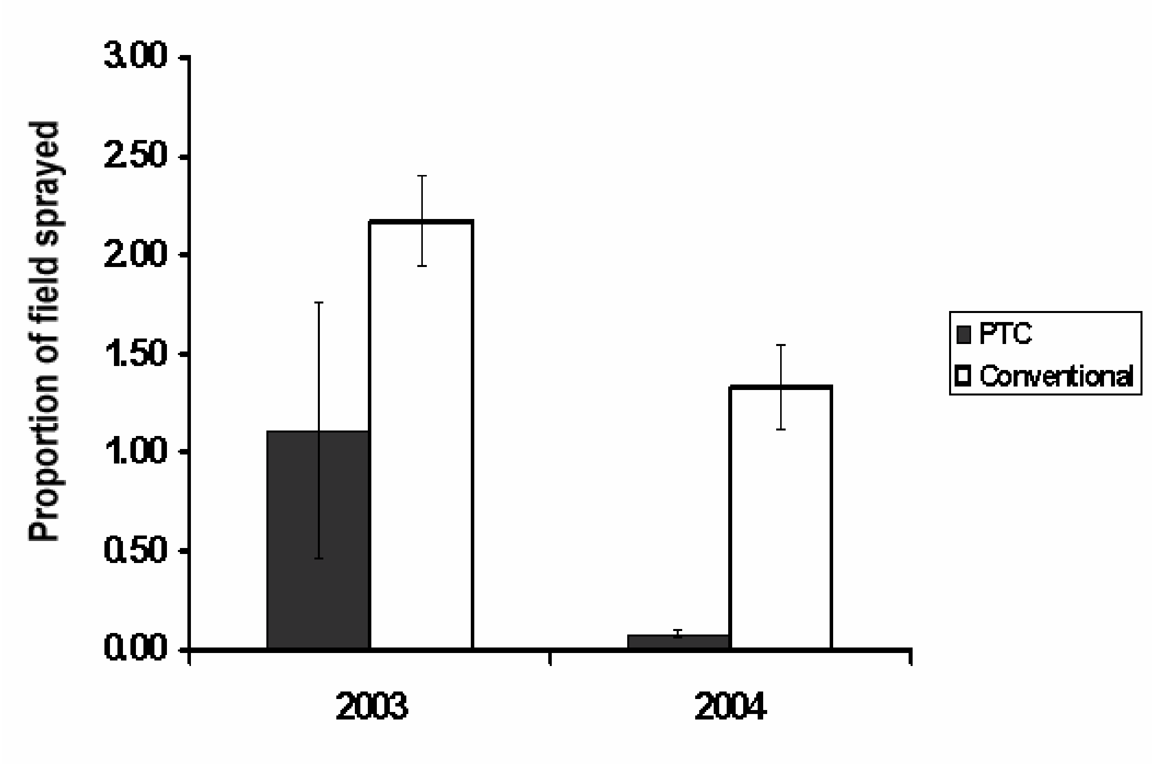


Fig. 1.2 Total proportion of experimental fields requiring treatment for beetle control in 2003 and 2004. Error bars represent standard error. Multiple insecticide applications to individual fields resulted in proportions greater than one.



CHAPTER 2

BUTTERCUP SQUASH PROVIDES A MARKETABLE ALTERNATIVE TO BLUE HUBBARD AS A TRAP CROP FOR CONTROL OF STRIPED CUCUMBER BEETLE (COLEOPTERA CHRYSOMELIDAE)

2.1 Introduction

Cucurbits are an important agricultural crop across the globe (Paris, 1989). Cucumber beetles (*Diabrotica* spp. and *Acalymma vittatum* Fabricius; Coleoptera: Chrysomelidae) constitute some of most serious pests of cucurbit crops in the world (Metcalf and Metcalf 1992). These beetles are considered to be one of the most important insect pest in cucurbit crops in the US, and are the primary target of insecticide applications on these crops in the Northeastern states (Hoffmann, 1996; Hollingsworth, Mordhurst, Hazzard, & Howell, 1998; Stivers, 1999). Recently, many growers have adopted the use of systemic insecticides (e.g., imidacloprid) in the furrow at planting (Hazzard, 2003) to target early feeding damage; however, the per-acre cost can be as much as five times higher than foliar applications. Trap cropping using Blue Hubbard squash (*C. maxima* Duchesne) has been shown to reduce the need for insecticides by as much as 90% in cucurbit crops (Cavanagh, Hazzard and Adler, unpublished data) (Boucher & Durgy, 2004; Pair, 1997). However, the need to dedicate a portion of the field to a trap crop with limited market demand may deter growers from using the system. Although trap cropping with Blue Hubbard dramatically reduced pesticide use, finding a more marketable alternative to Blue Hubbard is necessary for this method to be widely adopted for controlling *Acalymma vittatum*.

Winter Squash is an important cucurbit crop in the Northeastern US, with yields in excess of 20,000 lb/acre and a wholesale value estimated at $3400/acre (Clifton, 2007). Butternut squash (*C. moschata* Poir) in particular is a key winter squash crop for growers, in part because of strong market demand and excellent storage capability. Forty percent of Massachusetts growers store butternut through fall and winter months (Hollingsworth et al., 1998), providing them with much needed off season revenue. Striped cucumber beetle and the bacterial wilt disease caused by the bacterium that it vectors are two of the most important factors affecting butternut yield (NE Vegetable IPM Working Group; Clifton, 2007).

Perimeter trap cropping (PTC hereafter) with Blue Hubbard has been shown to significantly reduce the need for insecticide applications in butternut crops. Perimeter trap cropping systems design the crop layout to take advantage of pest colonization behavior and host preference. Border defenses are established by planting a more attractive trap crop to completely encircle the main crop, resulting in reduced infestation and reduced need for insecticides in the main crop (Aluja, Jimenez, Camino, Pinero, & Aldana, 1997; Mitchell, Guangye, & Johanowicz, 2000; Boucher, Ashley, Durgy, Sciabarrasi, & Calderwood, 2003; Boucher & Durgy, 2004). Blue Hubbard is highly preferred by striped cucumber beetle relative to butternut squash (McGrath & Shishkoff, 2000b), summer squash (*C. pepo* L.), and cucumber (*Cucumis sativus* L.) (Boucher & Durgy, 2004).When early season beetles encounter a perimeter of Blue Hubbard, they are likely to remain there rather than moving to the main crop. Insecticides can be used to kill pest populations in the perimeter while the need for pesticides is eliminated or dramatically reduced in the main crop.

While PTC with Blue Hubbard has been effective in controlling pest populations and reducing pesticide applications in butternut crops, this system relies on devoting a portion of the main crop area to the trap crop, which can result in an overall reduction in yield per acre if the trap crop is not marketable. Butternut squash has the largest market share of the winter squash grown in the Northeastern U.S., accounting for 54% of the crop in MA (Clifton, 2007). In contrast, Blue Hubbard represents only 5% of the total winter squash market (Clifton, 2007). In comparison to Blue Hubbard, buttercup squash and acorn squash have much greater market value (19% and 11% of the market in New England, respectively) (Clifton, 2007). Perimeter trap crop systems would be more likely to be accepted by growers if they could replace Blue Hubbard with a more marketable alternative, such as buttercup or acorn squash. However, these crops have not been compared to Blue Hubbard as potential PTC alternatives.

We performed preference trials to evaluate the attractiveness of eight types of winter squash from three species of cucurbits in comparison to Blue Hubbard and butternut squash. The most promising of these, in terms of both attractiveness to beetles and market potential, was then used in commercial field trials. We compared beetle numbers, herbivory, and insecticide use in a PTC treatment with a Blue Hubbard border, a PTC treatment with a border of the selected variety, and a conventional treatment with no border.

2.2 Materials and Methods

2.2.1 Preference Trials

2.2.1.1 Experimental Design

In 2004 we tested the relative attractiveness of winter squash varieties as potential trap crops for butternut squash. We included eight varieties from three species of cucurbits: Burgess buttercup (*Cucurbita maxima*), Red Kuri hubbard squash (*C. maxima*), Blue Hubbard hubbard squash (*C. maxima*), Waltham butternut (*C. moschata*), La Estrella calabasa (*C. moschata*), Bush Delicata delicata squash (*C. pepo*), a standard mix of gourds (*C. pepo)*, and Table Ace acorn squash (*C. pepo).* We chose varieties that were of commercial interest to growers. The buttercup, Red Kuri, butternut, delicata, standard gourd mix, and Blue Hubbard squash seed were provided by Johnny's Selected Seeds (Winslow, Maine). The acorn and calabasa squash seed were provided by Rupp Seeds (Wauseon, OH). Five blocks were planted by hand on 3 June at the University of Massachusetts Crop Research and Education Center, South Deerfield, MA. Each block contained one plot of each cultivar, for a total of 40 plots. Varieties were randomly assigned to plots within the block. Plots contained three rows of seven plants with 4.16 cm between each plant and 1.52 m between each row. Plots within each block were separated by 3.05 m. Blocks were separated by 4.57 m. Plots were fertilized on 28 May with 19-19-19 from Crop Production Services (South Deerfield, MA) at a rate of 560.43 kg per hectare (500 lbs per acre) based on soil test recommendations (Howell, 2008). Weed control was achieved with a commercial mixture of ethalfluralin and clomazone (Strategy herbicide, Loveland Products, Greeley CO) applied at the rate of 4.68 liters per hectare on 4 June, followed by mechanical cultivation as needed thereafter.

Plants were monitored at weekly intervals from 18 June to 1 July. Five plants from the middle row of each plot were scouted for number of beetles presence/absence of cotyledon damage, and overall defoliation of the plant. We rated defoliation on a 1-5 scale in 20% increments, with 0 for no damage.

2.2.1.2 Data Analysis

Our responses were beetle numbers, defoliation, and cotyledon damage. All responses were averaged over censuses to produce one value per response per plot. We chose not to use cotyledon damage in the analysis because it was measured as the presence or absence of damage, and nearly all plants had some cotyledon damage. All data here and below were analyzed using PROC GLM in SAS V.9.1 (SAS-Institute, 2004). To evaluate the effect of different cucurbit varieties and species on attractiveness to beetles, we used ANOVA to compare beetle numbers with species (*C. maxima*, *moschata*, or *pepo*) and variety nested within species as the independent factors. To assess which varieties within species would serve as potential trap crops, we performed a separate ANOVA on variety with *a priori* comparisons to contrast beetle numbers and defoliation on each variety with beetle numbers and defoliation on butternut squash and Blue Hubbard. Varieties that attracted significantly more beetles than butternut squash were considered potential trap crops.

2.2.2 On-Farm Trials

2.2.2.1 Experimental Design

The preference trial indicated that the buttercup and Red Kuri squashes were significantly more attractive to beetles than butternut squash. Buttercup squash was as attractive as Blue Hubbard, and Red Kuri was more attractive than Blue Hubbard (see

Results). However, buttercup varieties are much more marketable than Red Kuri (Clifton, 2007). Since our goal was to find a more marketable PTC alternative than Blue Hubbard with equivalent beetle attraction, buttercup was chosen for tests in commercial field trials. To assess the effectiveness of buttercup squash as a replacement for a Blue Hubbard trap crop in butternut squash, we randomly assigned 21 commercial butternut squash fields to one of three treatments (n = seven per treatment): a PTC system with a Blue Hubbard border, a PTC system with a buttercup squash border, and a conventional treatment with no treated border. The border of one Blue Hubbard PTC field was destroyed during early cultivation and all data from that field were discarded. In all treatments, the butternut crop was left untreated until beetles reached an economic threshold of one beetle per plant on average from emergence up to three true leaves and 2 beetles per plant on average until flowering, and sprayed with a foliar insecticide if the threshold was exceeded. Thresholds were adapted from previously published work on cucurbit crops (Burkness & Hutchison, 1998; Brust & Foster, 1999). Both the Blue Hubbard and the buttercup PTC borders were treated with the systemic insecticide imidacloprid (Admire 2F, Bayer CropScience, Research Triangle Park, NC) at planting, and received no further treatment. The butternut did not received insecticide at planting in any treatment. Fields ranged in size from 0.81 to 4.05 hectares. All growers planted their fields as they normally would, except for the inclusion of the treated border in the PTC fields. Cultivation and nutrient management were performed by the grower, as per the needs of the field and standard management practices.

Each field was monitored from seedling emergence until the first sign of beetles, and then censused weekly for four weeks. During each census, 25 plants were randomly selected and scouted in the field borders to determine beetle numbers, defoliation, and cotyledon damage using the same methods as the preference trial. Another 25 were randomly selected and scouted from a row half way between the border and the center of the field to determine beetle numbers, cotyledon damage, and defoliation in the main crop.

We recorded pesticide use as the proportion of each field that required treatment in each system, based on growers' spray records. Pesticide use was analyzed as total proportion of field sprayed. As fields were of uneven size and shape, proportion of field requiring pesticides was a more universal measurement than area treated, amount of insecticide used, or other absolute measures of insecticide use. Because fields were roughly rectangular but unevenly shaped, the border area was estimated as if the fields were rectangular with length to width proportions of 1:2. For example, a two hectare field of irregular proportions would be standardized as a rectangular 2 hectare field with a width of 100 m and a length of 200 m. Assuming that the PTC borders were 1.8 m wide, this would give an estimated border area of 1092 m^2, or a proportion of 0.05. Standardizing the fields in this way allowed us quantify and compare pesticide use between fields of different size and shape. Exact measurement of the sometimes curved or jagged field edges was not practical, and as all fields were roughly rectangular we believe that this method provides an accurate estimation of border area. Using the proportion of the field that was treated as our response also allows us to account for the use of the systemic insecticide in the borders of the PTC fields, which contains different active ingredients and are applied at different rates than the foliar material.

2.2.2.2 Data Analysis

Our responses were beetle numbers, cotyledon damage, and leaf herbivory in the border and main crop, and proportion of field treated with pesticide. We compared beetle numbers and damage in the main crops using ANOVA with border treatment (Blue Hubbard, buttercup, or conventional) as the independent factors. All responses were averaged over censuses to compare herbivory across the early growing season. We also compared beetle counts and damage in the borders of each field, with border treatment as the independent variable. Cotyledon damage in the borders was log(x+1) transformed to normalize the data; all other data were normal without transformation.

The total proportion of fields sprayed in each system was compared using ANOVA with border treatment (Blue Hubbard, buttercup, or conventional) as the independent variable. We used log(x+1) transformation instead of the arcsin(sqrt(x)) transformation typically used for proportional data because multiple sprays of the entire field resulted in proportions greater than 1.

2.3 Results

2.3.1 Preference Trials

There were significantly higher beetle numbers in *C. maxima* compared to *C. moschata* or *C. pepo* ($F_{2,28}$=20.27 p=<0.0001) (Fig. 2.1), and correspondingly higher defoliation ($F_{2,28}$=139.88, p=<0.0001) (Fig. 2.2). Varieties within species also differed in beetle numbers ($F_{5,28}$ = 3.01, p = 0.01) and defoliation ($F_{5,28}$ = 3.371, p = 0.02). A separate ANOVA using *a priori* contrasts between varieties revealed that Burgess buttercup squash was equally attractive to beetles as Blue Hubbard ($F_{1,32} = 0.09$, $p = 0.76$), and more attractive than Waltham butternut ($F_{1,32} = 10.08$, $p = 0.003$). Blue Hubbard was significantly more attractive than the butternut squash ($F_{1,32} = 8.23$, $p = 0.007$). Red Kuri squash was more attractive than both Blue Hubbard ($F_{1,32} = 12.85$, $p = 0.001$) and the butternut squash ($F_{1,32} = 41.64$, $p < 0.0001$) (Fig. 2.3). Defoliation followed a similar pattern, with Blue Hubbard ($F_{1,32} = 64.88$, $p < 0.0001$), Red Kuri ($F_{1,32} = 124.91$, $p < 0.0001$) and Table Ace buttercup ($F_{1,32} = 91.98$, $p < 0.0001$) suffering higher defoliation than butternut. Red Kuri had higher defoliation than Blue Hubbard ($F_{1,32} = 9.74$, $p = 0.004$). All of the other varieties had significantly lower defoliation ratings than Blue Hubbard and were not different from the butternut; with the exception of the standard gourds, which had more defoliation than the butternut ($F_{1,32} = 6.58$, $p < 0.013$) but less than Blue Hubbard ($F_{1,32} = 29.56$, $p < 0.0001$) (Fig. 2.4).

2.3.2 On-Farm Trials

There was a notable increase in beetles in the PTC borders vs the conventional borders ($F_{2,17} = 5.25$, $p = 0.02$) (Fig. 2.5); there were no significant differences in cotyledon damage ($F_{2,17} = 0.94$, $p = 0.41$) or defoliation ($F_{2,17} = 1.10$, $p = 0.36$). Using a PTC system with either a Blue Hubbard or buttercup border reduced the proportion of the field that was sprayed by 97% (Blue Hubbard) and 97.4% (buttercup) (treatment effect: $F_{2,15} = 180.63$, $p < 0.0001$; Fig. 2.6.

2.4 Discussion

Preference trials show that the *Cucurbita maxima* species we tested were overall more attractive to the striped cucumber beetle than either *C. pepo* or *C. moschata*, based on both beetle numbers and defoliation. Direct comparisons showed that Red Kuri and the buttercup squash variety were at least as attractive (buttercup) or more attractive (Red Kuri) than Blue Hubbard, and both were more attractive than the butternut variety we tested. It is interesting to note that the *C. pepo* varieties were not more attractive to beetles than *C. moschata*, with the exception of the standard gourds. This indicates that it may be possible to control striped cucumber beetles in some *C. pepo* varieties using a PTC system, as suggested by previous work (Boucher & Durgy, 2004). There is a great deal of variation in attractiveness within *C. pepo* varieties (McGrath & Shishkoff, 2000a), and additional field trials would be necessary to determine the range of varieties that would benefit from a PTC treatment.

Variation in beetle attractiveness between cucurbit species has been well established in the literature (Andersen & Metcalf, 1987; Brust & Rane, 1995; McGrath & Shishkoff, 2000a; Pair, 1997; Smyth, Tallamy, Renwick, & Hoffman, 2002; Boucher & Durgy, 2004), and is generally held to be associated with different concentrations and ratios of bitter cucurbitacin compounds within the plant (Chambliss & Jones, 1966; Metcalf, Metcalf, & Rhodes, 1980). Blue Hubbard and buttercup squash are relatively high in cucurbitacin B, which is highly attractive to beetles (Chambliss & Jones, 1966); in comparison, butternut squash is relatively low in cucurbitacins (Andersen & Metcalf, 1987). It should be noted, however, that at least one study has found that in no-choice tests beetles were just as likely to compulsively feed on cucumbers lacking cucurbitacins as they were to feed on an isogenic line with high cucurbitacin levels (Smyth et al., 2002), despite their clear preference for the high cucurbitacin line in choice trials. This suggests that low cucurbitacin levels may confer some levels of resistance to beetle feeding only if the low cucurbitacin crop is grown in proximity to a high cucurbitacin crop, as is the case with PTC systems.

The results of the commercial field experiment confirm that buttercup squash is an effective replacement for Blue Hubbard as a perimeter trap crop in butternut squash Using either a Blue Hubbard or buttercup PTC system reduced insecticide use by 97% compared to conventionally managed fields. There were no differences in beetle numbers or herbivory between the main crops of the Blue Hubbard PTC, buttercup PTC, or conventional fields, indicating that all three methods were equally effective at controlling damage to the main crop. However, the butternut crop in the PTC fields never required insecticides, while the conventional butternut was sprayed an average of 1.86 times.

Employing a PTC system offers many benefits to growers beyond simply reducing the amount of insecticide needed to produce a viable crop. Perimeter trap crop systems also provide for a large portion of the field to be used as an unsprayed refuge. This refuge can help to protect beneficial insects (Collins & Qualset, 1998; Çilgi & Jepson, 1992) as well as potentially delaying the development of insecticide resistance in the target pest (Liu & Tabashnik, 1997; Ives & Andow, 2002). In addition, leaving the majority of the field untreated with insecticides can potentially increase yield by protecting pollinators (Brust & Foster, 1995) and reduce the likelihood of secondary pest outbreaks (Foster & Brust, 1995).

Despite the benefits of implementing a system that offers these advantages, there are still many barriers to growers adopting a new system. Growers may be unlikely to adopt a new system if it is time intensive, involves new or unfamiliar equipment, or reduces the acreage available for marketable crops. Perimeter trap cropping in butternut squash is a good candidate for adoption because it integrates well with growers' existing crop systems and equipment, and does not require additional time. Using Blue Hubbard squash as a trap crop effectively reduces pesticide use while controlling pest insects(Boucher & Durgy, 2004; Pair, 1997)(Cavanagh, Adler, and Hazzard, in prep), but can also reduce marketable yield.

These results support previous work indicating that using a Blue Hubbard PTC system can reduce the need for insecticides (Cavanagh et al, unpublished data) (Boucher & Durgy, 2004), and indicate that buttercup squash would be a suitable replacement for growers looking for a trap crop that is more marketable than Blue Hubbard. Having the option of using a more marketable variety of squash should provide additional incentive for growers to use PTC for beetle control in their butternut squash crops. In addition, the preference trials suggest the potential for buttercup squash as a trap crop to reduce insecticide use in some *C. pepo* squash, though further studies are needed to test this hypothesis.

Fig. 2.1 Beetle numbers by species in preference trials. Means with the same letter are not significantly different. Error bars represent standard error.

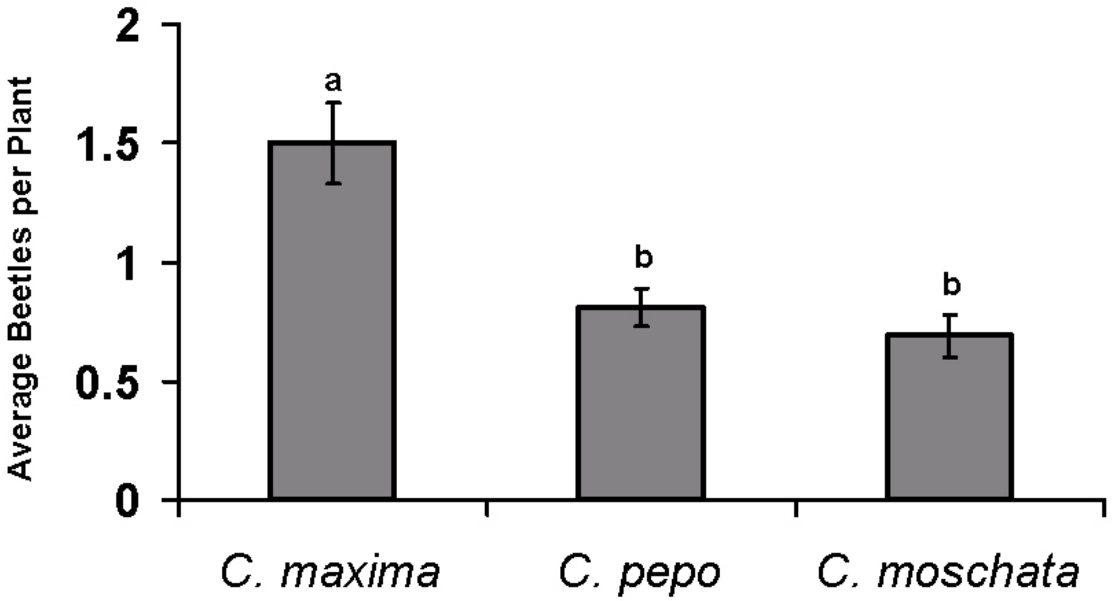


Fig. 2.2 Defoliation by species in preference trials. Means with the same letter are not significantly different. Error bars represent standard error.

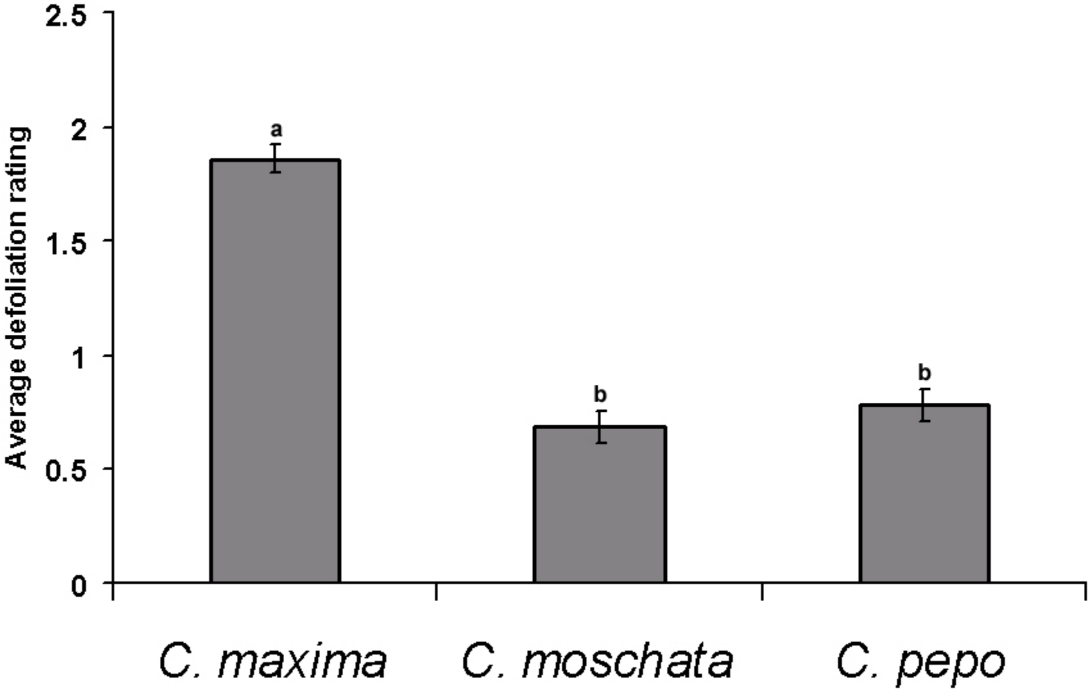


Fig. 2.3 Beetle numbers by variety in preference trials. Species are grouped by color. Error bars represent standard error.

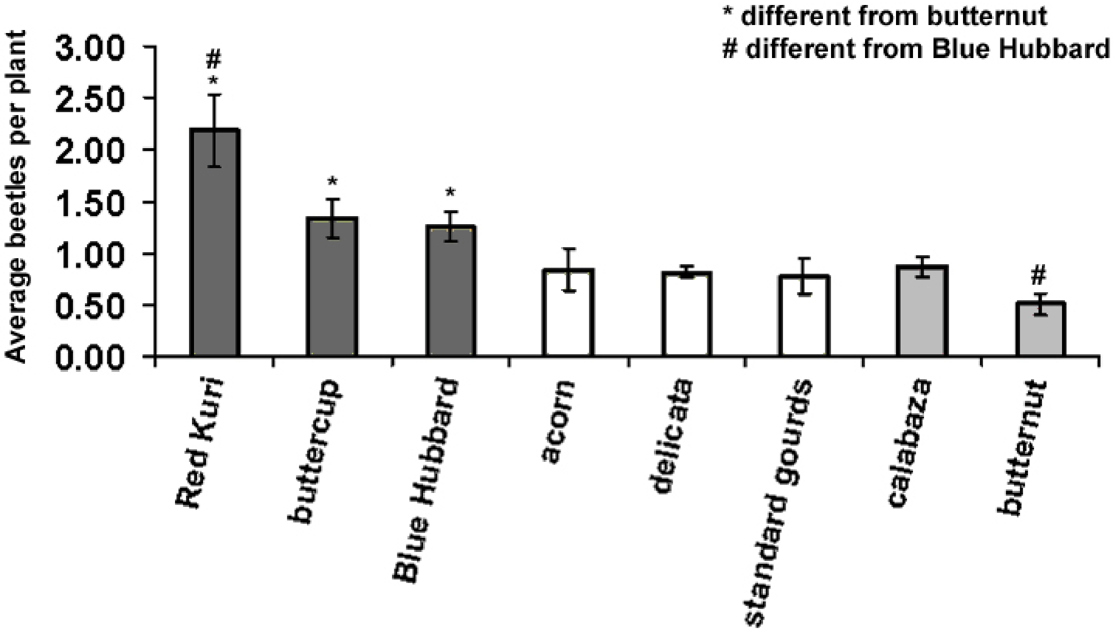


Fig. 2.4 Defoliation by variety in preference trials. Species are grouped by color. Error bars represent standard error.

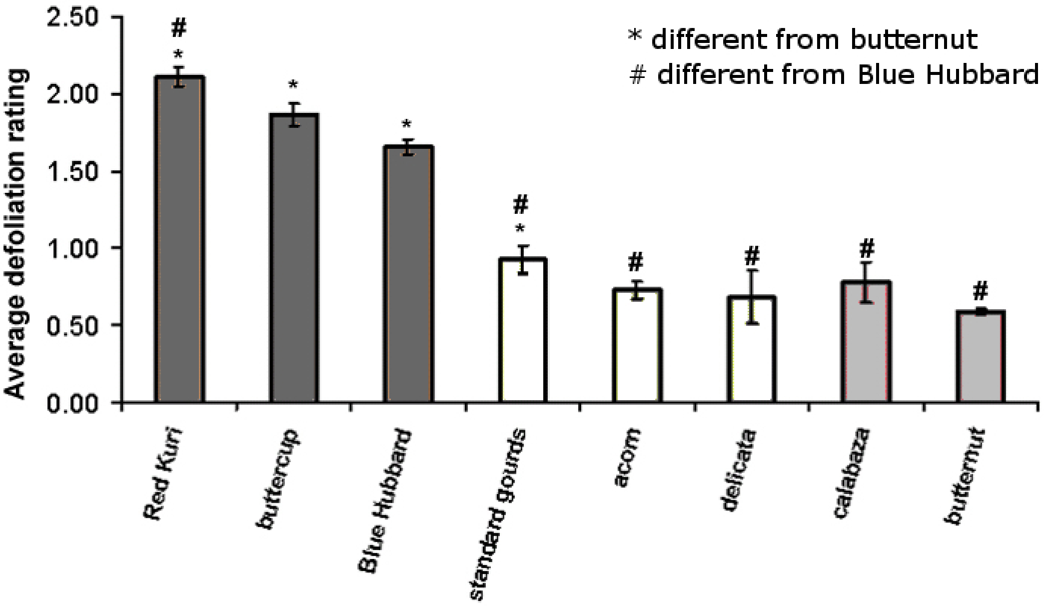


Fig. 2.5 Beetle numbers in the borders and main crops of PTC and conventional fields in 2006. Means with the same letter are not significantly different. Error bars represent standard error.

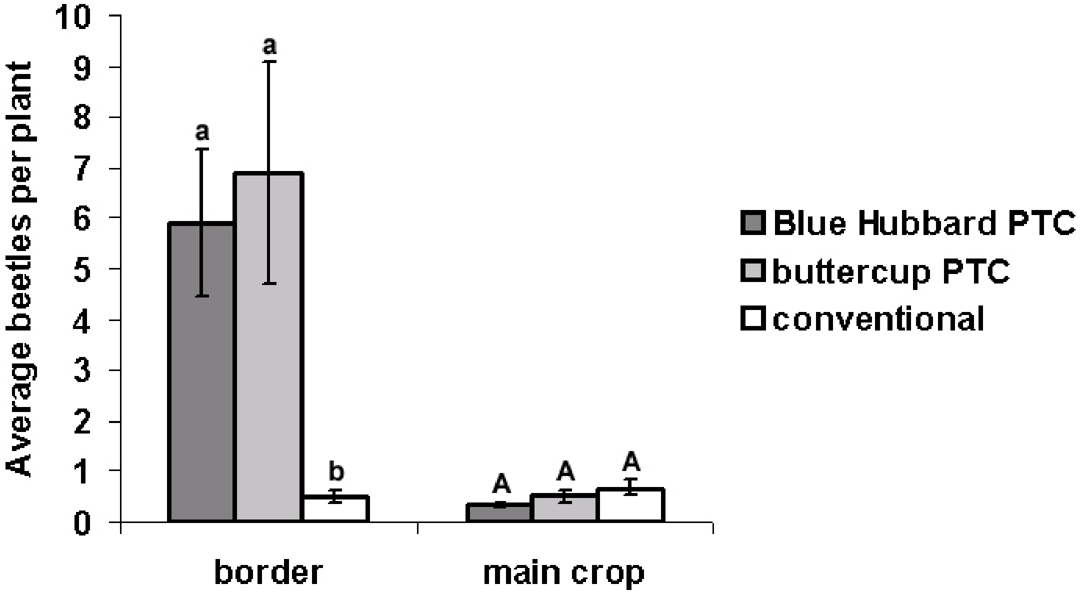
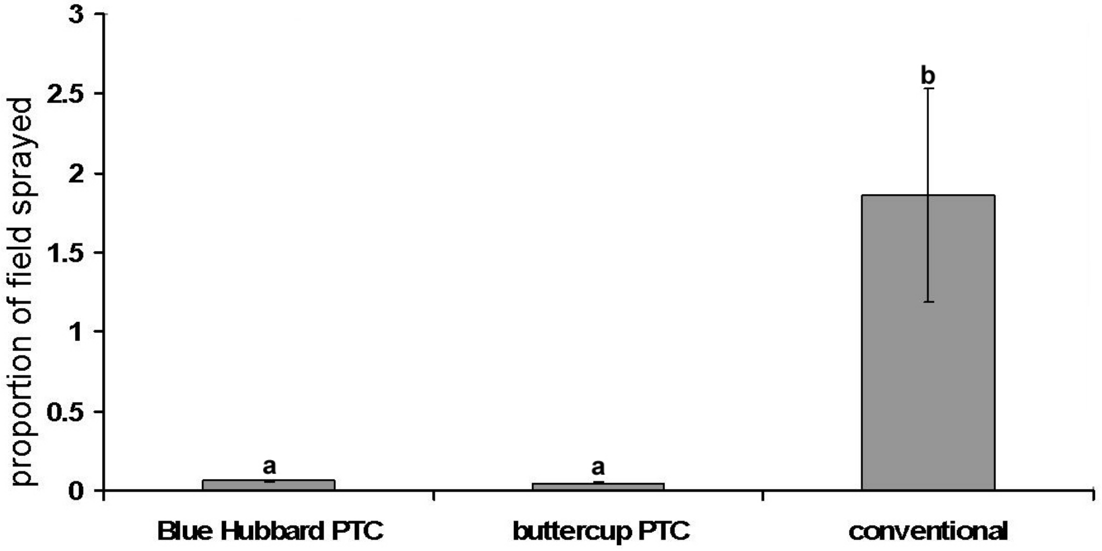


Fig. 2.6 Total proportion of experimental fields requiring treatment for beetle control in 2006. Means with the same letter are not significantly different. Error bars represent standard error. Multiple insecticide applications to individual fields resulted in proportions greater than one.



BIBLIOGRAPHY

Aluja, M., Jimenez, A., Camino, M., Pinero, J., & Aldana, L. (1997). Habitat manipulation to reduce papaya fruit fly (diptera : Tephritidae) damage: Orchard design, use of trap crops and border trapping. J. Econ. Entomol., 90(6), 1567.

Andersen, J. F., & Metcalf, R. L. (1987). Factors influencing distribution of diabrotica spp. in blossoms of cultivated cucurbita spp. Journal of Chemical Ecology, 13(4), 681.

Baker, M. B., Alyokhin, A., Porter, A. H., Ferro, D. N., Dastur, S. R., & Galal, N. (2007). Persistence and inheritance of costs of resistance to imidacloprid in colorado potato beetle. J. Econ. Entomol., 100(6), 1871-1879.

Boucher, T. J., Ashley, R., Durgy, R., Sciabarrasi, M., & Calderwood, W. (2003). Managing the pepper maggot (diptera : Tephritidae) using perimeter trap cropping. J. Econ. Entomol., 96(2), 420-432.

Boucher, T. J., & Durgy, R. (2004). Demonstrating a perimeter trap crop approach to pest management on summer squash in new england. Journal of Extension, 42(5) Retrieved from http://www.joe.org/joe/2004october/rb2.shtml

Brust, G. E. (1997). Differential susceptibility of pumpkins to bacterial wilt related to plant growth stage and cultivar. Crop Prot., 16(5), 411-414.

Brust, G. E., & Foster, R. E. (1995). Semiochemical-based toxic baits for control of striped cucumber beetle (coleoptera, chrysomelidae) in cantaloupe. J. Econ. Entomol., 88(1), 112-116.

Brust, G. E., & Foster, R. E. (1999). New economic threshold for striped cucumber beetle (coleoptera : Chrysomelidae) in cantaloupe in the midwest. J. Econ. Entomol., 92(4), 936-940.

Brust, G. E., & Rane, K. K. (1995). Differential occurrence of bacterial wilt in muskmelon due to preferential striped cucumber beetle feeding. HortScience, 30(5), 1043-1045.

Burkness, E. C., & Hutchison, W. D. (1998). Action thresholds for striped cucumber beetle (coleoptera: Chrysomelidae) on ‘Carolina’cucumber. Crop Protection, 17(4), 331.

Chambliss, O. L., & Jones, C. M. (1966). Cucurbitacins: Specific insect attractants in cucurbitaceae. Science, 153(3742), 1392.

Çilgi, T., & Jepson, P. C. (1992). The use of tracers to estimate the exposure of beneficial insects to direct pesticide spraying in cereals. Annals of Applied Biology, 121(2), 239-247.

Clifton, N. (2007). New england winter squash crop profile. New England Pest Management Network.

Collins, W. W., & Qualset, C. O. (1998). Uses of beneficial insect diversity in agroecosystem management. Biodiversity in agroecosystems (pp. 50) CRC Press.

Ehler, L. E., & Bottrell, D. G. (2000). The illusion of integrated pest management. Issues in Science and Technology, 16(3), 61.

Fleischer, S. J., de Mackiewicz, D., Gildow, F. E., & Lukezic, F. L. (1999). Serological estimates of the seasonal dynamics of erwinia tracheiphila in acalymma vittata (coleoptera : Chrysomelidae). Environ. Entomol., 28(3), 470.

Hazzard, R. V. (2003). Admire for striped cucumber beetle control. Proceedings of the New York State Vegetable Conference, 187-190.

Hoffmann, M. P., Ayyappath, R., & Kirkwyland, J. J. (2000). Yield response of pumpkin and winter squash to simulated cucumber beetle (coleoptera : Chrysomelidae) feeding injury. J. Econ. Entomol., 93(1), 136-140.

Hokkanen, H. M. T. (1991). Trap cropping in pest-management. Annu. Rev. Entomol., 36, 119-138.

Hollingsworth, C., Mordhurst, C. A., Hazzard, R., & Howell, J. (1998). Pumpkin & winter squash project:1998 grower survey and ICM project goals.

Howell, J. (Ed.). (2008). New england vegetable management guide. Amherst, MA: New England Extension Systems, University of Massachusetts.

Ives, A. R., & Andow, D. A. (2002). Evolution of resistance to bt crops: Directional selection in structured environments. Ecology Letters, 5(6), 792-801.

Lewis, W. J., van Lenteren, J. C., Phatak, S. C., & Tumlinson, J. H.,III. (1997). A total system approach to sustainable pest management. Proc. Natl. Acad. Sci., 94(23), 12243-12248.

Liu, Y. B., & Tabashnik, B. E. (1997). Experimental evidence that refuges delay insect adaptation to bacillus thuringiensis. Proc. R. Soc. of Lond. Biol., 264(1381), 605-610.

Maus, C., Cure, G., & Schmuck, R. (2007). Safety of imidacloprid seed dressings to honey bees: A comprehensive overview and compilation of the current state of knowledge. Bulletin of Insectology, 56(1), 51.

McGrath, M. T. (2004). Diseases of cucurbits and their management. In S. A. Naqvi (Ed.), Diseases of fruits and vegetable: Diagnosis and management (pp. 455). New York: Springer-Verlag New York, LLC.

McGrath, M. T., & Shishkoff, N. (2000). Comparison of cucurbit crop types and cultivars for their attractiveness to cucumber beetles and susceptibility to bacterial wilt. Biological and Cultural Tests 15:154 .

Metcalf, R. L., Metcalf, R. A., & Rhodes, A. M. (1980). Cucurbitacins as kairomones for diabroticite beetles. Proceedings of the National Academy of Sciences of the United States of America, 77(7), 3769.

Mitchell, E. R., Guangye, H., & Johanowicz, D. (2000). Management of diamondback moth (lepidoptera : Plutellidae) in cabbage using collard as a trap crop. HortScience, 35(5), 875.

NE Vegetable IPM Working Group. IPM priorities for vegetables in the northeast. Retrieved 2/7/2008, from http://northeastipm.org/work_vegepriority.cfm

Olson, E. R., Dively, G. P., & Nelson, J. O. (April 2000). Baseline susceptibility to imidacloprid and cross resistance patterns in colorado potato beetle (coleoptera: Chrysomelidae) populations. J. Econ. Entomol., 93, 447-458(12).

Pair, S. D. (1997). Evaluation of systemically treated squash trap plants and attracticidal baits for early-season control of striped and spotted cucumber beetles (coleoptera: Chrysomelidae) and squash bug (hemiptera: Coreidae) in cucurbit crops. J. Econ. Entomol., 90(5), 1307-1314.

Paris, H. S. (1989). Historical records, origins, and development of the edible cultivar groups of cucurbita pepo (CUCURBITACEA). Economic Botany, 43(4), 423.

SAS-Institute. (2004). Base SAS 9.1 procedures guide, vol 1-4. Cary, NC: SAS Publishing.

Shelton, A. M., & Badenes-Perez, F. R. (2006). Concepts and Applications of Trap Cropping in Pest Management. Annu. Rev. Entomol., 51(1), 285-308.

Smyth, R. S., Tallamy, D. W., Renwick, A. A., & Hoffman, M. P. (2002). Effects of age, sex, and dietary history on response to cucurbitacin in acalymma vittatum. Entomologia Experimentalis Et Applicata, 104(1), 69.

Stivers, L., editor. (1999). Crop profile for squash in New York. Retrieved May 26, 2008, from http://www.ipmcenters.org/cropprofiles/docs/nysquash.html

Tang, J. D., Collins, H. L., Metz, T. D., Earle, E. D., Zhao, J. Z., Roush, R. T., et al. (2001). Greenhouse tests on resistance management of Bt transgenic plants using refuge strategies. J. Econ. Entomol., 94(1), 240-247.

Yao, C. B., Zehnder, G., Bauske, E., & Klopper, J. (1996). Relationship between cucumber beetle (coleoptera: Chrysomelidae) density and incidence of bacterial wilt of cucurbits. J. Econ. Entomol., 89(2), 510-514.

Zhao, J., Bishop, B. A., & Grafius, E. J. (October 2000). Inheritance and synergism of resistance to imidacloprid in the colorado potato beetle (coleoptera: Chrysomelidae). J. Econ. Entomol., 93, 1508-1514(7).