INTEGRATED MANAGEMENT OF KEY PESTS IN CORN-POTATO SYSTEMS: VOLUNTEER POTATO AND COLORADO POTATO BEETLE

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ABSTRACT

Colorado potato beetle (*Leptinotarsa decemlineata* (Say), CPB) and volunteer potatoes (*Solanum tuberosum* L.) are detrimental pests in potato producing regions. Warming winter temperatures has increased the likelihood of volunteer potato survival, an early season food source for CPB. Therefore, field experiments were conducted in 2023 and 2024 to evaluate integrated management strategies of these key pests. Experiments included: (1) management of volunteer potatoes and CPB in corn rotations using tillage and tank-mixed herbicides-insecticides, and (2) planting delayed potato trap crops to manage second generation CPB. In volunteer potato studies, reduced intensity tillage reduced volunteer emergence by 80% compared to high intensity tillage, due to increased exposure of volunteers to lethal winter temperatures. Late season volunteer control was greatest with mesotrione, which reduced the number and weight of daughter tubers by 55-78% and 80-88%, respectively, in the moldboard plow tillage system. Insecticide tank mixes reduced CPB density on volunteers and decreased defoliation of volunteers throughout the season. Corn injury was less than 5% across all tank-mixed herbicide-insecticide treatments. In the trap crop study, delaying potato trap crop planting by 2 wks resulted in increased CPB density by at least 57% or greater relative to the 0 wk treatment. Trap crop treatments did not reduce the rate of defoliation in the potato crops planted next to the trap crops, resulting in no difference in yield. However, results from this study demonstrate that delaying potato trap crop planting can alter CPB infestation of field edges providing an opportunity for localized management with foliar insecticide applications. Overall, this research investigated multiple integrated management approaches to control these key pests in corn and potato rotations.

Dedicated to Jo Johnson

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CHAPTER I: LITERATURE REVIEW

Volunteer Potatoes

Volunteer potatoes (*Solanum tuberosum* L.) are a problematic weed resulting from potatoes left in the field after the prior season's harvest. In regions with mild winter temperatures, tubers can survive overwinter and emerge the following spring as a weed in the subsequent crop. Volunteer potatoes are highly competitive with rotational crops, causing significant yield loss if unmanaged (Boydston 2001; Boydston and Seymour 2002; Lutman 1977b). Volunteers compete for light, nutrients, and water thus reducing the resources available to rotational crops. Furthermore, volunteer plants produce daughter tubers which can persist in the soil and prolong volunteer issues for several years following a potato crop (Boydston et al. 2008). As a result, future rotations to potatoes are negatively impacted through undesired mixing of varieties. Many of the positive effects of crop rotation may be lost if these volunteers are allowed to persist in a field (Boydston 2001).

Volunteer-Pest Complex

In addition to increasing competition with rotational crops, volunteer potatoes can harbor detrimental pests including insects, diseases, and nematodes (Ellis 1992; Thomas 1983; Wright and Bishop 1981). Potato production is threatened annually by many pests that cause significant economic damage. Volunteer potatoes further exacerbate these problems by supporting the survival of these pests.

Colorado potato beetle *(Leptinotarsa decemlineata* (Say), CPB) is a major defoliator of potatoes worldwide, causing substantial yield loss and decreased crop competitiveness (Williams et al. 2004). Volunteer potatoes are an early season food source for CPB. In a study in eastern Washington, Xu and Long (1997) evaluated volunteers, cultivated potatoes, and hairy nightshade

(*Solanum physalifolium* Rusby) as food sources for CPB throughout the growing season. They reported that volunteer potatoes were the earliest host of CPB due to earlier emergence of volunteers compared to cultivated potato crops.

Late blight of potato (*Phytophthora infestans* (Mont.) de Bary) is a historically devastating disease to potato production. Late blight causes substantial economic loss to U.S. potato production through high costs of management and crop loss from disease epidemics (Guenthner et al. 2001). *Phytophthora infestans* can survive between growing seasons on infected potato tubers (Fry and Goodwin 1997; Zwankhuizen et al. 1998). Therefore, volunteers are a potential source of inoculum for epidemics of late blight. Through providing CPB with an early season food source and facilitating the overwinter survival of diseases such as late blight, these volunteers can increase the pressure of economically damaging pests of potato.

Freezing Dynamics

Winter soil temperatures influence the survival of volunteer potatoes since tubers are susceptible to cold temperatures (Boydston et al. 2006). In laboratory experiments, the freezing point of potato tubers was reported between -1.4 to -1.5 C in dry soil columns and -1.9 C in hydrated (7% soil water content) soil columns. Furthermore, the effect of low temperatures on tuber mortality will depend on exposure time. As exposure time to cold temperatures increases, tuber injury increases. However, tuber mortality will occur in the soil when minimum temperatures reach -2.0 C even for brief periods of time. Overall, the freezing dynamics of potatoes in the field will depend on soil temperature, exposure time, soil water content, and tuber burial depth. Therefore, in regions where winter soil temperatures remain mild, increased volunteer survival can occur.

Volunteer Management in Corn

Corn (*Zea mays* L.) is a commonly grown rotational crop with potatoes (Boydston 2001). Volunteer potato management in field corn is a significant problem when winter soil temperatures are not low enough to cause tuber mortality (Boydston et al. 2006). When volunteer potatoes are left unmanaged, they can reduce corn yields by 23-62% (Boydston 2004). Effectively managing volunteer potatoes is difficult due to their ability to reemerge after management and produce daughter tubers that persist in the soil (Boydston et al. 2008; Williams and Boydston 2002). Corn is a commonly used rotational crop following potatoes because it provides growers with cultivation and numerous herbicide options for weed and volunteer control (Boydston 2001). Tillage practices and herbicide applications are two key tools for managing volunteer potatoes in corn to mitigate yield loss from competition and reduce the persistence of volunteer issues in the field.

Management via Tillage

The depth at which tubers are buried in the soil from tillage practices will influence tuber mortality through freezing. For example, tubers at shallow burial depths are more likely to be subjected to lethal cold temperatures than tubers buried at deeper depths (Boydston et al. 2006). Research comparing tuber mortality at burial depths between 5 and 20 cm reported that at 20 cm over 90% of tubers germinated in five of 6 years. Conversely, few or no tubers survived when buried at the 5 cm depth due to soil temperatures falling below 0 C at this burial depth. Therefore, shallow tillage practices can increase the likelihood that tubers are exposed to lethal winter temperatures. However, the minimum soil temperatures throughout the soil profile will be influenced by snow cover thickness, residue cover, and soil moisture content (Boydston et al. 2006).

In addition to tillage depth, the timing of tillage practices can influence the distribution of tubers within the soil and the potential exposure to lethal temperatures. Volunteer potato control was increased by delaying tillage until midwinter to expose additional tubers to lethal temperatures near the soil surface (Thomas and Smith 1983). Additionally, spring tillage practices reduced volunteer emergence compared to fall tillage because tubers were not buried deeper in the soil profile.

However, in potato-producing regions where shallow soil temperatures remain high throughout the winter, alternative management strategies are needed. The use of tillage as a management tool for volunteer potatoes must be re-evaluated in these regions. The depth of tuber burial through tillage will influence the time of shoot emergence in the spring (Lutman 1977a). Tubers buried deeper in the soil profile will emerge later in the spring than shallow buried volunteer potatoes. Additionally, potato tubers have carbohydrate reserves that are exhausted by the production of stems and resprouting (Williams and Boydston 2002). This indicates that volunteer potatoes buried deeper in the soil will exhaust more reserves than shallow buried tubers to produce stems that reach the soil surface. Potato tubers with decreased vigor are more effectively controlled by herbicide applications (Lutman 1977b). Therefore, there is potential that deeper tillage practices will increase the effectiveness of herbicide applications on volunteer potatoes by decreasing the vigor of this weed.

Management with Herbicides

Volunteer potato management using herbicides can be difficult because of resprouting and daughter tuber production, even after aboveground growth is suppressed through postemergence herbicide applications (Boydston et al. 2008). Additionally, the late and staggered emergence of volunteer potatoes makes timing herbicide applications difficult (Lutman 1977a;

Rahman 1980). For a herbicide to effectively manage volunteer potatoes, it must control aboveground growth and limit daughter tuber production to ensure the volunteer problem does not persist.

Various herbicides have been evaluated for their use in effectively managing volunteer potatoes. Applications of glyphosate can kill aboveground shoots but often fail to reduce tuber production (Boydston 2001). Boydston and Williams (2005) evaluated the use of mesotrione, carfentrazone-ethyl, fluroxypyr, dicamba, and mixes of these herbicides to manage volunteer potatoes when applied at various timings. This study reported that mesotrione reduced tuber production and tuber weight more than each of the other herbicide treatments, and control was increased when applications were made at or near the time of volunteer tuber initiation.

Several 4-hydroxyphenyl pyruvate dioxygenase (HPPD) inhibiting herbicides have been evaluated for volunteer potato control (Koepke-Hill et al. 2010). Volunteer potato control was compared between HPPD inhibiting herbicides including mesotrione, topramezone, and tembotrione, with and without the addition of photosystem-II (PSII) inhibiting herbicides including atrazaine, bentazon, or bromoxynil. Mesotrione combined with PSII inhibitors increased initial control 2 weeks after application, however, few differences were observed 6 weeks after treatment. The addition of atrazine to mesotrione and topramezone can effectively reduce daughter tuber production (Burns and Long 2020). Additionally, herbicide applications were more effective when volunteer potatoes were small (less than 15 cm) compared to medium (15-50 cm) or tall (greater than 50 cm) plants. Therefore, comparing the results across these studies highlights the potential for HPPD-inhibiting herbicides to be used in combination with PSII-inhibiting herbicides to control volunteer potatoes and reduce daughter tuber production.

Colorado Potato Beetle

CPB is a notorious pest of potato production worldwide. It is considered the most important insect defoliator of potatoes (Alyokhin 2009). Entire potato crops can be destroyed through CPB feeding on plant canopies causing yield loss. This pest is challenging to manage and causes significant economic loss annually, warranting the need for the development of additional management strategies.

Yield loss in defoliated canopies results from decreased light interception (Ziems et al. 2006). The level of yield loss from CPB defoliation varies with potato variety, defoliation severity, and defoliation timing (Zehnder and Evanylo 1989; Ziems et al. 2006). Previous research evaluating the effect of defoliation timing on yield has found that potato plants are impacted more by defoliation at full bloom compared to defoliation at tuber initiation and maturity (Cranshaw and Radcliffe 1980; Dripps and Smilowitz 1989; Hare 1980; Senanayake et al. 1993; Senanayakei and Holliday 1990; Shields and Wyman 1984; Wellik et al. 1981; Zehnder and Evanylo 1989). However, the level of yield loss reported across this research differs greatly depending on the growing region, environment, and variety.

The negative impact this pest has on the potato industry is intensified by high levels of insecticide-resistant populations (Alyokhin et al. 2008). CPB is known to have developed resistance to all major classes of insecticides (over 50 compounds) used for control in commercial production (Alyokhin et al. 2008; Grafius 1997). Widespread insecticide-resistant CPB populations have resulted from high selection pressure and this species' natural ability to adapt to toxic substances (Alyokhin et al. 2008).

Neonicotinoid insecticides, such as imidacloprid and thiamethoxam, were released for commercial use in 1995 and were rapidly adopted for CPB control due to a lack of other effective chemical control options at the time (Alyokhin et al. 2008; Szendrei et al. 2012). While neonicotinoids are fundamental for CPB control, insecticides from other chemical families including benzoylureas, diamides, and spinosyns are alternative for controlling CPB in potatoes. Szendrei at al. (2012) analyzed the status of CPB resistance to imidacloprid and thiamethoxam, which are the two main neonicotinoid insecticides used in commercial potato production. This research found CPB resistance to have increased to both products since 1988, and that resistance levels were higher in summer generation adults than overwintered adults. This is potentially due to decreased fitness from a loss of fat reserves in overwintering adults or exposure to sublethal doses of insecticides in potato plants, which may increase the rate of resistance development (Gressel 2011; Szendrei et al. 2012). This finding highlights the need for resistance levels and lifecycle stage of CPB to be considered when developing management strategies. Overall, insecticide resistance in this pest is cause for concern about the future of sustainable potato production.

CPB Biology

Developing CPB management strategies requires understanding of the lifecycle and behavior of this pest. The lifecycle of CPB includes an egg stage, four larval stages, pupal stages and an adult stage (Maharijaya and Vosman 2015). Timing of lifecycle events such as emergence, mating, and plant colonization are dependent on the accumulation of degree days (DD). CPB overwinter as adults and emerge in the spring in response to temperatures above 10 C and typically are visible on the soil surface after an accumulation of 50-250 DD > 10 C (Ferro et al. 1999; de Kort 1990). Once overwintering adults emerge, they begin to mate, feed, and lay eggs. Oviposition can occur after an accumulation of 51-80 DD (Ferro et al. 1999). Eggs will hatch after 4-12 days depending on temperatures (Tauber et al. 1988). Developing larva will then feed on potato foliage, with the most severe defoliation occurring when larva reach the third and fourth instar stages (Ferro et al. 1985). Once fourth stage instars are done feeding, they pupate in the soil and adults emerge 5-7 days later (Tauber et al. 1988).

Adults may produce up to three generations per year depending on environmental conditions of the growing region (Ferro et al. 1985). It has been reported that 300–400 DD over 10 C are required for complete development of one CPB generation (Alyokhin and Ferro 1999). Emergence of the subsequent generations of CPB in a season is not synchronous (Hiiesaar et al. 2013). This prolonged emergence makes control summer generation CPB difficult. In Michigan, a summer generation of CPB is observed each year, which contributes to the economic damage caused by this pest. Management strategies must include control of second generation CPB to help growers mitigate losses throughout the entire growing season.

Understanding the dispersal and movement of CPB is another key to effective management. In the spring, emerged beetles colonize plants by flying or walking (Voss and Ferro 1990). Walking is common for short distance dispersal to nearby potato fields. Lack of food sources nearby encourages CPB flight once flight muscles have developed through an accumulation of 150-200 DD (Caprio and Grafius 1990; Ferro et al. 1991; Yang 1994). Long distance flight is possible by overwintering adults to colonize new fields (Voss and Ferro 1990). However, summer generation adults may not fly due to lack of complete development (de Kort 1990; Voss and Ferro 1990). Crop damage is first observed on field edges as CPB move into fields from overwintering sites. Management practices often focus on field edges to target early season plant colonization.

Potato Trap Crops

As a result of increased CPB pressure and resistance, growers are interested in developing integrated pest management strategies. These strategies would include the use of cultural management practices that can be implemented to exploit the lifecycle and spatial behavior of beetles as they overwinter and move into potato crops. Cultural practices can be combined with chemical control to provide additional management of problematic pests such as CPB.

Particularly of interest is the use of potato trap crops. Trap crops are grown to attract pest populations away from the primary crop so that management can occur before pests cause economic damage to primary crops. Field research trials completed by Hoy et al. (2000) examined the use of spring planted potato trap crops to enhance and maintain the concentration of adult beetles at field edges to increase the efficiency of control. These field studies assessed the use of various types of barriers as trap crops as well as different planting timings of potato trap crops. While this research did not find that trap crops provide a significant advantage over treating field edges, it demonstrated that planting date would affect the pattern of beetle infestation. Furthermore, this research highlighted the potential for increased efficiency of insecticide applications to field edges based on the timing of plant colonization by overwintering CBP. Additionally, these results show the potential of using systemic insecticides such as imidacloprid, which can be applied as a seed treatment, to kill beetles before they leave field edges.

Further research has evaluated how trap crops can be used as a tool to decrease frequency and volume of insecticide applications (Martel et al. 2005). In this study, field trials were conducted to evaluate if applications of synthetic host volatile blends would attract CPB to trap crops and reduce the number of insecticide applications needed in primary crop plantings. Insecticide application need was based on established economic threshold densities of CPB and made to both trap crop and primary crop plots individually when thresholds were crossed. This study evaluated the total insecticide volume needed in plots that included a trap crop with a primary crop compared to conventionally managed plots with no trap crops surrounding them. Insecticide input was reduced by 44% in trap crop with primary crop plantings compared to conventionally managed crops. When CPB were concentrated in trap crops, insecticide applications could be made to localized regions thus reducing the need for applications to primary crops. This increased application efficiency could be an opportunity for growers to decrease management costs.

Previous research on CPB management through trap cropping strategies has focused on early planted trap crops. This research has highlighted the potential to increase the efficiency of insecticide applications when CPB are concentrated. Planting trap crops around field edges exploits CPB spatial habits of walking from overwintering sites to potato crops. However, no research has examined the use of potato trap crops to manage summer generation CPB.

Climate Change

Since winter survival of volunteer potatoes and the lifecycle of CPB are both dictated by temperature, changing environmental conditions will continue to affect the abundance of these pests in Michigan. The Great Lakes Integrated Sciences and Assessments Program (2019) has reported an increase in the annual average temperatures of 1.1 C since 1900 in the Great Lakes region and projects an increase of 1 to 3 C by 2050. Additionally, from 1958 to 2012 the frost-free period in the Midwest has lengthened by 9 days. As a result, volunteer potatoes and CPB may become more problematic in potato producing regions in the future. Lack of harsh winter temperatures that cause tuber mortality, may increase volunteer survival. Lengthening growing seasons and increasing accumulation of degree days may affect CPB development and pressure (Smatas et al. 2008). Overall, the observed and predicted environmental changes in the Great Lakes region demonstrate the need for additional management tools of these key pests of potato production.

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CHAPTER II: INTEGRATED MANAGEMENT OF VOLUNTEER POTATO AND COLORADO POTATO BEETLE IN CORN

Abstract

Volunteer potatoes (*Solanum tuberosum* L.) are a problematic weed in rotational crops and are a host for Colorado potato beetle (*Leptinotarsa decemlineata* (Say), CPB), a major pest of potato production. Three studies were conducted in Michigan to evaluate integrated management of volunteer potatoes and CPB in field corn (*Zea mays* L.) using tillage intensity and herbicide-insecticide combinations. Experiments included a fall planted volunteer potato study conducted at three site-years, a spring planted volunteer potato study conducted at two site-years, and a greenhouse study. In one fall study site-year, disk tillage reduced volunteer potato emergence by 80% compared to moldboard plow, due to increased exposure of tubers to harsh winter temperatures. In the spring study when winter temperatures were not a factor, deeper tuber burial with the moldboard plow reduced volunteer emergence by 53% in one site-year. In the fall planted study, treatments including mesotrione provided the greatest level of control, reducing volunteer growth by 53-65% in the moldboard plow tillage system and by 80-100% in the disk tillage system 21 d after application. In the fall study, Chlorantraniliprole and spinetoram insecticide treatments reduced CPB density on volunteers by more than 80% relative to untreated controls and reduced defoliation of volunteers by CPB in the plow system where CPB pressure was high. Treatments including mesotrione reduced the number and weight of daughter tubers by 55-78% and 80-88%, respectively, in the plow treatment. Across all three studies and site-years, herbicide-insecticide treatments resulted in less than 5% corn injury. This integrated approach can be utilized to reduce volunteer emergence and manage both CPB and volunteer potatoes without injuring corn.

Introduction

Michigan is a major contributor to the U.S. potato (*Solanum tuberosum* L.) industry. In 2023, potatoes were planted on over 20 thousand hectares in Michigan which produced 900,000 MT of potatoes (USDA-NASS 2024). Potato production is threatened annually by numerous pests including insects, diseases, nematodes, and weeds that can cause significant crop loss. One method to reduce the buildup of pest pressure in potato fields is crop rotation. In Michigan, field corn (*Zea mays* L.) is an important agricultural crop and is a common rotational crop with potatoes. Planting field corn following potatoes provides producers with rotational benefits in addition to tillage and diversifying herbicide options for weed control.

Volunteer potatoes are a problematic weed in rotational crops when tubers left in the field after harvest survive the winter. Historically, harsh winter temperatures can kill tubers in the soil (Boydston et al. 2006). However, in regions with warming winter temperatures, increased volunteer survival can occur. Due to projected increases in annual temperatures and lengthening frost-free period in the Great Lakes region (Great Lakes Integrated Sciences and Assessments Program 2019), volunteer potato survival over the winter is of increasing concern in Michigan. This warming winter trend has already been observed in Michigan, leading to increased volunteer potato abundance in potato producing regions throughout the state. Therefore, effective management of volunteer potatoes in rotational crops is a priority across regions experiencing mild winter conditions. Furthermore, volunteer potatoes are highly competitive and difficult to manage. Volunteer potato competition with rotational crops can cause high levels of yield loss (Boydston 2004; Boydston and Seymour 2002; Williams and Boydston 2006). In corn rotations, yield losses ranging from 23-62% were reported when volunteer potatoes were left unmanaged (Boydston 2004). In addition to aboveground foliage, volunteer potatoes produce daughter tubers which persist in the soil and may prolong volunteer issues for multiple years following a potato crop (Lutman 1974). Effective management of volunteer potatoes requires control of both aboveground foliage and daughter tubers.

Moreover, volunteer potatoes serve as a host for numerous economically damaging pests of potatoes including insects, diseases, and nematodes (Ellis 1992; Thomas 1983; Wright and Bishop 1981). Most notably, volunteer potatoes are a host for the Colorado potato beetle (*Leptinotarsa decemlineata* (Say), CPB), which is considered the most important insect defoliator of potatoes (Alyokhin 2009). Research by Xu & Long (1997) reported that CPB feed on volunteer potatoes early in the growing season due to the earlier emergence of volunteer potatoes relative to cultivated potato crops. Once volunteer plants have been completely defoliated, CPB move into nearby potato fields causing substantial crop loss. Additionally, volunteer potatoes can be an inoculum source for late blight (*Phytophthora infestans* (Mont.) de Bary) of potato because this pathogen can survive over the winter on infected tubers (Fry and Goodwin 1997; Kirk 2003; Zwankhuizen et al. 1998).

Several aspects of volunteer biology make this weed difficult to manage. First, volunteer potatoes can emerge over a long period depending on tuber burial depth, tuber size, environmental conditions, and the rotational crop (Lutman 1974). Additionally, since potato tubers are a vegetative storage organ that contains carbohydrate reserves, volunteer potatoes can continually produce stems and resprout throughout the growing season. Tubers can regrow stems following physical shoot removal (Williams and Boydston 2002) and applications of several postemergence herbicides (Boydston 2001, 2004; Boydston et al. 2008). Given this, preventing daughter tuber production is challenging.

Tillage practices are an important aspect of volunteer management. The type and depth of tillage utilized will affect the distribution of tubers within the soil, which in turn will influence the exposure of tubers to lethal temperatures. In field trials comparing tuber mortality at various burial depths, Boydston et al. (2006) found that shallow burial depth increased the likelihood thattubers were exposed to lethal cold temperatures. Tillage practices that expose the greatest number of tubers to lethal temperatures has been found to provide the greatest level of control (Boydston et al. 2006; Thomas and Smith 1983). However, warming winter temperatures warrants the need for alternative management strategies that do not rely on unpredictable winter conditions. Since tuber carbohydrate reserves are depleted by the production of stems and resprouting, volunteer potatoes buried deeper in the soil profile will potentially exhaust more reserves to produce stems that can reach the soil surface.

Several postemergence herbicides can be applied in field corn to control volunteer potatoes, but few effectively prevent stem regrowth and reduce daughter tuber production. Additionally, the effectiveness of herbicide applications has been shown to vary based on volunteer growth stage at the time of application (Boydston 2001; Boydston and Williams 2005). Boydston and Williams (2005) reported increased control of volunteer potatoes using the herbicide mesotrione which reduced the number of new tubers produced compared with fluroxypyr and dicamba. Additionally, studies have shown effective control with other 4-hydroxyphenyl pyruvate dioxygenase (HPPD) inhibiting herbicides such as topramezone (Koepke-Hill et al. 2010). These herbicides currently are the most effective options for reducing daughter tuber production of volunteer potatoes in corn.

Management of CPB is typically focused on seed treatment and insecticide applications on cultivated potato crops. However, CPB feeding on volunteer potatoes early in the season is an opportunity for growers to manage populations and reduce pressure on potato fields later in the season. Previous research has not examined the use of insecticide applications made to volunteer potatoes. Tank mixing insecticides with herbicides could reduce the number of applications necessary to manage both pests. However, crop injury can result from interactions between some herbicides and insecticides that would not normally occur when applied alone. Crop damage to field corn has been reported to several herbicide-insecticide combinations (Biediger et al. 1992; Jewett et al. 2008; Kreuz and Fonné-Pfister 1992; Kwon and Penner 1995; Steckel et al. 2015). Cases include two HPPD-inhibiting herbicides. Jewett et al., (2008) reported 34% corn injury when mesotrione was applied postemergence following an at-plant application of terfubos and Steckel et al. (2015) reported 58% yield reduction when tembotrione was applied in combination with an in-furrow or foliar application of chlorpyrifos. Due to these known interactions, the safety of proposed herbicide-insecticide treatments must be evaluated for field corn.

Therefore, the overall goal of this study was to develop integrated management strategies targeting both CPB and volunteer potatoes in potato-corn rotations. Specific objectives were to: (1) investigate the impacts of tillage intensity on volunteer survival and emergence, (2) evaluate the effectiveness of herbicide-insecticide programs to simultaneously control volunteer potatoes and CPB in field corn, and (3) assess corn injury resulting from herbicide-insecticide tank-mixtures.

Methods and Materials

Experimental Design

Fall Study

Field studies were conducted at the Montcalm Research Center (MRC) near Lakeview, MI (43.352633ºN, -85.183146ºW), the Kellogg Biological Station (KBS) near Hickory Corners, MI (42.402020ºN, -85.377086ºW), and the Michigan State University (MSU) Agronomy farm in East Lansing, MI (42.6884144ºN, -84.4969238ºW) to investigate the impacts of fall tillage treatments on volunteer potato control. Previous crop rotations were potatoes at MRC, soybean at KBS, and alfalfa at MSU. All studies were arranged in a split-split plot randomized complete block design with four replications. Plot sizes were 3 m wide x 7.62 m long. The main plot factor was tillage type, the subplot factor was herbicide-insecticide application timing, and the sub-subplot factor was herbicide-insecticide treatment. Untreated controls were included in all studies.

In fall 2023 round white chip-processing potatoes were hand spread at a density of 16,500 tubers ha^{-1} to simulate volunteer potatoes. Fields were chisel plowed and then soil finished prior to spreading potatoes. Tillage treatments were then applied to incorporate potatoes. A disk was used for reduced intensity tillage, incorporating potatoes approximately 10 cm deep, and a two bottom moldboard plow was used for high intensity tillage, incorporating potatoes approximately 25 cm deep (Nyiraneza et al. 2024).

In spring 2024, pre-plant fertilizer was spread and incorporated using a soil finisher prior to planting corn. Corn hybrid P0035AM (Corteva Agriscience, Indianapolis, IN) was planted in 76 cm rows. Additional details on planting, fertilizer, and field operations are shown in Table 2.1.

Four different postemergence herbicide-insecticide treatments applied at two timings (Table 2.2). Application timings were made one week apart, when the average volunteer potato height was less than 15 cm tall (EARLY) and greater than 15 cm tall (LATE). Mesotrione and topramezone were each tank-mixed with spinetoram and chlorantraniliprole (Table 2.2). All pesticide applications were made with a CO_2 backpack sprayer outfitted with AIXR 11003 spray nozzles (TeeJet Technologies, Wheaton, IL), calibrated to deliver 178 L ha^{-1} spray volume at 206 kPa of pressure.

Spring Study

Field studies were conducted at the MRC near Lakeview, MI in 2023 (MRC-23) (43.3524914ºN, -85.1798407ºW) and 2024 (MRC-24) (43.3526221ºN, -85.1828978ºW) to investigate the impacts of spring tillage treatments on volunteer control. Previous crop rotation was potatoes in both site-years. Similar to the fall study, this experiment was set up in a in a split-split plot randomized complete block design with four replications. Field preparation, treatment factors (Table 2.2), and application methods were the same as in the fall planted volunteer experiment outlined above.

In spring 2023 and 2024, white chip potatoes were spread to simulate volunteer potatoes, followed immediately by application of tillage treatments. Pre-plant fertilizer was spread and incorporated using a soil finisher, followed by planting corn hybrid DKC47-55 (Bayer Crop Science, Saint Louis, MO). Details on planting, fertilizer, and field operations for the spring planted volunteer study are provided in Table 2.3.

Greenhouse Study

Greenhouse studies were conducted at MSU in East Lansing, MI in 2024 to investigate corn injury from herbicide-insecticide tank-mixtures when applied at various corn growth stages. The study followed a split plot randomized complete block design with four replications, repeated twice. The main plot factor was application timing, made at corn growth stages V1, V2, V3, and V4. Subplot factors included the same herbicides and insecticides examined in the fall and spring volunteer field studies, applied alone and in each combination (Table 2.4).

Corn plants, hybrid DKC44-97 (Bayer Crop Science, St Louis, MO), were grown in 9,464 cm^3 pots with a peat and perlite mixture (SureMix, Michigan Grower Products, Inc, Galesburg, MI). To reduce variability, planting was staggered so that treatments could be applied on the same day to all corn growth stages. Plants were watered daily. Greenhouse temperature was set to 27 C (diurnal range 25-29 C) and 16 h photoperiod. Spray applications were made using a Generation 4 DeVries Research Track Sprayer outfitted with an 8001EVS spray nozzle (TeeJet Technologies, Wheaton, IL) that was calibrated to deliver 187 L ha^{-1} spray volume at 207 kPa pressure.

Data Collection

Fall and Spring Studies

Volunteer potato emergence was assessed by counting the number of emerged volunteers in each plot at the EARLY application timing. Corn injury was evaluated at 7, 14, and 21 d after application (DAA) on a scale of 0 to 100% with 0 indicating no crop injury and 100 indicating complete crop death. To evaluate any lasting impacts of crop injury to corn ears, three ears were collected at the end of the season from each plot and assessed for visual injury symptoms including stunting, poor grain fill, and ear deformity.

Fall Study

Volunteer control was evaluated at 7, 14, and 21 DAA on a scale of 0 to 100% with 0 indicating no volunteer control and 100 indicating complete volunteer death. Five volunteer potato plants $plot^{-1}$ were flagged and evaluated for further data collection throughout the season. To evaluate naturally occurring CPB pressure on volunteer potatoes, the number of CPB egg masses, larvae, and adults on each flagged volunteer were counted at 14, 28, and 42 DAA from the EARLY timing. CPB defoliation was assessed through visual estimation of defoliation on a scale of 0 to 100%, with 0 indicating no defoliation and 100 indicating complete skeletonization of the plant. Volunteer daughter tuber production was assessed at the end of the growing season (September) by digging up three volunteer plants plot^{-1} and recording the number and weight of tubers produced.

Additionally, soil temperature data was collected from the time of volunteer potato dispersal in fall 2023 until the end of the season in fall 2024. Soil temperature data loggers (DS 1925L-F5# Thermochron iButton; iButtonLink Technology, Whitewater, WI) were buried at 10 and 25 cm to represent the depth of volunteer potato incorporation at the reduced and high intensity tillage, respectively.

Greenhouse Study

Corn injury was evaluated at 3, 7, and 14 DAA on a scale of 0 to 100% with 0 indicating no crop injury and 100 indicating complete crop death. Aboveground tissue was collected 14 DAA and dried for 3 d at 66 C, then dry weights were recorded.

Statistical Analysis

For all statistical analyses linear mixed effects models were constructed using the lmer function in R v. 4.4.0 (R Core Team 2024). Differences in means were further investigated using Tukey's HSD post hoc tests in the EMMEANS package in R (Lenth 2024). Treatment means were separated using an $\alpha \leq 0.05$. Normality assumptions and unequal variance assumptions were checked by examining normality histograms, side-by-side box plots of the residuals, and normality probability plots.

Fall Study

To determine the impacts of site-year and tillage intensity on volunteer emergence, site-year, tillage intensity, and their interaction were considered fixed effects and replication and replication nested within site-year were considered random effects. When site-year was significant, site-years were analyzed separately.

Due to insufficient volunteer emergence for comparison at the MSU and MRC site-years, volunteer control, beetle density, volunteer defoliation, and daughter tuber production were only analyzed at KBS and were analyzed separately by tillage treatment due to large differences in emergence. To determine the impacts of application timing and herbicide-insecticide treatment on these factors, application timing, herbicide-insecticide treatments, and their interaction were considered fixed effects and replication and was considered a random effect.

To determine the impacts of site-year, tillage intensity, and herbicide-insecticide treatment on corn injury, site-year, tillage intensity, application timing, herbicide-insecticide treatment, and their interactions were considered fixed effects and replication and replication nested within site-year were considered random effects. When site-year was significant, site-years were analyzed separately.

Spring Study

Due to insufficient volunteer emergence at MSU-23, volunteer emergence was analyzed for MSU-24 only. To determine the impact of tillage intensity on volunteer emergence, tillage intensity was considered a fixed effect and replication was considered a random effect.

To determine the impacts of site-year, tillage intensity, and herbicide-insecticide treatment on corn injury, site-year, tillage intensity, application timing, herbicide-insecticide treatments, and their interactions were considered fixed effects and replication and replication nested within site-year were considered random effects. When site-year was significant, site-years were analyzed separately.

Greenhouse Study

To determine the impact of herbicide-insecticide treatments on corn biomass at each growth stage, herbicide-insecticide treatments were considered a fixed effect and replication was considered a random effect. Analysis was completed separately for each corn growth stage.

Results and Discussion

Volunteer Potato Emergence

Fall Study

Volunteer potato emergence was impacted by the interaction between tillage treatment and site-year (Table 2.5). The disk tillage treatment reduced volunteer potato emergence by 80 and 87% compared to the plow treatment at KBS and MSU, respectively (Figure 2.1). There was no difference in volunteer potato emergence amongst tillage treatments at MRC. Differences in volunteer potato emergence between tillage treatments at KBS and MSU were most likely due to differences in soil temperature at each tuber burial depth. Over the winter, volunteer potato tubers incorporated approximately 10 cm deep by the disk tillage treatment were exposed to soil temperatures below 0 C for 26 h at KBS (Figure 2.2A). Conversely, in the plow treatment where volunteer potatoes were incorporated approximately 25 cm deep, soil temperatures never fell below 0 C (Figure 2.2A). At MSU soil temperatures fell below 0 C for 184 h at 10 cm and never fell below 0 C at 25 cm (Figure 2.2B). Shallow tillage increased the exposure of volunteer potatoes to lethal winter temperatures, leading to increased tuber mortality. Similarly, Boydston et al. (2006) observed reduced volunteer potato survival at shallow depths (5 cm) since tubers were more likely to experience lethal cold temperatures than tubers buried deeper in the soil profile. Tillage practices utilized in volunteer potato control should aim to maximize tuber exposure to lethal cold temperatures, through shallow incorporation in the soil profile.

Interestingly, volunteer potato emergence was approximately 85% less at MRC and MSU compared with KBS (Figure 2.1). This reduction was due to an unintended application of maleic hydrazide to plants used as seed lots for volunteer potatoes at MRC and MSU. Maleic hydrazide is a plant growth regulator that can be applied to growing potato crops to suppress tuber sprouting in storage. However, some research has shown that mid-season applications can also suppress volunteer potato sprouting in the field the following season, but this was dependent on cultivar, tuber size, and application timing (Blauwer et al. 2012; Newberry and Thornton 2007). The application of maleic hydrazide in our study effectively reduced volunteer potato emergence in both site-years where treated seed was planted (MRC and MSU, Figure 2.1). Therefore, there is potential for plant growth regulators such as maleic hydrazide to be utilized as a treatment for volunteer potato control. Further research should investigate the effects of various application timings across varieties.

Spring Study

Volunteer potato emergence was impacted by tillage at MRC-24 (Table 2.5). The moldboard plow treatment decreased volunteer potato emergence by 53% compared to the reduced tillage intensity of the disk treatment (Figure 2.3). No volunteer potatoes emerged in MRC-23, most likely due to severe hot and dry conditions following planting. Since volunteer potatoes in this study were not exposed to winter conditions, results from the spring planted study demonstrate the impact of volunteer potato burial depth on emergence patterns in the absence of lethal temperatures. The decreased emergence of deeper buried tubers in the moldboard plow treatment may be explained by the increase in resources required for sprouts to reach the soil surface. Deep burial of tubers has been reported to delay volunteer potato emergence relative to shallow planted volunteer potatoes (Lutman 1974). Additionally, since shoot production depleted tuber reserves (Williams and Boydston 2002), many of the tubers buried deeper in the soil may not have the energy necessary to produce stems that reach the soil surface, leading to the decreased emergence observed in the moldboard plow treatment. When winter temperatures are not a factor for volunteer potato control, or in years when fall tillage cannot be performed, reduced emergence can be achieved by utilizing deep tillage practices to bury tubers and exhaust reserves. However, as observed in the fall study, exposing tubers to lethal winter temperatures more effectively reduces volunteer potato survival than deeper burial through tillage.

Volunteer Control

Fall Study

Volunteer control was only evaluated at KBS due to insufficient volunteer emergence from the maleic hydrazide application at MRC and MSU. Volunteer control in the plow tillage system was impacted by the interaction between herbicide-insecticide treatment and application timing (Table 2.6). At 7 DAA, there was no difference in control when topramezone was applied early compared to late. Further, there was no difference in control when mesotrione was applied with chlorantraniliprole at either timing or the early applied mesotrione + spinetoram treatment. However, when mesotrione + spinetoram was applied late, volunteer potato control was 20% less than when it was applied early. Furthermore, when mesotrione + spinetoram was applied late, volunteer control was 23 and 15% less than mesotrione + chlorantraniliprole treatments when applied early and late, respectively. There was no difference between volunteer potato control within the early applied treatments, regardless of herbicide-insecticide treatment. In the late applied treatments, the level of control differed by herbicide-insecticide treatment. When topramezone + spinetoram and mesotrione + spinetoram were applied late, volunteer potato control was reduced by 17 and 15% compared to mesotrione + chlorantraniliprole applied late.

At 14 DAA, volunteer control was impacted by the interaction between application timing and herbicide-insecticide treatment (Table 2.6). When topramezone treatments were applied early, volunteer potato control was 15 and 25% greater than topramezone + chlorantraniliprole applied late. There was no difference in control between mesotrione treatments when applied early versus late. In the early application timing, volunteer control in mesotrione treatments was 55-67% greater than topramezone treatments, regardless of insecticide treatment. In the late application timing, control in mesotrione treatments was 32-52% greater than topramezone treatments, regardless of insecticide treatment.

At 21 DAA, control was impacted by the interaction between application timing and herbicide-insecticide treatment (Table 2.6). There was no difference in control when topramezone was applied late compared to early. Control differed by application timing in mesotrione treatments. When mesotrione + chlorantraniliprole was applied late, control was 35% greater than when it was applied early and 43% greater than mesotrione + spinetoram applied early. In the early application timing, there was no difference in control between topramezone treatments and the mesotrione + chlorantraniliprole treatment. However, control was 8-24% greater in the early applied mesotrione + chlorantraniliprole treatment compared to all other early applied treatments. When mesotrione treatments were applied late, control was 35-52% greater than late applied topramezone treatments. Control was reduced across treatments over time due to volunteer regrowth. By 21 DAA control was less than 20% in all topramezone treatments and less than 30% in early applied mesotrione treatments. In the plow system, late season volunteer control (21 DAA) was the greatest in mesotrione treatments applied late, averaging 53 and 63% when applied with spinetoram and chlorantraniliprole, respectively.

In the disk tillage system, volunteer control 7 DAA was impacted by the main effect of herbicide-insecticide treatment (Table 2.7). Overall, there was no difference in volunteer potato control amongst herbicide-insecticide tank-mixtures. Averaged across application timings, volunteer potato control was 55-75% across all treatments. At 14 DAA, control was impacted by the interaction between application timing and herbicide-insecticide treatment. Amongst topramezone treatments, control was the greatest (95%) in the late applied topramezone + spinetoram, which was 75% greater than early applied topramezone + spinetoram and 60% greater than early applied topramezone + chlorantraniliprole. There was no difference in control when mesotrione was applied late compared to early. When applied early, control was 60-76% greater in mesotrione treatments compared to topramezone treatments. Control was 36% greater in the late applied mesotrione + chlorantraniliprole treatment than the late applied topramezone + chlorantraniliprole treatment. At 21 DAA, control was impacted by the interaction between application timing and herbicide-insecticide treatment. Control was 89-94% greater in the late applied topramezone + spinetoram compared to early applied topramezone treatments. There was no difference amongst mesotrione treatments when applied early compared to late. When applied early, control was 85-95% greater in mesotrione treatments compared to topramezone treatments. When applied late, there was no difference amongst treatments.

Increased control of aboveground volunteer growth by mesotrione is consistent with findings by Koepke-Hill et al. (2010), which reported 62% control with mesotrione treatments compared to 10-20% control observed in topramezone and tembotrione treatments. Additionally, mesotrione provided greater control (>95%) than applications of carfentrazone-ethyl, fluroxypyr, dicamba, and combinations of these herbicides (Boydston and Williams 2005).

The overall poor control of volunteers in the plow system can be explained by variability in volunteer size and the ability of volunteers to regrow following management. In the plow system, volunteer height at the early application timing averaged 13 cm and ranged from 5-20 cm. At the late application timing, volunteer height averaged 30 cm and ranged from 15-43 cm. In the disk system, volunteer height was less variable at the late application timing. At the early application timing, volunteers averaged 12 cm and ranged from 5-20 cm. At the late application timing volunteers averaged 18 cm and ranged from 13-30 cm. Potato tubers have carbohydrate reserves that can continually generate new shoots and resprout until reserves are exhausted (Williams and Boydston 2002). As a result, volunteer regrowth is commonly observed even after aboveground shoots are suppressed through postemergence herbicide application (Boydston 2001, 2004; Boydston et al. 2008). This issue largely contributes to the difficulty in controlling volunteer potatoes in rotational crops, and explains the limited control observed in treatments in the moldboard plow system.

Volunteer potatoes can have a long emergence window depending on environmental conditions, tuber size, and burial depth (Lutman 1977). As a result, timing herbicide applications to effectively control volunteers is difficult due to variability in volunteer size. The improvement in control (31-35%) by 21 DAA in late applied mesotrione treatments compared to early applied, may be due to variability in volunteer size. Boydston and Williams (2005) reported increased control by 14 and 23% when mesotrione was applied when volunteer potatoes were 12-20 cm tall compared with volunteer potatoes 6-11 cm tall. Therefore, increased control in late applied treatments is consistent with previous research. Due to the variability in volunteer size observed in this study, the length of time between applications may not have been long enough to adequately evaluate differences in control between application timings. Further investigation of the impact of application timing on volunteer control should include additional application timings based on volunteer stage in addition to height.

CPB Dynamics

Fall Study

CPB density was only assessed at KBS due to insufficient volunteer emergence from the maleic hydrazide application at MRC and MSU. CPB density was combined across life stages due to overall low CPB pressure at KBS, which made analyzing each life stage separately impossible. In the plow tillage system, CPB density was impacted by the main effect of herbicide-insecticide treatment 14 DAA (Table 2.8). Herbicide-insecticide treatments reduced CPB density on volunteers by over 80% compared to the untreated control, averaged across application timings. There was no difference amongst herbicide-insecticide treatments on CPB density, ranging from 0.25-2.10 CPB vol^{-1}. At 28 DAA, CPB density was impacted by the main effects of herbicide-insecticide treatment and application timing, but not their interaction. Averaged across application timing, control decreased by 73% in the mesotrione + chlorantraniliprole treatment compared to the topramezone + spinetoram treatment. At 28 and 42 DAA, CPB pressure was negligible, averaging less than 3 CPB vol^{-1} across all treatments and the untreated control (Table 2.8). At 42 DAA there was no difference in CPB amongst herbicide-insecticide treatments and the untreated control.

In the disk tillage system, CPB density was impacted by the main effect of herbicide-insecticide treatment (Table 2.9). Herbicide-insecticide treatments reduced CPB density vol^{-1} by over 80% compared to the untreated control, averaged across application timings. There was no difference amongst herbicide-insecticide treatments on CPB density, ranging from 0-0.57 CPB vol^{-1}. However, overall CPB pressure in the disk tillage system was lower than the plow with 3.2 vs. 14.6 CPB vol^{-1}, respectively. This was most likely due to the low volunteer population in the disk tillage treatment (Figure 2.1), providing less food resources to attract CPB. There was no difference in CPB density in the disk system by 28 and 42 DAA (Table 2.9)

In the plow tillage treatment, defoliation was impacted by the main effect of herbicide-insecticide treatment at 14, 28 and 42 DAA (Table 2.10). Compared to all herbicide-insecticide treatments, defoliation was 4, 20, and 28% greater on untreated volunteers 14, 28, and 42 DAA, respectively, averaged across application timing (Figure 2.4). Within a DAA there was no difference in defoliation amongst herbicide-insecticide treatments. Overall, defoliation increased over time in all treatments, but remained below 50% in herbicide-insecticide treatments compared to 92% in the untreated control.

In the disk tillage treatment, there was no difference in defoliation 14 and 28 DAA (Table 2.10). However, 42 DAA treatments containing spinetoram reduced defoliation by 53 and 73% compared to the untreated control (Figure 2.5). Overall, defoliation increased over time in all treatments, but remained below 40% in herbicide-insecticide treatments compared to 76% in the untreated control.

The lack of volunteers in the disk treatment to attract CPB contributed to less apparent differences in defoliation between treatments. When CPB pressure was high in the plow system, both insecticide treatments effectively controlled CPB on volunteers. Chlorantraniliprole and spinetoram insecticides have been reported to provide effective control of CPB when applied to potato crops (Groves et al. 2017; Kuhar and Doughty 2009, 2016). Activity of these products on target organisms includes both contact and ingestion. This increases their versatility by controlling CPB present at the time of application in addition to later emerging CPB feeding on volunteers. Since volunteer potatoes are reported to be an early season food source for CPB (Xu and Long 1997), applying spinetoram or chlorantraniliprole to high densities of volunteers will reduce CPB populations early in the season. Integrating insecticide and herbicide applications when appropriate creates an opportunity for producers to simultaneously manage both CPB and volunteers and may help reduce CPB pressure on cultivated potato crops throughout the growing season.

Volunteer Daughter Tuber Production

Fall Study

Due to insufficient volunteer emergence from the maleic hydrazide application at MRC and MSU, daughter tuber production was only assessed at KBS. Daughter tuber production was impacted by herbicide-insecticide treatments in the plow tillage system (Table 2.11). Untreated volunteers in the plow treatment produced an average of 4.6 tubers vol^{-1} (Figure 2.6A). Averaged across application timing, the mesotrione + chlorantraniliprole or spinetoram treatments reduced the number of daughter tubers vol^{-1} by 55 and 78%, respectively, relative to untreated control. Topramezone + spinetoram also reduced the number of daughter tubers vol^{-1} by 48% compared to the untreated control, averaged across application timing. There was no difference amongst herbicide-insecticide treatments and the number of daughter tubers vol^{-1} produced.

Herbicide-insecticide treatments impacted the total weight of daughter tubers vol^{-1} in the plow system (Figure 2.6B). Total tuber weight vol^{-1} averaged 97.6 g in the untreated control. Averaged across application timings, mesotrione treatments reduced tuber weight by 80 and 88% when applied with chlorantraniliprole and spinetoram, respectively. There was no difference in tuber weight vol^{-1} when volunteers were treated with topramezone and either insecticide compared to the untreated control, averaged across application timing. Overall, treatments containing mesotrione effectively reduced daughter tuber number and weight in the plow tillage treatment. This mirrored aboveground control evaluations in which mesotrione treatments reduced growth relative to untreated control.

Daughter tuber production was impacted by herbicide-insecticide treatments in the disk tillage system also (Table 2.11). In this system, untreated volunteers produced an average of 4.8 tubers vol^{-1} (Figure 2.7A). Averaged across application timings, treatments containing topramezone reduced the number of daughter tubers produced vol^{-1} by 67% compared to the untreated control. The mesotrione + chlorantraniliprole treatment reduced daughter tuber number vol^{-1} by 76% relative to untreated control, averaged across application timings. There was no difference amongst herbicide-insecticide treatments and daughter tuber production vol^{-1}. Overall, averaged across application timing, all treatments reduced daughter tuber weight vol^{-1} relative to untreated control by greater than 88% in the disk system (Figure 2.7B). Interestingly, while aboveground evaluations showed decreased control from early applications of topramezone in the disk system (Table 2.7), this was not reflected in tuber number or weight (Figure 2.7A-B).

Aboveground volunteer control in both tillage treatments was impacted by application timing in addition to herbicide-insecticide programs (Table 2.6 and 2.7). However, application timing did not impact tuber production in either tillage treatment. Herbicide application timing has been reported to impact tuber production (Boydston and Williams 2005). This study reported that postemergence applications of mesotrione reduced the number of daughter tubers when compared to preemergence and early-postemergence applications, but was not different from the early- plus late-postemergence application made 10 d later. Results from this study suggest that tuber reduction was most effective when applications were made at the time of tuber initiation.

Additionally, Boydston (2001) reported increased control when glyphosate applications were applied at the 8-leaf stage when daughter tubers had just started to form, compared to the 6-leaf stage. The lack of difference in control of tuber production between application timings observed in the plow and disk tillage treatments may be due to potato stage at the time of both applications. Since applications were made only one week apart in this study, volunteers were most likely at a similar stage belowground at both application timings, similar to findings by Boydston and Williams (2005) which reported no difference in postemergence and late-postemergence application timings. Fully understanding the impact of application timing on tuber reduction using these herbicide treatments requires analysis of volunteer growth stage, and not simply height, and should include additional application timings to elucidate these patterns. However, since weed competition at or near the time of crop emergence is the most detrimental to development and yield (Page et al. 2012), producers must consider the impacts of early season weed competition when making application timing decisions. Therefore, waiting until tuber initiation to control volunteers may not be a viable option in production settings.

Overall, mesotrione treatments effectively reduced tuber production in both tillage systems. The differences observed in control can be attributed to differences in the activity of these herbicides. While mesotrione and topramezone herbicides are both HPPD inhibiting herbicides, they are in different chemical families (mesotrione is a triketone while topramezone is a pyrazolone) and therefore these active ingredients have differing activity within a plant (Jhala et al. 2023). Mesotrione has been reported to have the unique attribute of reducing daughter tuber production more than other HPPD inhibiting herbicide (Boydston and Williams 2005). The increased control provided by mesotrione relative to topramezone can be attributed to differences in activity between these active ingredients.

Corn Injury

Fall Study

Overall, herbicide-insecticide treatments did not cause deleterious injury to corn. The main effect of site-year and its interactions were not significant, therefore data were combined across site-years for analysis. Corn injury 7 DAA was impacted by the interaction between application timing and herbicide-insecticide treatment (Table 2.12). There was no difference in corn injury between all mesotrione treatments and late applied topramezone treatments. The greatest injury was observed in the early applied topramezone + spinetoram and topramezone + chlorantraniliprole treatments at 3.7 and 4.0%, respectively. At 14 DAA, injury was impacted by the interaction between application timing and herbicide-insecticide treatment. However, by 14 DAA injury was less than 2% across all treatments. By 21 DAA there was no difference in injury amongst herbicide-insecticide treatments, with all treatments resulting in less than 1% injury. Visual assessment of corn ear development showed no signs that herbicide-insecticide applications impacted ear development or grain fill relative to the untreated control (data not shown).

Spring Study

Overall, herbicide-insecticide treatments did not cause deleterious injury to corn. The main effect of site-year and its interactions were not significant, therefore data were combined across site-years for analysis. At 7 DAA, there was no difference in injury amongst herbicide-insecticide treatments (Table 2.13). At 14 and 21 DAA injury was impacted by the interaction between timing and herbicide-insecticide. The early applied mesotrione + chlorantraniliprole treatment resulted in greater injury than all topramezone treatments and late applied mesotrione treatments at 3.3% 14 DAA and 2.2% at 21 DAA. Injury decreased at each evaluation timing.

Visual assessment of corn ear development showed no signs that herbicide-insecticide applications impacted ear development or grain fill relative to the untreated control (data not shown).

Greenhouse Study

A greenhouse study was conducted to evaluate additional herbicide-insecticide treatment application timings on corn injury and biomass. There were no visible corn injury symptoms (0%) in any of the herbicide-insecticide treatments or application timings (data not shown). Additionally, there was no difference in corn biomass 14 DAA amongst herbicide-insecticide treatments, application timings, or their interaction (Table 2.14). Overall, results from the greenhouse study indicate that applications of these herbicide-insecticide treatments to corn growth stages V1-V4 will not result in damage to plants.

Results from injury assessments across all three studies demonstrate that these products can safely be tank-mixed and applied to field corn without causing significant injury or impacting ear development. Previous research has reported injury to field corn when HPPD-inhibiting herbicides were applied following insecticide application. Particularly, yield reductions have been reported when mesotrione applications follow at plant applications of terfubos insecticide (Jewett et al. 2008) and when applications of tembotrione follow applications of chlorpyrifos insecticide (Steckel et al. 2015). However, previous research has not evaluated the activity of tank-mixing the products utilized in this study. While slight injury was observed in some of the treatments in this study, it remained <5% and did not cause deleterious injury to corn, that has been reported in other studies. Therefore, this provides the opportunity for integrated management of volunteer potatoes and CPB simultaneously in corn rotations.

In conclusion, volunteer potatoes and CPB can cause significant crop loss in corn-potato systems annually therefore effective management strategies should be developed from an integrated approach. Volunteer management should begin following harvest, using reduced intensity tillage practices to keep volunteers as close to the soil surface as possible. This will increase the likelihood tubers are exposed to harsh winter temperatures causing tuber mortality. Based on volunteer pressure in the spring, postemergence herbicide applications of mesotrione can effectively reduce volunteer growth and daughter tuber production. However, the lack of differences in application timing observed in this study warrants the need for further research on the potato stage where herbicide applications will be the most effective, as opposed to volunteer height. When volunteer and CPB pressure is high, applying spinetoram and chlorantraniliprole insecticides can effectively reduce CPB feeding on volunteers by over 80%. Management of CPB populations on volunteers has the potential to reduce defoliation from CPB observed in cultivated potato crops. Less than 5% corn injury observed in all three studies demonstrates that combinations of mesotrione or topramezone herbicides tank-mixed with chlorantraniliprole or spinetoram insecticides will not cause significant injury to corn. Therefore, management of volunteer potatoes and CPB can be integrated in this system. Combining herbicide-insecticide applications will allow producers to reduce the number of applications required to manage these pests while protecting from yield loss in both corn and potato crops.

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APPENDIX A: CHAPTER II TABLES AND FIGURES

Table 2.1. Fertilizer, potato and corn varieties, planting dates, populations, and application timings for each site-year of the fall study.

	Site-year[a]		
	KBS	MRC	MSU
Fertilizer			
urea ammonium nitrate (28-0-0) (L ha^{-1})	309	-	-
urea (46-0-0) (kg ha^{-1})	56	46	46
ammonium sulfate (19-0-0-22) (kg ha^{-1})	112	101	101
MES10 (12-40-0-10) (kg ha^{-1})	112	-	-
potash (0-0-60) (kg ha^{-1})	112	112	112
monoammonium phosphate (8-40-0) (kg ha^{-1})	-	86	86
Potato variety	Manistee	MSBB626-11	MSBB630-2
Potato planting date	October 24, 2023	October 3, 2023	October 12, 2023
Corn variety	P0035AM	P0035AM	P0035AM
Corn planting date	May 2, 2024	May 7, 2024	May 9, 2024
Corn population (seeds ha^{-1})	70,672	81,545	81,545
Early application	May 29, 2024	June 11, 2024	June 12, 2024
Late application	June 4, 2024	June 18, 2024	June 20, 2024
Soil series	Kalamazoo loam	Tekenink-Elmdale loamy sands	Hillsdale-Riddles sandy loam
Soil pH	6.0	6.4	6.0
Soil organic matter (%)	1.5	1.4	2.1

[a]Abbreviations: KBS, Kellogg Biological Station; MRC, Montcalm Research Center; MSU, Michigan State University.

Table 2.2. Herbicide and insecticide products, application rates, and manufacturer information for Colorado potato beetle and volunteer control treatments in the fall and spring planted volunteer studies.

Treatments[a]	Trade names	Rates	Manufacturer[b]
		kg ai ha^{-1}	
mesotrione + spinetoram	Callisto + Radiant	0.11 + 0.04	Syngenta + Corteva
mesotrione + chlorantraniliprole	Callisto + Coragen	0.11 + 0.09	Syngenta + FMC
topramezone + spinetoram	Armezon + Radiant	0.02 + 0.04	BASF + Corteva
topramezone + chlorantraniliprole	Armezon + Coragen	0.02 + 0.09	BASF + FMC

[a]All treatments contained atrazine (AAtrex nine-0; Syngenta) at 1.09 kg ai ha^{-1}, ammonium sulfate at 1.02% w w^{-1}, and nonionic surfactant at 0.25% v/v.

[b]Manufacturer information: BASF corporation, Research Triangle Park, NC; Corteva Agriscience, Indianapolis, IN; Syngenta Crop Protection LLC, Greensboro, NC; FMC Corporation, Philadelphia, PA.

Table 2.3. Potato and corn varieties, planting dates, populations, and application timings for each site-year of the spring study.

	Site-year[a]	
	MRC-23	MRC-24
Fertilizer		
urea (46-0-0) (kg ha^{-1})	488	46
ammonium sulfate (19-0-0-22) (kg ha^{-1})	-	101
potash (0-0-60) (kg ha^{-1})	-	112
monoammonium phosphate (8-40-0) (kg ha^{-1})	-	86
Potato variety	Snowden	Snowden
Potato planting date	May 30, 2023	May 6, 2024
Corn variety	DKC47-55	P0035AM
Corn planting date	June 1, 2023	May 7, 2024
Corn population (seeds ha^{-1})	81,545	81,545
Early application		
Disk	July 10, 2023	June 3, 2024
Plow	July 10, 2023	June 11, 2024
Late application		
Disk	July 18, 2023	June 11, 2024
Plow	July 18, 2023	June 18, 2024
Soil series	Tekenink-Elmdale loamy sands	Tekenink-Elmdale loamy sands
Soil pH	5.8	6.4
Soil organic matter (%)	1.7	1.1

[a]Abbreviations: MRC-23, Montcalm Research Center 2023, MRC-24 Montcalm Research Center 2024.

Table 2.4. Herbicide and insecticide products, application rates, and manufacturer information for Colorado potato beetle and volunteer control treatments in the greenhouse study.

Herbicide	Insecticide	Trade name	Rates	Manufacturer[b]
			kg ai ha^{-1}	
mesotrione	-	Callisto	0.11	Syngenta
topramezone	-	Armezon	0.02	BASF
-	spinetoram	Radiant	0.04	Corteva
-	chlorantraniliprole	Coragen	0.09	FMC
mesotrione	spinetoram	Callisto + Radiant	0.11 + 0.04	Syngenta + Corteva
mesotrione	chlorantraniliprole	Callisto + Coragen	0.11 + 0.09	Syngenta + FMC
topramezone	spinetoram	Armezon + Radiant	0.02 + 0.04	BASF + Corteva
topramezone	chlorantraniliprole	Armezon + Coragen	0.02 + 0.09	BASF + FMC

[a]All treatments contained atrazine (AAtrex nine-0; Syngenta) at 1.09 kg ai ha^{-1}, ammonium sulfate at 1.02% w w^{-1}, and nonionic surfactant at 0.25% v/v.

[b]Manufacturer information: BASF corporation, Research Triangle Park, NC; Corteva Agriscience, Indianapolis, IN; Syngenta Crop Protection LLC, Greensboro, NC; FMC Corporation, Philadelphia, PA.

Table 2.5. ANOVA p-values from a linear mixed effect model for the effects of site-year, tillage, and their interaction on volunteer emergence in the fall study. ANOVA p-values from a linear mixed effect model for the effect of site-year on volunteer emergence in the spring study at MRC-24.

	Volunteer emergence	
Effects (p-values)	Fall study	Spring study
Site-year	<0.0001	-
Tillage	<0.0001	<0.0001
Site-year*tillage	<0.0001	-

Table 2.6. Mean (SE) volunteer potato control impacted by herbicide-insecticide treatment and application timing in the plow tillage system at the Kellogg Biological Station site-year in the fall study.

		Control[a]		
Timing	Herbicide-insecticide	7 DAA	14 DAA	21 DAA
		%		
-	untreated	0 (0) d	0 (0)d	0 (0)d
EARLY	topramezone + chlorantraniliprole	58 (3.2) abc	36 (5.5)c	18 (10.9)cd
LATE	topramezone + chlorantraniliprole	53 (6.0) bc	51 (6.6)b	18 (3.2)cd
EARLY	topramezone + spinetoram	59 (3.2) abc	26 (2.4)c	6 (1.3)cd
LATE	topramezone + spinetoram	46 (2.4) c	40 (4.1)bc	13 (3.3)cd
EARLY	mesotrione + chlorantraniliprole	71 (1.3) a	93 (2.5)a	30 (7.1)bc
LATE	mesotrione + chlorantraniliprole	63 (4.8) ab	92 (2.7)a	65 (5.4)a
EARLY	mesotrione + spinetoram	68 (1.4) a	91 (1.3)a	22 (14.2)cd
LATE	mesotrione + spinetoram	48 (1.4) c	83 (3.2)a	53 (7.2)ab
Effects (p-values)				
Timing		<0.0001	<0.0001	<0.0001
Herbicide-insecticide		<0.0001	0.0562	0.0003
Timing*herbicide-insecticide		0.0197	0.0020	0.0072

[a]Means within an days after application (DAA) column followed by the same letter are not statistically different for the interaction between application timing and herbicide-insecticide treatment ($\alpha = 0.05$).

Table 2.7. Mean (SE) volunteer potato control impacted by herbicide-insecticide treatment and application timing in the disk tillage system at the Kellogg Biological Station site-year in the fall study.

Timing	Herbicide-insecticide	Control 7 DAA[a]	Control 14 DAA[b]	Control 21 DAA[b]
		%		
-	untreated	0 (0) b	0 (0) d	0 (0) d
EARLY	topramezone + chlorantraniliprole	60 (-[c]) a	30 (-) cd	10 (-) cd
LATE	topramezone + chlorantraniliprole	55 (9.6) a	61 (15.5) bc	59 (15.6) bc
EARLY	topramezone + spinetoram	55 (-) a	20 (-) cd	5 (-) cd
LATE	topramezone + spinetoram	55 (25.1) a	95 (5.0) ab	99 (1.5) ab
EARLY	mesotrione + chlorantraniliprole	75 (2.9) a	96 (1.0) ab	95 (5.0) ab
LATE	mesotrione + chlorantraniliprole	61 (6.9) a	97 (1.0) a	95 (5.0) ab
EARLY	mesotrione + spinetoram	65 (7.9) a	90 (3.5) ab	100 (0) a
LATE	mesotrione + spinetoram	60 (7.4) a	88 (4.3) ab	86 (12.0) ab
Effects (p-values)				
Timing		0.4700	0.0021	0.0014
Herbicide-insecticide		<0.0001	<0.0001	<0.0001
Timing*herbicide-insecticide		0.9146	0.0067	0.0011

[a]Means within a days after application (DAA) column followed by the same letter are not statistically different for the main effect of herbicide-insecticide treatment (α = 0.05).

[b]Means within a days after application (DAA) column followed by the same letter are not statistically different for the interaction between application timing and herbicide-insecticide treatment (α = 0.05).

[c]- =standard error cannot be calculated due to only one data point in comparison.

Table 2.8. Mean (SE) Colorado potato beetle (CPB) density (combined for eggs, larvae, and adults) impacted by main effects of herbicide-insecticide treatments and application timing in the plow tillage system at the Kellogg Biological Station site-year in the fall study.

	CPB density (vol^{-1})[a]		
Herbicide-insecticide	14 DAA	28 DAA	42 DAA
untreated	14.6 (2.1) a	2.1 (0.4) a	0 (0) a
topramezone + chlorantraniliprole	0.4 (0.2) b	0.8 (0.2) ab	1.1 (0.3) a
topramezone + spinetoram	2.1 (0.5) b	2.2 (0.6) a	1.3 (0.4) a
mesotrione + chlorantraniliprole	0.3 (0.1) b	0.6 (0.4) b	1.3 (0.4) a
mesotrione + spinetoram	1.2 (0.5) b	0.9 (0.4) ab	0.9 (0.3) a
Timing			
EARLY	4.5 (0.9) a	1.7 (0.3) a	1.2 (0.2) a
LATE	3.2 (0.9) a	1.0 (0.2) b	0.9 (0.2) a
Effects (p-values)			
Timing	0.1419	0.0187	0.4300
Herbicide-insecticide	<0.0001	0.0017	0.2756
Timing*herbicide-insecticide	0.8062	0.7011	0.5193

[a]Means within a days after application (DAA) column followed by the same letter are not statistically different for each main effect ($\alpha = 0.05$).

Table 2.9. Mean (SE) Colorado potato beetle (CPB) density (combined for eggs, larvae, and adults) impacted by herbicide-insecticide treatments averaged across application timings in the disk tillage system at the Kellogg Biological Station site-year in the fall study.

	CPB density (vol^{-1})[a]		
Herbicide-insecticide	14 DAA	28 DAA	42 DAA
untreated	3.2 (0.9) a	0.8 (0.3) a	0 (0) a
topramezone + chlorantraniliprole	0.6 (0.3) b	1.4 (0.8) a	1.3 (0.7) a
topramezone + spinetoram	0.1 (0.1) b	0 (0) a	0 (0) a
mesotrione + chlorantraniliprole	0 (0) b	0 (0) a	1.5 (1.5) a
mesotrione + spinetoram	0 (0) b	0.4 (0.3) a	0.4 (0.4) a
Effects (p-values)			
Timing	0.2733	0.4678	0.7647
Herbicide-insecticide	<0.001	0.4649	0.3633
Timing*herbicide-insecticide	0.3599	0.2538	0.4883

[a]Means within a days after application (DAA) column followed by the same letter are not statistically different for the main effect of herbicide-insecticide treatment ($\alpha = 0.05$).

Table 2.10. ANOVA p-values from a linear mixed effect model for the effects of application timing, herbicide-insecticide treatment, and their interaction on Colorado potato beetle defoliation of volunteers at each evaluation timing (14, 28, and 42 days after application (DAA)) in the fall study at the Kellogg Biological Station site-year.

	Volunteer defoliation					
	Plow			Disk		
Effect (p-values)	14 DAA	28 DAA	42 DAA	14 DAA	28 DAA	42 DAA
Timing	0.4307	0.2305	0.3449	0.9649	0.1202	0.0742
Herbicide-insecticide	0.0046	<0.0001	<0.0001	0.0881	0.1443	0.0156
Timing*herbicide-insecticide	0.7876	0.8067	0.4527	0.2656	0.4523	0.4708

Table 2.11. ANOVA p-values from a linear mixed effect model for the effects of application timing, herbicide-insecticide treatment, and their interaction on volunteer daughter tuber production (tuber number and weight) in the fall study at the Kellogg Biological Station site-year.

	Disk		Plow	
Effects (p-values)	tuber number	tuber weight	tuber number	tuber weight
Timing	0.6846	0.8283	0.6846	0.9808
Herbicide-insecticide	0.0007	0.0025	0.0007	<0.0001
Timing*herbicide-insecticide	0.3102	0.9655	0.3102	0.9929

Table 2.12. Mean (SE) corn injury impacted by application timing and herbicide-insecticide treatment averaged across tillage treatment combined for all site-years in the fall study.

Timing	Herbicide-insecticide	Injury 7 DAA[a]	14 DAA[a]	21 DAA[b]
		%		
-	untreated	0 (0) c	0 (0)c	0 (0)b
EARLY	topramezone + chlorantraniliprole	4.0 (0.5) a	1.6 (0.3)a	0 (0)ab
LATE	topramezone + chlorantraniliprole	1.3 (0.4) bc	0.2 (0.1)c	0.1 (0.1)ab
EARLY	topramezone + spinetoram	3.7 (0.5) a	0.8 (0.3)abc	0.3 (0.2)a
LATE	topramezone + spinetoram	1.7 (0.3) b	0.4 (0.2)bc	0.1 (0.1)a
EARLY	mesotrione + chlorantraniliprole	1.7 (0.3) b	0.9 (0.3)abc	0.1 (0.1)ab
LATE	mesotrione + chlorantraniliprole	1.2 (0.2) bc	0.3 (0.1)bc	0 (0)ab
EARLY	mesotrione + spinetoram	1.3 (0.4) bc	1.1 (0.4)ab	0 (0)ab
LATE	mesotrione + spinetoram	1.2 (0.2) bc	0.2 (0.1)c	0 (0)ab
Effects (p-values)				
Tillage		0.4322	0.2742	0.3369
Timing		<0.0001	<0.0001	0.5342
Herbicide-insecticide		<0.0001	0.0011	0.0209
Tillage*timing		0.3990	0.8848	0.7196
Tillage*herbicide-insecticide		0.8358	0.9058	0.3369
Timing*herbicide-insecticide		<0.0001	0.0169	0.9861
Tillage*timing*herbicide-insecticide		0.3181	0.9968	0.2143

[a]Means within a days after application (DAA) column followed by the same letter are not statistically different for the interaction between application timing and herbicide-insecticide treatment ($\alpha = 0.05$).

[b]Means within a days after application (DAA) column followed by the same letter are not statistically different for the main effect of herbicide-insecticide treatment ($\alpha = 0.05$).

Table 2.13. Mean (SE) corn injury impacted by application timing and herbicide-insecticide treatment averaged across tillage treatment combined for all site-years in the spring study.

Timing	Herbicide-insecticide	Injury		
		7 DAA[a]	14 DAA[b]	21 DAA[b]
		%		
-	untreated	0 (0) b	0 (0)c	0 (0)c
EARLY	topramezone + chlorantraniliprole	2.3 (0.7) ab	0.8 (0.2)bc	0.2 (0.1)bc
LATE	topramezone + chlorantraniliprole	3.6 (1.0) a	1.3 (0.6)bc	0.1 (0.1)bc
EARLY	topramezone + spinetoram	1.4 (0.3) ab	1.0 (0.2)bc	0.4 (0.2)bc
LATE	topramezone + spinetoram	1.8 (0.6) ab	0.5 (0.2)c	0.1 (0.1)c
EARLY	mesotrione + chlorantraniliprole	3.6 (0.7) a	3.3 (0.8)a	2.2 (0.5)a
LATE	mesotrione + chlorantraniliprole	3.4 (0.7) a	1.1 (0.4)bc	0.3 (0.1)bc
EARLY	mesotrione + spinetoram	3.3 (0.7) a	2.6 (0.7)ab	2.0 (0.5)ab
LATE	mesotrione + spinetoram	1.8 (0.4) ab	0.4 (0.2)c	0.3 (0.2)c
Effects (p-values)				
Tillage		0.3792	0.2263	0.5765
Timing		0.9460	0.0014	<0.0001
Herbicide-insecticide		<0.0001	<0.0001	<0.0001
Tillage*timing		0.4567	0.7090	0.4729
Tillage*herbicide-insecticide		0.2940	0.8385	0.9536
Timing*herbicide-insecticide		0.1866	0.0034	<0.0001
Tillage*timing*herbicide-insecticide		0.3217	0.8029	0.8267

[a]Means within a days after application (DAA) column followed by the same letter are not statistically different for the main effect of herbicide-insecticide treatment ($\alpha = 0.05$).

[b]Means within a days after application (DAA) column followed by the same letter are not statistically different for the interaction between application timing and herbicide-insecticide treatment ($\alpha = 0.05$).

Table 2.14. Mean (SE) corn biomass impacted by herbicide-insecticide treatment within each corn growth stage (V1, V2, V3 and V4) in the greenhouse study.

Herbicide	Insecticide	Growth stage V1[a]	V2	V3	V4
		Weight (g)			
untreated	untreated	3.1 (0.5)a	6.1 (0.8) a	12.6 (1.0) a	18.5 (0.3) a
mesotrione	-	2.9 (0.5)a	6.3 (0.9) a	12.7 (0.9) a	18.5 (0.7) a
topramezone	-	2.6 (0.4)a	5.9 (0.6) a	12.7 (1.0) a	20.2 (0.7) a
-	spinetoram	2.1 (0.4)a	5.6 (0.7) a	11.6 (1.3) a	18.9 (0.6) a
-	chlorantraniliprole	2.2 (0.3)a	6.4 (0.8) a	11.2 (1.2) a	19.5 (1.1) a
mesotrione	spinetoram	2.9 (0.4)a	6.5 (0.8) a	13.6 (0.9) a	20.3 (0.7) a
mesotrione	chlorantraniliprole	2.4 (0.5)a	6.7 (0.9) a	11.3 (0.9) a	19.3 (0.6) a
topramezone	spinetoram	2.3 (0.4)a	6.1 (0.8) a	11.6 (0.6) a	19.3 (1.0) a
topramezone	chlorantraniliprole	2.6 (0.2)a	6.9 (1.8) a	13.3 (0.9) a	20.0 (0.6) a
Effects (p-values)					
Herbicide-insecticide treatment		0.4122	0.9928	0.5180	0.4340

[a]Means within a growth stage column (V1-V4) followed by the same letter are not statistically different for the main effect of herbicide-insecticide treatment (α = 0.05).

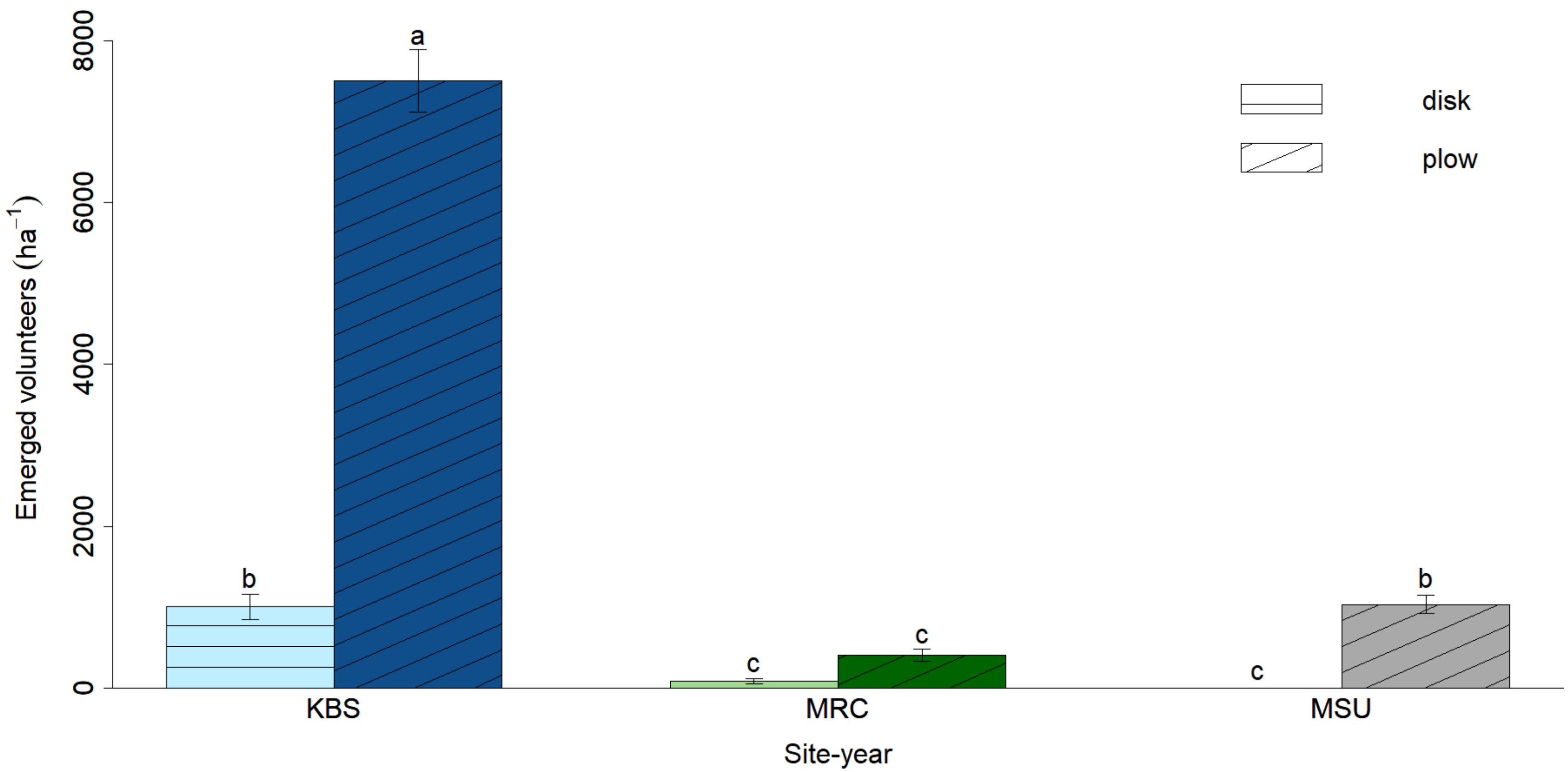

Figure 2.1. Mean (SE) volunteer potato emergence impacted by site-year and tillage treatment in the fall study. Bars sharing the same letter are not statistically different (α = 0.05). Abbreviations: KBS, Kellogg Biological Station; MRC, Montcalm Research Station; MSU, Michigan State University.

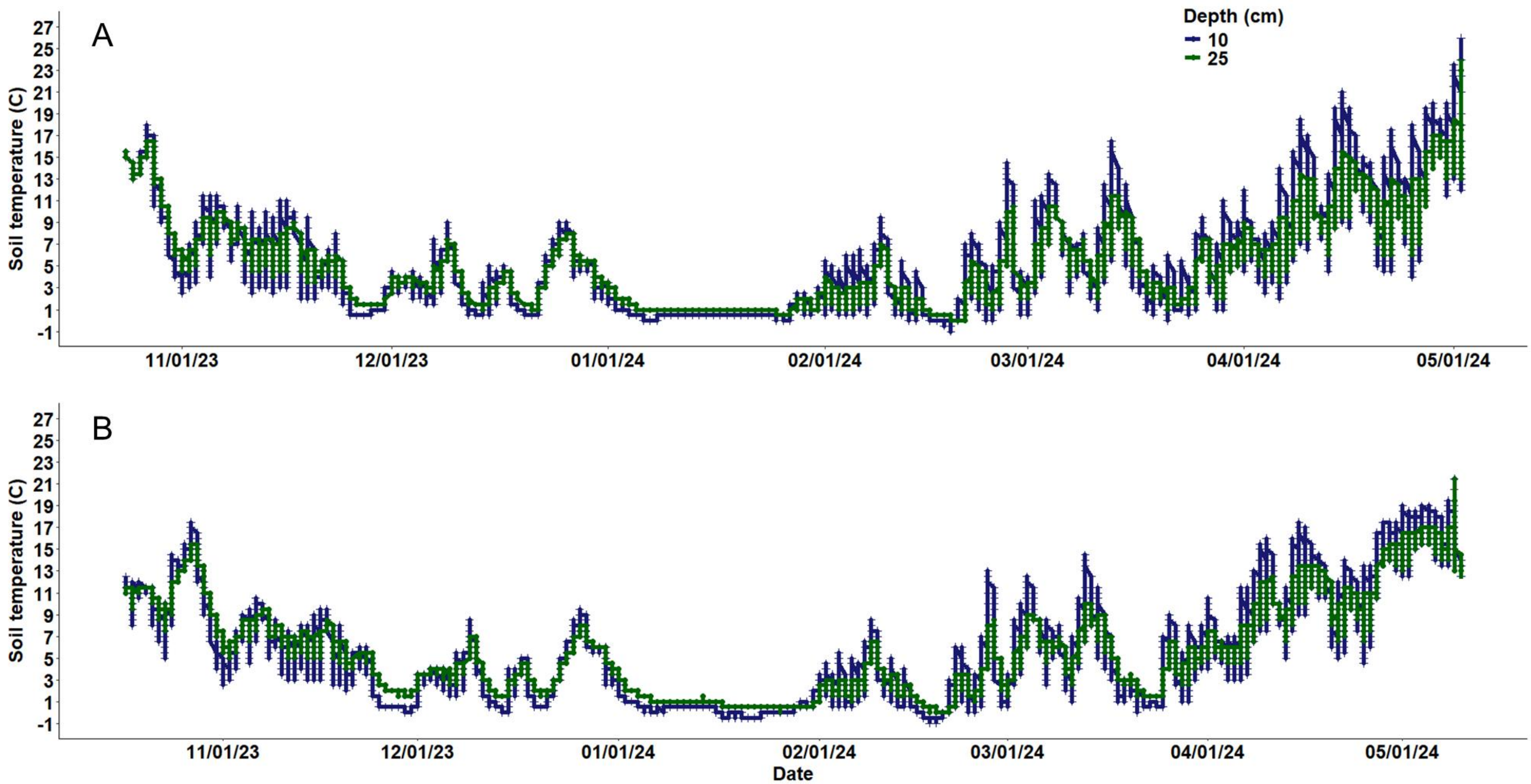

Figure 2.2. Soil temperature at Kellogg Biological Station (A) and Michigan State University (B) site-years over the winter at the depth of disk tillage treatment (10 cm) and plow tillage treatment (25 cm).

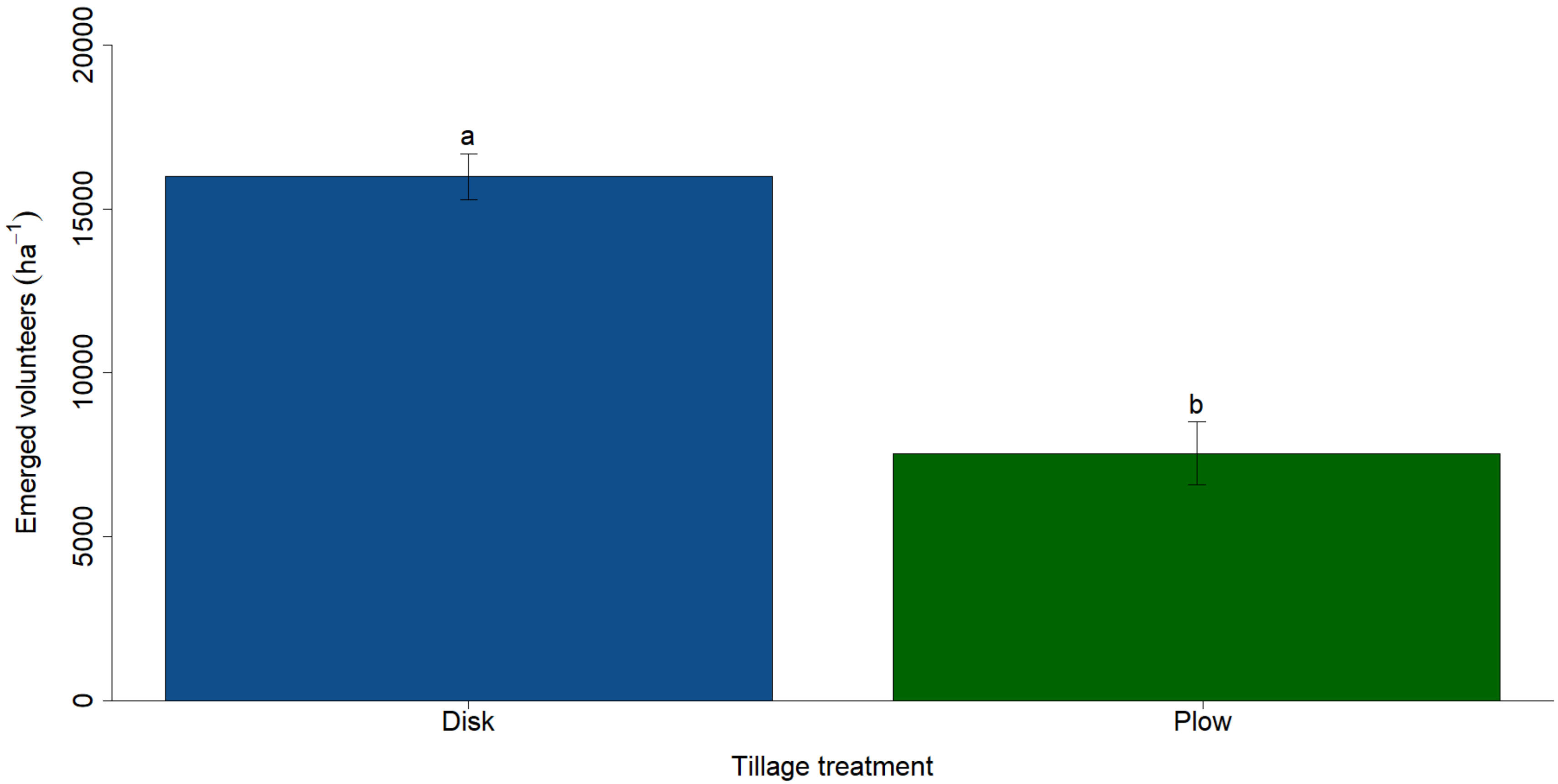

Figure 2.3. Mean (SE) volunteer potato emergence impacted by tillage treatment in the spring study at MRC-24 (Montcalm Research Center 2024). Bars sharing the same letter are not statistically different (α = 0.05).

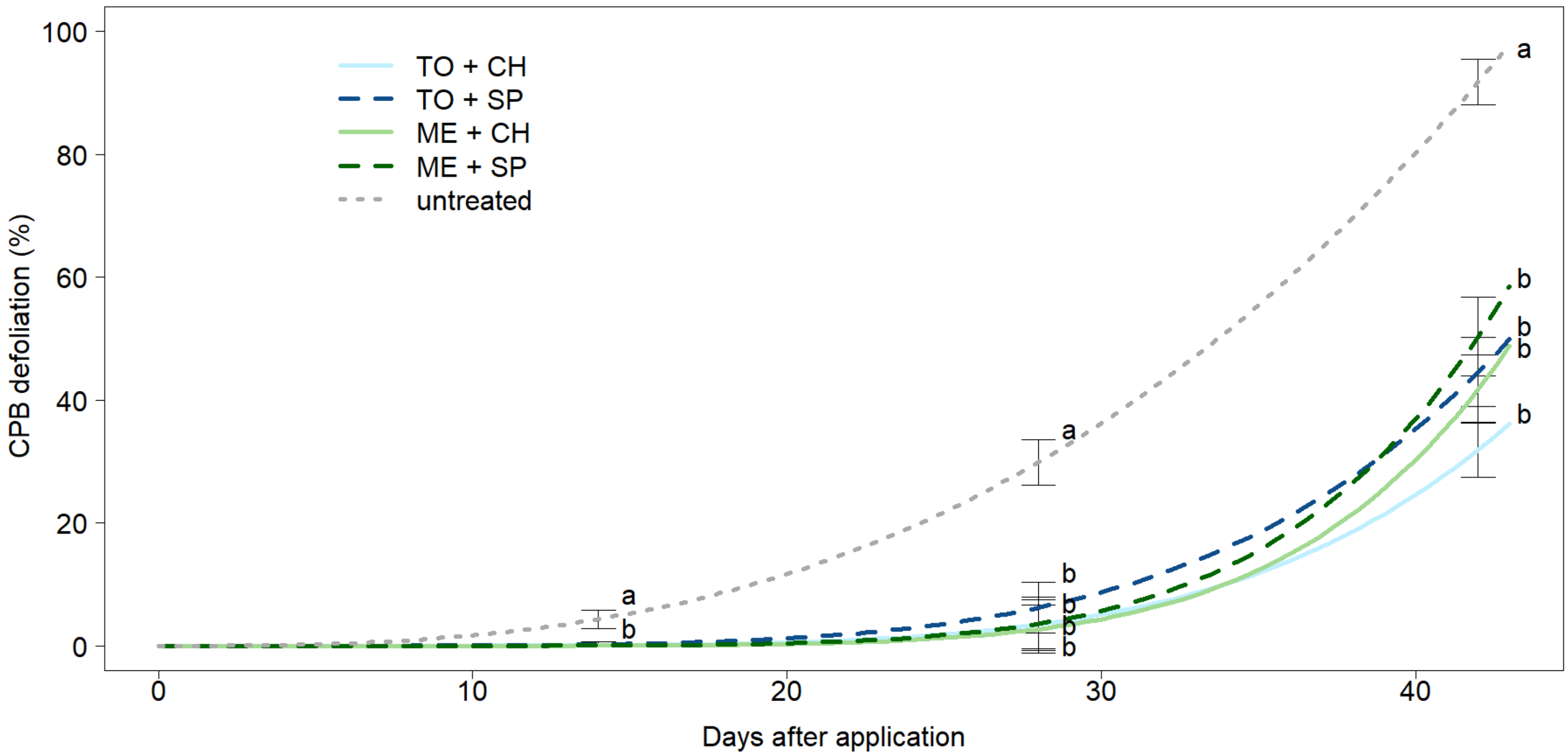

Figure 2.4. Mean (SE) volunteer potato defoliation by Colorado potato beetle (CPB) impacted by herbicide-insecticide treatment in the plow tillage system at the Kellogg Biological Station site-year in the fall study. Bars sharing the same letter within an evaluation timing (14, 28, and 42 d) are not statistically different (α = 0.05). Abbreviations: TO, topramezone; ME, mesotrione; SP, spinetoram; CH, chlorantraniliprole.

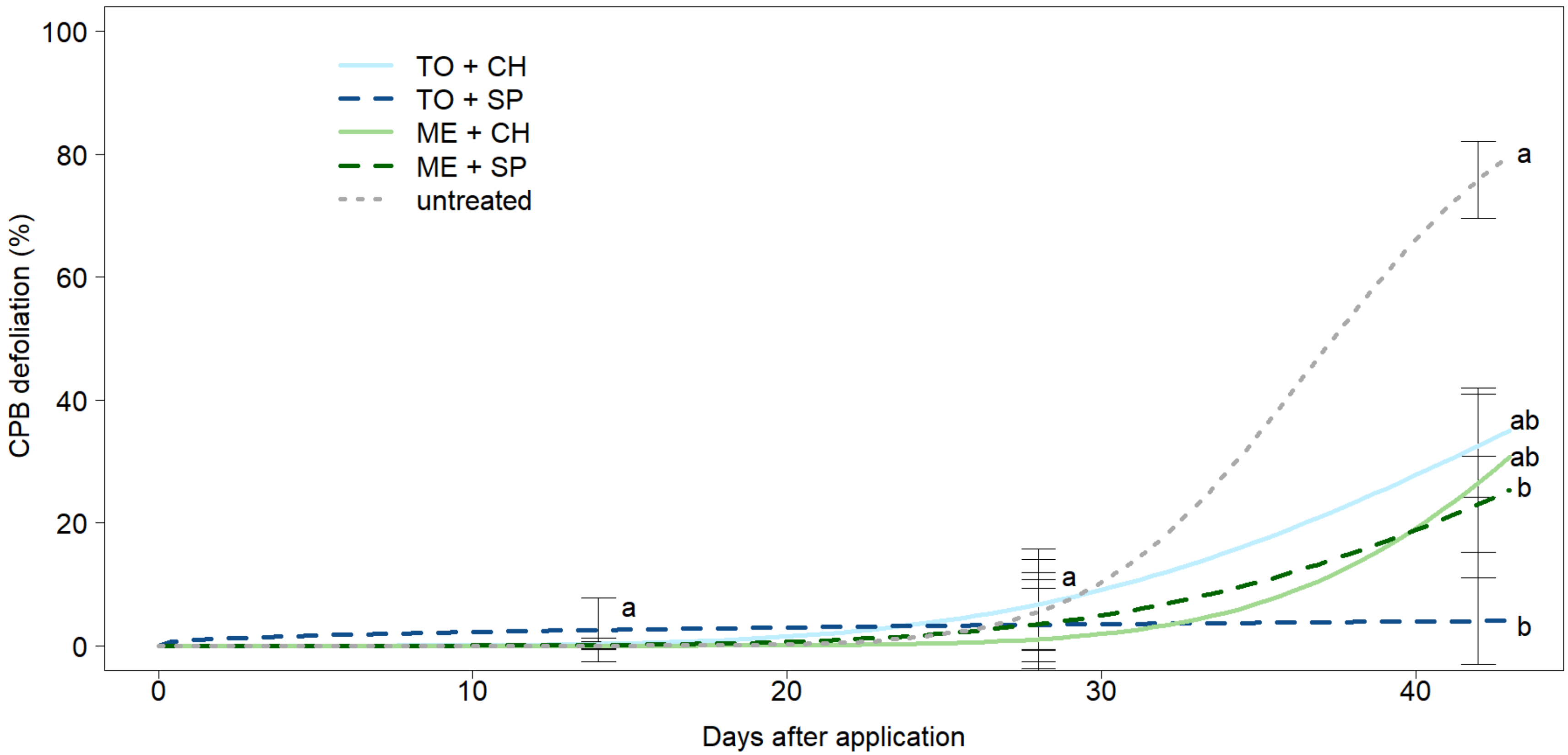

Figure 2.5. Mean (SE) volunteer potato defoliation by Colorado potato beetle (CPB) impacted by herbicide-insecticide treatment in the disk tillage system at the Kellogg Biological Station site-year in the fall study. Bars sharing the same letter within an evaluation timing (14, 28, and 42 d) are not statistically different ($\alpha = 0.05$). Abbreviations: TO, topramezone; ME, mesotrione; SP, spinetoram; CH, chlorantraniliprole.

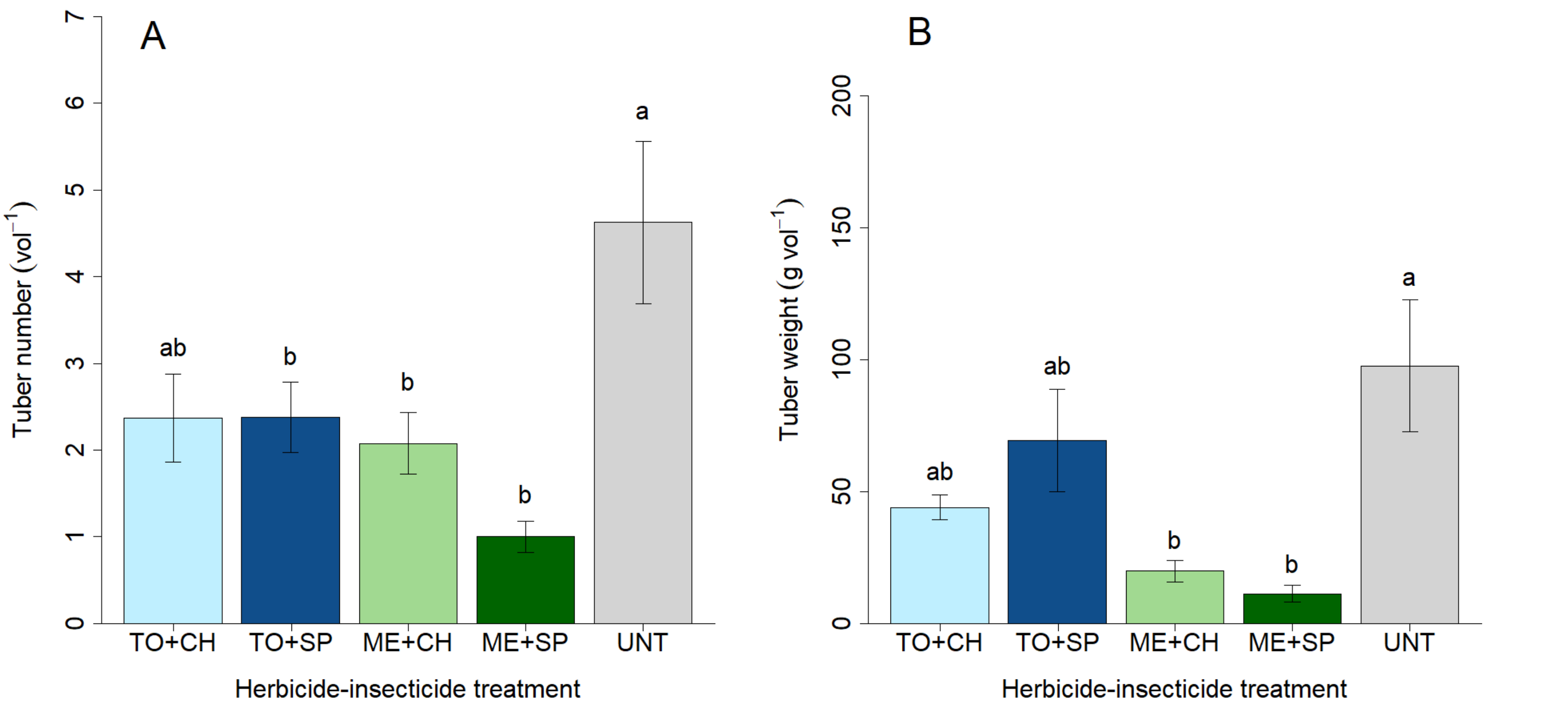

Figure 2.6. Mean (SE) number (A) and weight (B) of volunteer potato daughter tuber production impacted by herbicide-insecticide treatment in the plow tillage system at the Kellogg Biological Station site-year in the fall study. Bars sharing the same letter are not statistically different ($\alpha = 0.05$). Abbreviations: TO, topramezone; ME, mesotrione; SP, spinetoram; CH, chlorantraniliprole; UNT, untreated.

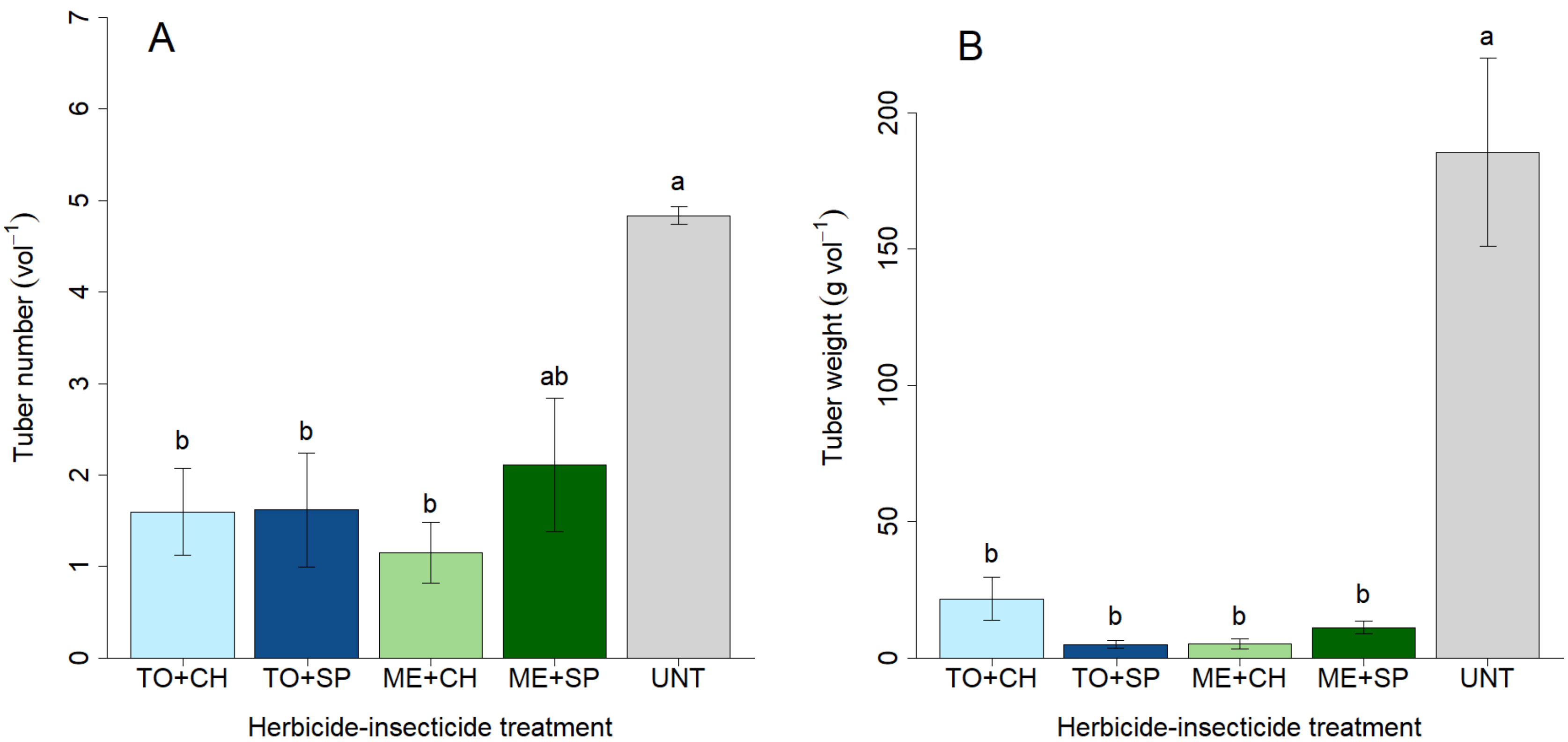

Figure 2.7. Mean (SE) number (A) and weight (B) of volunteer potato daughter tuber production impacted by herbicide-insecticide treatment in the disk tillage system at the Kellogg Biological Station site-year in the fall study. Bars sharing the same letter are not statistically different ($\alpha = 0.05$). Abbreviations: TO, topramezone; ME, mesotrione; SP, spinetoram; CH, chlorantraniliprole; UNT, untreated.

CHAPTER III: INVESTIGATING COLORADO POTATO BEETLE MANAGEMENT USING DELAYED POTATO TRAP CROP PLANTING

Abstract

Potato production is threatened annually by the major insect pest Colorado potato beetle (CPB; *Leptinotarsa decemlineata* (Say); Coleoptera: Chrysomelidae) which defoliates the plant canopy resulting in yield loss. Increased severity of canopy defoliation can occur in growing regions where CPB develop a summer generation. Therefore, field experiments were conducted in 2023 and 2024 at the Montcalm Research Center near Lakeview Michigan, to evaluate the use of late planted potato traps to control summer generation CPB. Experiments included three trap crop planting timings at 0, 2, and 4 wks after the main potato crop. A systemic insecticide, imidacloprid, was applied in-furrow at planting to manage CPB on potato trap crops. In both site-years, trap crop planting timing modified CPB densities, however this was location and evaluation timing dependent. In 2023, adult CPB density was greater in the 2 wk trap crop treatment at 55 and 62 days after planting (DAP) relative to other treatments. In 2024, extreme densities of larvae resulted in complete defoliation of all trap and main crops rows by 60 DAP. Despite localized differences in CPB density throughout trap crop rows, no differences were observed in the rate of canopy loss or yield of main potato crops planted adjacent to each trap crop. While differences in yield were observed between trap crop plots in 2023, yield was extremely reduced in 2024 due to complete skeletonization of plants. Therefore, while trap crop planting timing can alter CPB colonization along field edges, management of CPB cannot be achieved through imidacloprid-treated trap crops alone. Findings of this study highlight the potential that delayed trap crop planting could be utilized to maintain CPB concentrations at field edges to allow for targeted foliar applications of insecticides.

Introduction

Colorado potato beetle (CPB; *Leptinotarsa decemlineata* (Say); Coleoptera: Chrysomelidae) is an economically damaging pest in potato production. Regarded as the most important insect defoliator of potatoes (Alyokhin 2009), CPB can completely destroy potato crops if left unmanaged. Yield reductions up to 91% have been reported from CPB defoliation of the plant canopy (Stieha and Poveda 2015). In commercial potato production yield loss can vary significantly depending on the variety, plant growth stage at the time of defoliation, length of defoliation, and location of defoliation on the plant (Hoback et al. 2021). Widespread insecticide resistance to all major classes of insecticides used in commercial production (Alyokhin et al. 2008) increases the difficulty of effectively managing this pest in potato growing regions.

In Michigan, CPB is a detrimental pest to the potato industry, causing significant crop loss annually. Michigan produces over 900,000 MT of potatoes annually, ranking seventh in overall production nationally and first for potatoes utilized for chip production (USDA-NASS 2024, Michigan Potatoes Industry Commission 2023). Potatoes are grown on over 20,000 hectares throughout the state (USDA-NASS 2024), many of which are threatened annually by numerous pests, including CPB.

Control of CPB in potato production relies heavily on the use of insecticide applications. Imidacloprid is a neonicotinoid insecticide which provides systemic control of CPB (Crossley et al. 2018). This product has been widely adopted since its release and is commonly applied at planting to provide systemic control for multiple weeks into the season (Blom et al. 2002). While in-furrow applications of imidacloprid provide a first line of defense against early season CPB, multiple in-season foliar applications of insecticides are often necessary in regions with high CPB pressure.

The lifecycle of CPB includes eggs, four larval stages, a pupal stage, and an adult stage (Maharijaya and Vosman 2015). The timing of emergence of overwintered adults in the spring, as well as development through life stages, is dictated by temperature and the accumulation of degree days (DD) (Pulatov et al. 2016). CPB infestations on potato crops increases through the development of multiple generations within a growing season. Adults can produce up to three generations per year depending on the environmental conditions of the growing region (Ferro et al. 1985, Pulatov et al. 2016). Development of one CPB generation requires between 300-400 DD (base 10°C) (Alyokhin and Ferro 1999). In Michigan, a summer generation of CPB is observed each year, thus increasing crop loss caused by this pest. Since larval stages can cause severe defoliation, development of summer generation larvae results in increased defoliation mid-season (Alyokhin 2009).

Exploiting the spatial dynamics of this pest is integral for effective management. When overwintered adults emerge in the spring, they seek out nearby food sources through flying or walking. However, flight requires development of flight muscles through an accumulation of 150-200 DD and is encouraged by lack of nearby food sources (Caprio and Grafius 1990, Voss and Ferro 1990, Yang 1994). Therefore, short distance dispersal by walking to nearby fields is common in the spring. As a result, crop damage is first observed on field edges as CPB move into fields (Szendrei et al. 2009). Management practices often target high concentrations of CPB along field edges as they move into crops.

Habitat manipulation via trap crops is one example of management that utilizes the spatial dynamics of CPB. Trap crops are plants utilized to decrease damage in a main crop by attracting, diverting, intercepting, or retaining targeted pests (Shelton and Badenes-Perez 2006). The way in which trap crops can be deployed depends largely on the characteristics of the target pest and its interaction with the main crop. Shelton & Badenes-Perez (2006), define conventional trap cropping as the practice of planting a trap crop next to a high value crop to either decrease the likelihood the pest reaches the main crop, or concentrating the pest to allow for management to a smaller area that is more economical. This is further defined by the specific deployment of the trap crop within the habitat including perimeter (placed around the border of the main crop), sequential (altering the timing of planting in relation to the main crop), multiple (planting multiple species simultaneously), or push-pull (integrating an attractive trap crop with a repellent intercrop). Furthermore, the effectiveness of trap crops can be increased through combining trap crop planting with supplemental biological or insecticidal management practices.

In the case of CPB, both perimeter and sequential trap cropping can aid in management through targeting CPB emerging from overwintering sites. Previous research by Hoy et al. (2000) examined the use of barrier trap crops planted around potato field edges to deter CPB colonization and reported that while trap crops had only a localized effect on CPB, thus, increasing the effectiveness of trap crops requires management within the trap crop. Additionally, this research reported CPB colonization of potato trap crops when borders were planted earlier in the season relative to main crops. Potato trap crop research has also included the use of synthetic host volatile blends to attract CPB to trap crop areas thus increasing the concentration in a small space that can be managed using foliar insecticide applications (Martel et al. 2005). Overall, trap crops are a useful tool in aiding the management of CPB.

Previous research has focused only on targeting CPB emerging from overwintering sites using early-planted trap crops (prior to main potato crop planting). However, with increased damage resulting from the development of summer generation CPB, there is potential that altering the sequential aspect of trap crop planting could help reduce mid-season pressure. By applying a systemic insecticide to trap crop seed and delaying trap crop planting relative to the main crop, mid-season crop loss could be reduced. Therefore, the overall goal of this study was to evaluate the use of combined perimeter and sequential trap crops treated with systemic insecticides to manage CPB in potato crops. Specific objectives were to investigate the impact of delayed trap crop planting timing on control of second generation CPB, canopy loss, and yield of the potato main crop.

Methods and Materials

Field trials were conducted at the Michigan State University Montcalm Research Center (MRC) near Lakeview MI in 2023 (MRC-23) (43.3525385ºN, -85.1745611ºW) and 2024 (MRC-24) (43.3525385ºN, -85.1745635ºW) to investigate the impacts of delaying potato trap crop planting on the dynamics of summer generation CPB. The previous crop was potatoes in both years. In the spring, the plot area was chisel plowed prior to planting potatoes. Studies followed a grower standard fertilizer program (Table 3.1).

To examine the impacts of CPB defoliation on potato crops, trials were planted next to an area on the farm in continuous potato rotation (CPB nursery) to support the survival of CPB populations (Figure 3.1). Trials were arranged in a randomized complete block design with four replications. To represent a cultivated potato crop, main crop plots were planted 12 rows wide by 6 m long using Snowden potato seed. Potato trap crops were then planted in between the CPB nursery and main crop plots, to evaluate the movement of CPB from the nursery into the trap and main crop rows (Figure 3.1). Trap crop plots were 6 rows wide by 6 m long and planted with Dark Red Norland potato seed for visual differentiation between trap and main crop rows. All plots had a between-row spacing of 86 cm, a between-seed spacing of 25 cm, and seed depth of 13 cm.

Treatments included three delayed trap crop planting timings: 0, 2, or 4 wks after the main crop planting (Table 3.1). All potato seed was treated in-furrow at planting with the systemic insecticide, imidacloprid at 0.35 kg ai ha^{-1}, with the goal of managing second generation CPB (Bayer Crop Science, St Louis, MO).

Data Collection

To evaluate CPB movement across plot rows, data collection points were established after planting in alternating rows across plots (Figure 3.1). Data collection rows were labeled 1-9, rows 1-3 were trap crop rows and rows 4-9 were main crop rows. Data collection points within rows were 1 m long by the row width.

CPB density was evaluated by counting the number of eggs, larvae, and adults in each data collection point every 7-10 d starting approximately 50 d after planting (DAP) and continuing through the end of the season. Canopy loss from CPB defoliation was evaluated every 7-10 d by taking a photo of each data collection area. The photo area was defined by a quadrat 1 m long by 0.86 m wide that was placed on 20 cm legs to account for potato hills. Pictures were cropped to the exact quadrat dimensions to measure canopy only in the data collection area. To analyze the percent green cover, photos were uploaded to the online app Canapeo (Oklahoma State University, Stillwater, OK), in which photos were processed using ratios of red to green and blue to green at thresholds of 95%, and an excess green index of 20 (Patrignani and Ochsner 2015). This analysis resulted in fractional green canopy ratings ranging from 0-100%, with 0 indicating no green canopy and 100% indicating complete green canopy cover.

To compare yield, two rows were harvested from four sections of the plot area (Figure 3.1). This included the middle of the trap crop (A), in the main crop right next to the trap crop (B), in the middle of the main crop (C), and furthest away from the trap crop (D).

Statistical Analysis

CPB Density

To determine the impacts of trap crop planting timing and row location on CPB density, linear mixed effects models were constructed using the lmer function in R v. 4.4.0 (R Core Team 2024). Site-year, trap crop planting timing, row number, and their interaction were considered fixed effects and replication and replication nested within site-year were considered random effects. When site-year was significant, site-years were analyzed separately. Differences in means were further investigated using Tukey's HSD post hoc tests in the EMMEANS package in R (Lenth 2024). Treatment means were separated using an $\alpha \leq 0.05$. To compare the effect of row location on CPB density between treatments, trap crop rows (1-3) were analyzed separately from main crop rows (4-9) in each site-year (Figure 3.1). CPB density was separated by lifestage (egg, larvae, and adult) and compared separately for each evaluation timing to provide insight into the timing of CPB colonization by lifestage.

Canopy Loss

Canopy loss data were analyzed via nonlinear regression using the drc package in R v. 4.4.0 (R Core Team 2024, Ritz et al. 2015) following the methods outlined in Knezevic et al. (2007). Model fit was evaluated for each row using the *drc modelFit* function in R, which is a lack-of-fit test, only models with P-values > 0.05 were chosen for analysis with one exception in which the model that yielded the smallest standard error values were chosen for analysis (Table 3.2). Models selected included three- and four-parameter log-logistic models (Equations 1,2), three- and four-parameter Weibull type two models (Equations 3, 4) (Ritz et al. 2015).

$$Y = \frac{d}{1 + \exp\left[b(\log x - e)\right]} \qquad [1]$$

For equation 1, Y is the average percent of potato canopy cover (response variable), *d* is the upper limit (fixed at 100), *b* is the slope, *x* is the days after planting, and *e* is the inflection point (Ritz et al. 2015).

$$Y = c + \frac{d - c}{1 + \exp\left(b(\log(x) - \log(e))\right)} \qquad [2]$$

For equation 2, Y is the average percent of potato canopy cover (response variable), *c* is the lower limit (fixed at 0), *d* is the upper limit (fixed at 100), *b* is the slope, *x* is the days after planting, and *e* is the inflection point (Ritz et al. 2015).

$$Y = d\ exp(1 - \exp(-\exp(b(\log(x) - \log(e))))) \qquad [3]$$

For equation 3, Y is the average percent of potato canopy cover (response variable), *d* is the upper limit (fixed at 100), *b* is the slope, *x* is the days after planting, and *e* is the inflection point (Ritz et al. 2015).

$$Y = c + (d - c)(1 - \exp(-\exp(b(\log(x) - \log(e))))) \qquad [4]$$

For equation 4, Y is the average percent of potato canopy cover (response variable), *c* is the lower limit (fixed at 0), *d* is the upper limit (fixed at 100), *b* is the slope, *x* is the days after planting, and *e* is the inflection point (Ritz et al. 2015).

To understand the spatial aspect of CPB defoliation of canopy, each row of the main crop (rows 4-9) was analyzed separately for each site-year. To evaluate the rate of CPB canopy defoliation, the number of days for canopy to be reduced to 80 and 20% were compared between treatments within each row.

Yield

To determine the impacts of trap crop planting timing on yield, linear mixed effects models were constructed using the lmer function in R 4.4.0 (R Core Team 2024). Site-year, trap crop planting timing, and their interaction were considered fixed effects and replication and replication nested within site-year were considered random effects. When site-year was significant, site-years were analyzed separately. Yield was analyzed averaged across row in order to compare the impact of defoliation on yield of trap and main crops. Differences in means were further investigated using Tukey's HSD post hoc tests in the EMMEANS package in R (Lenth 2024). Treatment means were separated using an $\alpha \leq 0.05$.

Results

CPB Density

MRC-23 and MRC-24 site-years were analyzed separately due to extreme differences in CPB pressure between site-years (Table 3.3-6).

MRC-23 Trap Crop Rows

In trap crop rows at MRC-23, there was no difference in CPB egg number amongst treatments 47 DAP (Table 3.3). The number of larvae 47 DAP was impacted by the main effect of trap crop planting timing. Averaged across row number, the number of larvae decreased by 92% in the 2 and 4 wk treatments relative to the 0 wk treatment, however larval numbers were relatively low, averaging 1.1 larvae m^{-1}. The number of adults was impacted by the interaction of trap crop planting timing and row number 47 DAP. Row 1 of the 2 wk treatment had 6 adults m^{-1}, which was greater than all other treatments.

At 55 DAP, there was no difference in the number of eggs or larvae amongst any treatments (Table 3.3). The number of adults was impacted by trap crop planting timing. Averaged across row number, the 0 wk treatment reduced the number of adults by 61% relative to the 2 wk treatment, which averaged 21.8 adults m^{-1}. There was no difference in adult number when the trap crop was planted 2 or 4 wks after the main crop.

At 62 DAP, there was no difference in the number of eggs or larvae amongst treatments (Table 3.3). The number of adults was impacted by the main effect of trap crop planting timing. Averaged across row number, the 0 wk treatment decreased the number of adults by 60% relative to the 2 wk treatment which averaged 18.9 adults m^{-1}. There was no difference in adult number when the trap crop was planted 2 or 4 wks after the main crop.

At 69 DAP, trap crop planting timing, row number, or their interaction did not impact the number of eggs or adults (Table 3.3). The number of larvae was impacted by the main effect of trap crop planting timing. Averaged across the main effect of row number, larvae in the 0 and 2 wk treatments were reduced by 97 and 99%, respectively, relative to the 4 wk treatment which averaged 1.4 larvae m^{-1}.

At 78 DAP, there was no difference in the number of eggs or larvae amongst treatments (Table 3.3). The number of adults was impacted by the main effect of trap crop planting timing. Averaged across row number, the 0 and 2 wk treatments reduced the number of adults relative to the 4 wk treatment by 94 and 88%, respectively.

MRC-23 Main Crop Rows

In the main crop rows, there was no difference in CPB egg, larvae, or adult number amongst treatments 47 DAP (Table 3.4). At 55 DAP, there was no difference in the number of eggs or larvae amongst treatments. The number of adults was impacted by the main effect of row number. Averaged across trap crop planting timing, rows 4 and 5 each contained 5.3 adults m^{-1} compared to only 2.8 and 2.6 adults m^{-1} in rows 8 and 9, a 74 and 68% reduction, respectively.

At 62 DAP, the number of eggs was impacted by row number (Table 3.4), however all counts were very low averaging less than 1 egg m^{-1}. There was no difference in the number of larvae 62 DAP. The number of adults was impacted by the main effect of row number. Averaged across trap crop planting timing, row 5 averaged 9.4 adults m^{-1}. In all other rows, the number of adults was 44-71% less than row 5.

At 69 DAP, there was no difference in number of eggs or adults amongst treatments (Table 3.4). The number of larvae was impacted by row number. Averaged across trap crop treatment, row 8 had 4.3 larvae m^{-1}. The number of larvae in rows 4, 5, 7, and 9 decreased by at least 70% relative to row 8. At 78 DAP, there was no difference in number of eggs, larvae, or adults amongst treatments (Table 3.4).

MRC-24 Trap Crop Rows

At 50 DAP in trap crop rows at MRC-24, the number of eggs, larvae, and adults were each impacted by the main effect of trap crop planting timing (Table 3.5). Although statistically different, the egg counts were all very low averaging less than 1.3 eggs m^{-1}. Larval pressure measured 50 DAP was extreme, ranging from 11-175 larvae m^{-1}, averaged across row number. When the trap crop was planted 0 or 4 wk after the main crop, the number of larvae m^{-1} was reduced by 59 and 68%, compared to the 2 wk treatment, respectively. Furthermore, when the trap crop was planted 0 or 2 wks after the main crop the number of adults m^{-1} decreased by 78 and 83%, compared to the 4 wk treatment.

At 57 DAP, there was no difference amongst treatments in the number of eggs or adults (Table 3.5). The number of larvae was impacted by the interaction of trap crop planting timing and row number. When the trap crop was planted 4 wk after the main crop, the number of larvae m^{-1} in rows 2 and 3 were reduced by 62 and 82% compared to row 1 which had 151.3 larvae m^{-1}. All other rows in each planting timing treatment reduced the number of larvae by at least 92%.

At 64 DAP, there was no difference in the number of eggs or larvae amongst treatments (Table 3.5). The number of adults was impacted by row number. Averaged across all planting timing treatments, the number of adults in row 1 was the greatest with 3.8 adults m^{-1}. Rows 2 and 3 were not different from each other, averaging 2.1 adults m^{-1}, which was a 46% decrease from row 1.

MRC-24 Main Crop Rows

In MRC-24 main crop rows at 50 DAP, the number of eggs and adults was not impacted by treatments (Table 3.6). The number of larvae was impacted by the main effects of trap crop planting timing and row number, but not their interaction. Averaged across row number, the 2 wk treatment reduced the number of larvae relative to the 4 wk treatment by 37%. The number of larvae was 79.6 m^{-1} in the 4 wk and 50.2 m^{-1} in the 2 wk treatment. Averaged across trap crop planting timing, row 8 and 9 had the highest larvae pressure with 98.2 and 86.7 m^{-1}, respectively. In rows 4, 5, 6, and 7 the number of larvae was reduced by 41-64% relative to row 8 where the greatest pressure was observed. Row 4 reduced the number of larvae by 59% relative to row 9.

At 57 and 64 DAP (Table 3.6), the number of eggs, adults, or larvae were not impacted by any of the treatments. Overall, at 57 and 64 DAP CPB density of each life stage was less than 6 m^{-1}.

Canopy Loss

MRC-23 and MRC-24 site-years were analyzed separately due to differences in rate of canopy loss between site-years due to extreme differences in CPB pressure outline above. Since trap crop treatments had variable canopy size due to differences in planting timings, canopy loss was evaluated in main crop rows only. At MRC-23, canopy cover was measured from the time of peak canopy (50 DAP) until the end of the season (78 DAP). At MRC-24 canopy cover was measured from peak canopy (50 DAP) until complete canopy loss (64 DAP).

In all main crop rows at MRC-23, trap crop planting timing did not impact the number of days it took for canopy to be reduced to 80 and 20% (Figure 3.2A-F). Canopy cover loss was highly variable within treatments, resulting in no distinguishable differences between treatments. However, in all rows and treatments, canopy cover decreased over time.

In all main crop rows at MRC-24, trap crop planting timing did not impact the number of days it took for the canopy to be reduced to 80 and 20% across all rows (Figure 3.3A-F). Overall, canopy loss occurred early in the season and was rapid. In all rows (Figure 3.3A-F), complete canopy loss (0% canopy cover) occurred by 60 DAP in all treatments.

Yield

Yield was analyzed separately for MRC-23 and MRC-24 due to variability between site-years. In MRC-23, yield was impacted by trap crop treatment (F =6.89; df =5, 27; P= 0.0001). However, in main crop plots which were planted adjacent to trap crop timing treatments, there was no difference in yield (Figure 3.4). This indicates that the adjacent trap crop treatment did not affect the level of yield loss in main crops. Differences in yield occurred between trap crop treatments. When trap crop planting was delayed by 2 or 4 wks, yield was reduced by 66 and 52% respectively, relative to the trap crop planted at 0 wk. There was no difference between the 2 and 4 wk planted trap crops. In the trap crop treatment planted at the same time as the main crop (0 wk), yield was between 49-71% greater than the main crop plots.

In MRC-24, yield was impacted by trap crop treatment (F =4.32; df =5, 29; P= 0.0032). However, extreme defoliation resulted in extremely low yields across treatments ranging from 0-0.65 MT ha^{-1} (Figure 3.5). Amongst main crop plots, there was no difference in yield between treatments. There was also no difference in yield amongst trap crop treatments. Yields of trap crops planted at 2 and 4 wks were decreased by 98 and 100%, relative to the yield of the main crop planted next to the 2 wk delayed trap crop treatment, however, this difference is not biologically relevant due to extremely low yields across treatments.

Discussion

This study utilized three common conventional trap crop approaches including: (1) perimeter trap cropping to target CPB movement from field edges inward, (2) sequential trap cropping to match trap crop planting timing to summer generation development, and (3) additional insecticide control to supplement the effects of the trap crop (Shelton and Badenes-Perez 2006). It was hypothesized that by utilizing these trap cropping approaches, second generation CPB pressure and canopy loss in main potato crops could be decreased by planting a delayed potato trap crop around field edges that was treated with the systemic insecticide, imidacloprid. Trap crop planting timings of 0, 2, and 4 wks after the main crop were evaluated. Differences were observed in CPB density across trap and main crop rows due to trap crop planting treatment, however, treatments did not reduce the rate of canopy loss or improve yield in the main crop planted next to trap crop.

At MRC-23, the density of CPB eggs and larvae observed was low throughout the season, averaging less than 1 egg and less than 5 larvae m^{-1} across trap and main crop rows. Differences in CPB density in this site-year were most notable in the number of adults in trap crop rows mid-season. The number of adults was the greatest at 55 and 62 DAP in the 2 wk trap crop treatment with greater than 18 adults m^{-1}. Conversely, across all treatments and rows in the main crop, the number of adults remained below 10 m^{-1} throughout the season.

To assist growers with managing this pest, Michigan State University has developed a CPB prediction model for Michigan counties which estimates the timing of lifecycle development based on accumulation of DD (base 11°C) since the time of planting (Enviroweather 2024).

In 2023, the greatest CPB pressure was observed in the number of adults present between 55 and 62 DAP, which occurred on July 24-31. The Enviroweather model predicted the emergence of summer generation adults to occur on July 17 following an accumulation of 820 DD from planting. From May 30 (planting) to July 24 (55 DAP), there was an accumulation of 839 DD (Table 3.7). Therefore, the peak in adults observed mid-season is consistent with the model prediction of summer generation adult emergence.

The model does not estimate the emergence of summer generation eggs, larva, or adults. No increase in the number of eggs or larva was observed following the emergence of summer generation adults and the number of adults decreased at subsequent evaluation timings, which is consistent with the life cycle of CPB in this area. The decrease in adults after 62 DAP indicates summer generation CPB adults moved into nearby fields to begin overwintering.

At MRC-24, elevated larval pressure occurred early in the season leading to severe levels of canopy loss. Across all treatments in both main and trap crop rows, larvae densities at 50 DAP were the greatest observed throughout the season. An extreme density of larvae was observed in the 2 wk trap crop treatment at 50 DAP, averaging 170 m^{-1}. Throughout the rest of the season, the density of all CPB life stages was low.

The peak larval pressure observed on June 25 (50 DAP) is consistent with the estimate from the Enviroweather model. For 2024, this model predicted peak larvae emergence occurring between June 3 and June 13, following an accumulation of 300-420 DD since planting. There was an accumulation of 688 DD from May 6 (planting) to June 25 (50 DAP) (Table 3.7) when the first evaluation timing was completed in this site-year. Therefore, this indicates peak larvae pressure had already occurred before the first evaluation was completed in MRC-24.

Following the peak of overwintered generation larval pressure, the density of all other life stages was low at subsequent evaluation timings. This can be explained by the severe canopy loss that occurred by July 5 (60 DAP). Compared to other life stages, defoliation of potato canopy is the most severe from third and fourth instar stage larvae (Alyokhin 2009). Extreme larval pressure early in the season resulted in complete canopy loss by 60 DAP across all rows (Figure 3.3A-F). Since severe defoliation encourages CPB emigration (Boiteau et al. 2003), CPB moved out of the plot area once plants had been completely skeletonized. Therefore, summer generation CPB were never observed in the trap or main crop plots in MRC-24. This trend is consistent in both 2023 and 2024, however, the rapid movement of CPB out of the plot area was more pronounced in 2024 due to increased severity of defoliation earlier in the season.

In commercial production, CPB management is determined based on economic thresholds (ET) which indicate when management should occur using economic injury levels of plant defoliation. While yield response to potato defoliation is highly variable, a conservative ET of 10% defoliation is commonly utilized by producers (Hoback et al. 2021). Therefore, using this defoliation threshold, foliar insecticide applications would have occurred at approximately 60 DAP in MRC-23 and 55 DAP in MRC-24, based on the level of canopy loss at these times (Figure 3.3 and Figure 3.4). Furthermore, due to insecticide resistance concerns in regions with high CPB pressure, management plans aim to optimize control using rotated insecticide treatments and application windows based on peak times of CPB development (Huseth et al. 2014). Therefore, based on grower standard practices, the CPB pressure observed in both site-years of this study would have required additional management using foliar insecticide applications in addition to in-furrow treatment.

The variability in CPB colonization and development between site-years can be explained by differences in temperatures and DD. CPB emergence in the spring is dictated by soil temperature (Liao et al. 2021). The average temperature in November, February, and March were warmer in MRC-24 than MRC-23 (Table 3.8). In 2023, the average temperature in March was -2.03°C and by the end of April 102 DD had accumulated. Conversely, in 2024 the March average temperature was 3.69°C and the DD accumulation at the end of April was 131 DD. CPB are capable of altering the length of overwintering time in the soil in order to reduce their risk of exposure to low temperatures (Liao et al. 2021). Therefore, it is likely that the increased spring temperatures in MRC-24 led to earlier CPB emergence and host plant colonization than in MRC-23.

Additionally, the difference in CPB pressure observed between the two site-years may be attributed to decreased survival due to harsh winter conditions. While winter mortality of CPB is highly variable based on temperature, soil type, soil moisture, and timing of temperature fluctuations, natural mortality can occur from exposure to extreme cold (Izzo et al. 2014). Therefore, it is possible that the high larval pressure observed in MRC-24 was due to the milder winter temperatures, relative to MRC-23. Furthermore, the mild winter in 2024 increased volunteer potato survival at MRC where studies were conducted, because potato tuber mortality over the winter is dependent on exposure to lethal temperatures (Boydston et al. 2006). Since volunteer potatoes typically emerge earlier in the season than cultivated potato crops they are an early season food source for CPB (Xu and Long 1997). Increased volunteer potato survival supported the development of CPB populations in MRC-24, contributing to the increased pressure observed in this site-year.

In both 2023 and 2024, yield results were consistent with canopy loss. In both site-years, trap crop planting treatments did not improve the yield of adjacent main crops. This is supported by the rate of canopy loss, which did not differ between treatments in any rows.

In MRC-23 however, yield of trap crop treatments provide insight into the colonization of CPB in the spring. The increased yield in the 0 wk trap crop treatment relative to the 2 and 4 wk treatments reflects the additional time this crop had to develop. Interestingly, the yield of the 0 wk trap crop treatment was greater than the yield of the main crops. The greater CPB density observed in the 2 wk treatment mid-season most likely explains this. It is possible that CPB dispersed from the 2 wk trap crop treatment to main crop rows, providing extra time for the 0 wk trap crop treatment rows to develop.

In MRC-24, the extreme canopy loss that occurred early in the season resulted in poor yields across treatments. While there were some minor differences between treatments, these were not biologically relevant due to the overall extreme reductions in yield across both trap and main crops. This site-year demonstrates that the management practices proposed in this study cannot effectively control extreme populations of CPB. Additional management would be required to prevent yield loss when CPB pressure is severe. Overall, yield reductions from canopy loss in potatoes are highly variable. Differences between varieties and growth habit (indeterminate versus determinate) as well as the timing and severity of defoliation will largely affect the impact defoliation has on yield (Hoback et al. 2021).

Several trap cropping systems have been proposed across various types of crop production and reported limited success in controlling the target pest (Pearsall 2000, Sequeira

2001, Åsman 2002, Shelton and Nault 2004). Implementing a successful trap crop system can be difficult due to many variables including insect ecology and behavior, the insect's interaction with the crop, and the practical considerations of implementing the system (Shelton and Badenes-Perez 2006).

Difficulties in managing CPB using delayed trap crop treatments can be attributed to the spatial dynamics of this pest in combination with its variable development depending on environmental conditions. Since CPB emerge from overwintering sites and colonize nearby fields first by walking and then by flying, crop damage is typically first observed on field edges and progresses inward as plants are fully defoliated. While CPB densities were greater in some trap crop treatments on the edge of the main crop, full defoliation of all rows by CPB eventually occurred in both site-years. Similarly, Hoy et al. (2000) reported localized reductions in CPB number within and right beyond trap crop barrier treatments, however, these treatments did not impact density further into the field.

Additionally, management of summer generation CPB is difficult because of the variability in development. In MRC-24, complete canopy loss resulted from overwintered generation larvae, so adults moved from the trial area by the time summer generation CPB developed. Since the accumulation of DD was slower in MRC-23 than MRC-24, the development of CPB through each life stage was slower. This led to a slower rate of canopy loss in MRC-23 compared to MRC-24. This highlights the variability in CPB pressure that can be observed between years, which contributes to the difficulty of effectively timing trap crop planting to target second generation CPB. Future research should integrate the use of DD prediction models to target specific life stages and development of CPB.

Previous research evaluating the integration of potato trap crops has demonstrated the potential for trap crops to increase the concentrations of CPB in a localized region allowing for targeted insecticide applications (Martel et al. 2005). Similarly, Boucher et al. (2003) reported the greatest protection from pepper maggot (*Zonosemata electa* (Say); Diptera: Tephritidae) in bell peppers through combinations of perimeter trap crop treated with foliar insecticide applications. Since pressure from first generation CPB caused enough canopy loss that CPB had moved from the plot area by the time the second generation developed in both site-years, future research should include the use of targeted spray applications to trap crops to increase their effectiveness. This approach would only be applicable if producers have extremely conservative threshold for crop loss on field edges of the main plot and therefore want to utilize a trap crop for targeted insecticide applications to increased concentrations of CPB.

In conclusion, CPB are a notorious pest of potatoes that can cause severe crop damage through complete defoliation of plants. Management of CPB is difficult due to widespread insecticide resistance, pressure from multiple generations within a season, and variability in development. Exploiting the spatial dynamics of how CPB colonize potato fields from the edges inward is an important aspect of management. In this study, planting sequential, insecticide treated potato trap crops along the field perimeter altered CPB density at several evaluation timings. In both site years, density was increased in the trap crop treatment planted 2 wk after the main crop. However, due to overall high overwintered generation CPB pressure, trap crop treatments alone were unable to prevent canopy and yield loss in main crops. Therefore, this demonstrates the potential that delayed trap crops could be used to maintain a concentration of CPB that can be targeted with insecticide applications. Localized insecticide applications would be beneficial to reduce the volume of insecticide applications needed compared to spraying entire fields. Future research should integrate trap crop planting with a grower standard insecticide plan by making targeted applications to trap crops. Additionally, the use of CPB prediction models should be utilized to more precisely target specific CPB generations and life stages when considering trap crop planting timing.

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APPENDIX A: CHAPTER III TABLES

Table 3.1. Potato varieties, planting dates, and soil information for both site-years of the delayed trap crop planting trial.

	Site-year[a]	
	MRC-23	MRC-24
Fertilizer		
Broadcast pre-plant		
0-0-22-11Mg-22S (kg ha^{-1})	336	532
0-0-0-21Ca-16S (kg ha^{-1})	560	560
10%B (kg ha^{-1})	14	14
0-0-62 (kg ha^{-1})	420	348
0-0-0-20Zn-12S-4Mn-1B (kg ha^{-1})	-	22
At planting		
28-0-0 (L ha^{-1})	122	122
10-34-0 (L ha^{-1})	65	65
0-0-0-9Zn (L ha^{-1})	-	5
At cultivation		
28-0-0 (L ha^{-1})	374	374
10-34-0 (L ha^{-1})	187	187
0-0-0-9Zn (L ha^{-1})	-	5
At hilling		
15.5-0-0-19CA (kg ha^{-1})	404	404
Seeding placement (cm)		
Between row spacing	86	86
Between seed spacing	25	25
Seed depth	13	13
Main crop potato variety	Snowden	Snowden
Main crop planting date	May 30, 2023	May 6, 2024
Trap crop potato variety	Dark Red Norland	Dark Red Norland
Trap crop planting dates		
0 wk	May 30, 2023	May 6, 2024
2 wk	June 13, 2023	May 20, 2024
4 wk	June 27, 2023	June 3, 2024
Soil series	Tekenink Elmdale Loamy sands	Tekenink Elmdale Loamy sands
Soil pH	6.0	6.1
Soil organic matter (%)	1.0	0.5

[a]Abbreviations: MRC-23 = Montcalm Research Center 2023, MRC-24 = Montcalm Research Center 2024.

Table 3.2. List of models used for main crop canopy loss evaluations and corresponding model fit values.

	MSU-23		MSU-24	
Main crop row number	Model	Model fit value	Model	Model fit value
4	LL.4	0.99	LL.3	0.99
5	LL.3	0.97	LL.3	0.99
6	LL.3	0.10	LL.3	0.00
7	LL.3	0.04	W2.3	0.99
8	LL.4	0.99	LL.3	0.99
9	W2.4	0.24	W2.3	0.99

Table 3.3. Mean (±SE) Colorado potato beetle (CPB) density impacted by trap crop planting timing and trap crop row at MRC-23.

Trap crop planting timing	Row no.[a]	DAP	CPB density Eggs	Larvae	Adults
			(m^{-1})		
0 wk	1	47	0 ± 0	1.3 ± 2.3a	0.8 ± 0.3b
	2	47	0.3 ± 0.3	0.5 ± 0.8a	0.3 ± 0.3b
	3	47	0 ± 0	1.4 ± 1.8a	0 ± 0b
2 wk	1	47	0.5 ± 0.5	0.5 ± 0.5b	6.0 ± 2.7a
	2	47	0 ± 0	0 ± 0b	1.3 ± 0.6b
	3	47	0.3 ± 0.3	0 ± 0b	1.0 ± 0.6b
4 wk	1	47	0 ± 0	0 ± 0b	0 ± 0b
	2	47	0 ± 0	0 ± 0b	0 ± 0b
	3	47	0 ± 0	0 ± 0b	0 ± 0b
Effects		Stats			
Trap crop planting timing		*P*	0.3136	0.0044	0.0022
		F	1.22	8.86	7.98
		df	2, 24	2, 24	2, 24
Row no.		*P*	0.8414	0.2927	0.0318
		F	0.17	1.29	4.00
		df	2, 24	2, 24	2, 24
Trap crop planting timing*row no.		*P*	0.4491	0.6120	0.0500
		F	0.96	0.68	2.78
		df	4, 24	4, 24	4, 24
0 wk	1	55	0 ± 0	1.8 ± 0.8	11.3 ± 2.5b
	2	55	0 ± 0	2.3 ± 1.0	10.5 ± 3.2b
	3	55	0 ± 0	1.5 ± 0.5	3.5 ± 1.3b
2 wk	1	55	0 ± 0	0 ± 0	13.5 ± 4.6a
	2	55	0.3 ± 0.3	0 ± 0	35.3 ± 18.5a
	3	55	0 ± 0	0.5 ± 0.3	16.5 ± 9.2a
4 wk	1	55	0 ± 0	0.8 ± 0.5	10.3 ± 4.5ab
	2	55	0.3 ± 0.3	2.0 ± 1.0	9.5 ± 3.8ab
	3	55	0.3 ± 0.3	4.3 ± 4.3	8.5 ± 2.2ab
Effects		Stats			
Trap crop planting timing		*P*	0.3727	0.2047	0.0322
		F	1.03	1.70	3.979
		df	2, 24	2, 24	2, 24
Row no.		*P*	0.3727	0.6037	0.2306
		F	1.03	0.52	1.56
		df	2, 24	2, 24	2, 24
Trap crop planting timing*row no.		*P*	0.7259	0.7476	0.3705
		F	0.51	0.48	1.12
		df	4, 24	4, 24	4, 24
0 wk	1	62	0 ± 0	0 ± 0	3.5 ± 1.0b
	2	62	0 ± 0	0 ± 0	10.3 ± 4.4b
	3	62	0 ± 0	0.5 ± 0.5	8.8 ± 1.5b

Table 3.3. (cont'd)

2 wk	1	62	0.3 ± 0.3	1.8 ± 1.4	22.8 ± 5.7a
	2	62	0 ± 0	0.5 ± 0.5	19.0 ± 3.3a
	3	62	0 ± 0	0.8 ± 0.5	14.8 ± 9.5a
4 wk	1	62	0 ± 0	0.3 ± 0.3	12.5 ± 2.5ab
	2	62	0.3 ± 0.3	0.3 ± 0.3	15.0 ± 3.0ab
	3	62	0 ± 0	0.5 ± 0.5	12.3 ± 2.4ab
Effects		Stats			
Trap crop planting timing		*P*	0.6127	0.2086	0.0092
		F	0.50	1.67	5.74
		df	2, 24	2, 24	2, 24
Row no.		*P*	0.6127	0.6627	0.6954
		F	0.50	0.42	0.37
		df	2, 24	2, 24	2, 24
Trap crop planting timing*row no.		*P*	0.3168	0.6882	0.5769
		F	1.25	0.57	0.74
		df	4, 24	4, 24	4, 24
0 wk	1	69	0 ± 0	0.3 ± 0.3b	2.0 ± 0.9
	2	69	0 ± 0	0 ± 0b	1.8 ± 0.8
	3	69	0 ± 0	0.3 ± 0.3b	2.0 ± 0.7
2 wk	1	69	0 ± 0	0 ± 0b	3.8 ± 1.8
	2	69	0 ± 0	0 ± 0b	9.0 ± 3.6
	3	69	0 ± 0	0.3 ± 0.3b	2.8 ± 1.3
4 wk	1	69	0 ± 0	2.0 ± 0.9a	5.8 ± 2.8
	2	69	0.3 ± 0.3	2.0 ± 0.6a	4.0 ± 2.0
	3	69	0 ± 0	0.3 ± 0.3a	2.5 ± 1.0
Effects		Stats			
Trap crop planting timing		*P*	0.3827	0.0077	0.1221
		F	1.00	6.00	2.30
		df	2, 24	2, 24	2, 24
Row no.		*P*	0.3827	0.5641	0.2860
		F	1.00	0.59	1.32
		df	2, 24	2, 24	2, 24
Trap crop planting timing*row no.		*P*	0.4269	0.2242	0.3017
		F	1.00	1.53	1.29
		df	4, 24	4, 24	4, 24
0 wk	1	78	0 ± 0	0.3 ± 0.3	0.3 ± 0.3b
	2	78	0 ± 0	0.3 ± 0.3	0.3 ± 0.3b
	3	78	0 ± 0	2.0 ± 1.1	0 ± 0b
2 wk	1	78	0 ± 0	1.3 ± 0.8	0.5 ± 0.3b
	2	78	0 ± 0	0.3 ± 0.3	0.8 ± 0.5b
	3	78	0 ± 0	0 ± 0	0 ± 0b
4 wk	1	78	0 ± 0	0.8 ± 0.5	2.3 ± 1.1a
	2	78	0 ± 0	0.5 ± 0.3	3.5 ± 1.2a
	3	78	0 ± 0	0.3 ± 0.3	4.5 ± 1.2a

Table 3.3. (cont'd)

Effects	Stats			
Trap crop planting timing	*P*	-[b]	0.6514	<0.0001
	F	-	0.44	24.09
	df	-	2, 24	2, 24
Row no.	*P*	-	0.5152	0.5497
	F	-	0.68	0.61
	df	-	2, 24	2, 24
Trap crop planting timing*row no.	*P*	-	0.0583	0.2461
	F	-	2.65	1.46
	df	-	4, 24	4, 24

[a]Abbreviations: DAP = days after planting, no. = number.

[b]- = No comparisons are available due to the zero occurrence of eggs 78 DAP.

Different letters indicate significant pairwise differences between treatments within a column and DAP via Tukey-HSD test applied to EMMs ($P < 0.05$).

Table 3.4. Mean (±SE) Colorado potato beetle (CPB) density impacted by trap crop planting timing and main crop row at MRC-23.

		CPB density		
Main effects	DAP[a]	Eggs	Larvae	Adults
Trap crop planting timing		(m⁻¹)		
0 wk	47	0 ± 0	2.0 ± 0.8	0.3 ± 0.1
2 wk	47	0 ± 0	1.0 ± 0.3	0.6 ± 0.2
4 wk	47	0 ± 0	1.0 ± 0.4	0.6 ± 0.2
Row no.				
4	47	0 ± 0	1.8 ± 0.7	0.7 ± 0.3
5	47	0 ± 0	0.5 ± 0.2	1.0 ± 0.3
6	47	0 ± 0	1.3 ± 0.4	0.3 ± 0.1
7	47	0 ± 0	0.1 ± 0.1	0.4 ± 0.2
8	47	0 ± 0	3.1 ± 1.5	0.3 ± 0.3
9	47	0 ± 0	1.4 ± 0.7	0.4 ± 0.2
Effects	Stats			
Trap crop planting timing	*P*	-[b]	0.3391	0.2302
	F	-	1.11	1.51
	df	-	2, 51	2, 51
Row no.	*P*	-	0.1411	0.1898
	F	-	1.75	1.55
	df	-	5, 51	5, 51
Trap crop planting timing*row no.	*P*	-	0.7994	0.2796
	F	-	0.61	1.26
	df	-	10, 51	10, 51
Trap crop planting timing				
0 wk	55	0 ± 0	2.6 ± 0.7	2.5 ± 0.4
2 wk	55	0 ± 0	2.3 ± 0.5	4.1 ± 0.8
4 wk	55	0 ± 0	3.0 ± 1.2	3.0 ± 0.6
Row no.				
4	55	0 ± 0	4.7 ± 1.3	5.3 ± 1.1a
5	55	0 ± 0	1.8 ± 0.6	5.3 ± 1.0a
6	55	0 ± 0	3.9 ± 2.1	2.8 ± 0.8ab
7	55	0 ± 0	1.3 ± 0.4	2.6 ± 0.6ab
8	55	0 ± 0	2.5 ± 0.7	1.4 ± 0.5b
9	55	0 ± 0	1.7 ± 0.8	1.7 ± 0.5b
Effects	Stats			
Trap crop planting timing	*P*	0.6095	0.8669	0.0836
	F	0.50	0.14	2.62
	df	2, 51	2, 51	2, 51
Row no.	*P*	0.5549	0.2596	0.0001
	F	0.80	1.35	6.31
	df	5, 51	5, 51	5, 51
Trap crop planting timing*row no.	*P*	0.3801	0.5190	0.3931
	F	1.10	0.92	1.08
	df	10, 51	10, 51	10, 51

Table 3.4. (cont'd)

Trap crop planting timing				
0 wk	62	0.1 ± 0.1	0.5 ± 0.1	4.8 ± 0.6
2 wk	62	0.1 ± 0.1	0.9 ± 0.3	5.1 ± 0.9
4 wk	62	0.1 ± 0.2	0.4 ± 0.2	3.8 ± 0.9
Row no.				
4	62	0.1 ± 0.1ab	0.2 ± 0.8	3.0 ± 0.5b
5	62	0.2 ± 0.1ab	0.2 ± 0.6	9.4 ± 1.6a
6	62	0 ± 0b	0.4 ± 0.9	3.3 ± 0.7b
7	62	0 ± 0b	0.3 ± 0.7	5.3 ± 1.3b
8	62	0.2 ± 0.4a	0.1 ± 0.3	2.7 ± 0.6b
9	62	0 ± 0b	0.2 ± 0.3	3.6 ± 0.6b
Effects	Stats			
Trap crop planting timing	*P*	0.6329	0.1687	0.2161
	F	0.47	1.84	1.58
	df	2, 51	2, 51	2, 51
Row no.	*P*	0.0318	0.4250	<0.0001
	F	2.68	1.00	10.27
	df	5, 51	5, 51	5, 51
Trap crop planting timing*row no.	*P*	0.6851	0.7907	0.3490
	F	0.74	0.62	1.15
	df	10, 51	10, 51	10, 51
Trap crop planting timing				
0 wk	69	0.1 ± 0.1	1.3 ± 0.6	1.8 ± 0.3
2 wk	69	0.4 ± 0.3	2.0 ± 0.7	2.4 ± 0.4
4 wk	69	0 ± 0	1.5 ± 0.3	1.7 ± 0.3
Row no.				
4	69	0 ± 0	1.3 ± 0.5b	1.7 ± 0.8
5	69	0 ± 0	0.4 ± 0.2b	1.7 ± 0.3
6	69	0.2 ± 0.2	2.3 ± 0.7ab	1.7 ± 0.4
7	69	0.1 ± 0.1	0.7 ± 0.2b	2.6 ± 0.6
8	69	0.7 ± 0.5	4.3 ± 1.4a	2.2 ± 0.4
9	69	0 ± 0	0.5 ± 0.2b	2.1 ± 0.4
Effects	Stats			
Trap crop planting timing	*P*	0.1897	0.6350	0.3270
	F	1.72	0.46	1.14
	df	2, 51	2, 51	2, 51
Row no.	*P*	0.2055	0.0018	0.7610
	F	1.50	4.51	0.52
	df	5, 51	5, 51	5, 51
Trap crop planting timing*row no.	*P*	0.3568	0.8917	0.6990
	F	1.13	0.49	0.72
	df	10, 51	10, 51	10, 51
Trap crop planting timing				
0 wk	78	0 ± 0	1.7 ± 1.0	1.2 ± 0.3

Table 3.4. (cont'd)

2 wk	78	0 ± 0	0.8 ± 0.2	1.5 ± 0.3
4 wk	78	0 ± 0	1.7 ± 0.5	1.4 ± 0.3
Row no.				
4	78	0 ± 0	2.6 ± 1.0	1.0 ± 0.3
5	78	0 ± 0	1.6 ± 0.6	2.0 ± 0.4
6	78	0 ± 0	0.6 ± 0.2	0.8 ± 0.3
7	78	0 ± 0	0.8 ± 0.2	1.3 ± 0.4
8	78	0 ± 0	2.1 ± 0.5	1.7 ± 0.4
9	78	0 ± 0	0.8 ± 0.3	1.4 ± 0.3
Effects	Stats			
Trap crop planting timing	*P*	-	0.1971	0.7174
	F	-	1.68	0.33
	df	-	2, 51	2, 51
Row no.	*P*	-	0.0794	0.2240
	F	-	2.12	1.45
	df	-	5, 51	5, 51
Trap crop planting timing*row no.	*P*	-	0.6409	0.7928
	F	-	0.79	0.62
	df	-	10, 51	10, 51

[a]Abbreviations: DAP = days after planting, no. = number.
[b]- = No comparisons are available due to the zero occurrence of eggs 47 and 78 DAP. Different letters indicate significant pairwise differences between treatments within a column and DAP via Tukey-HSD test applied to EMMs ($P < 0.05$).

Table 3.5. Mean (±SE) Colorado potato beetle (CPB) density impacted by trap crop planting timing and trap crop row at MRC-24.

Trap crop planting timing	Row no.[a]	DAP	Eggs	Larvae	Adults
			CPB density		
			——— no. (m^{-1}) ———		
0 wk	1	50	0 ± 0b	74.0 ± 16.0b	1.3 ± 0.8b
	2	50	0.3 ± 0.3b	69.8 ± 16.2b	0 ± 0b
	3	50	0 ± 0b	65.8 ± 30.0b	0 ± 0b
2 wk	1	50	0 ± 0b	175.5 ± 15.3a	0.5 ± 0.5b
	2	50	0.3 ± 0.3b	167.0 ± 21.1a	0.3 ± 0.3b
	3	50	0 ± 0b	166.0 ± 25.9a	0.3 ± 0.3b
4 wk	1	50	0.3 ± 0.3a	58.3 ± 28.9b	2.3 ± 1.4a
	2	50	0.8 ± 0.5a	11.0 ± 8.8b	2.5 ± 1.0a
	3	50	1.3 ± 0.8a	94.3 ± 23.9b	0.8 ± 0.3a
Effects		Stats			
Trap crop planting timing		*P*	0.0269	<0.0001	0.0200
		F	4.22	24.76	4.63
		df	2, 24	2, 24	2, 24
Row no.		*P*	0.3638	0.3237	0.2144
		F	1.06	1.18	1.64
		df	2, 24	2, 24	2, 24
Trap crop planting timing*row no.		*P*	0.5035	0.2979	0.5748
		F	0.86	1.30	0.74
		df	4, 24	4, 24	4, 24
0 wk	1	57	0 ± 0	0.8 ± 0.3b	0.3 ± 0.3
	2	57	0 ± 0	2.0 ± 2.0b	0.3 ± 0.3
	3	57	0 ± 0	1.0 ± 0.6b	0 ± 0
2 wk	1	57	0 ± 0	11.8 ± 8.5b	0 ± 0
	2	57	0 ± 0	3.8 ± 2.9b	0 ± 0
	3	57	0 ± 0	3.0 ± 1.8b	0 ± 0
4 wk	1	57	0 ± 0	151.3 ± 53.4 a	6.8 ± 4.9
	2	57	0 ± 0	47.8 ± 28.3b	16.0 ± 14.0
	3	57	0 ± 0	28.0 ± 27.0b	1.3 ± 1.3
Effects		Stats			
Trap crop planting timing		*P*	-[b]	0.0002	0.1011
		F	-	12.47	2.52
		df	-	2, 24	2, 24
Row no.		*P*	-	0.0318	0.4746
		F	-	4.00	0.77
		df	-	2, 24	2, 24
Trap crop planting timing*row no.		*P*	-	0.0277	0.5771
		F	-	3.29	0.74
		df	-	4, 24	4, 24
0 wk	1	64	0 ± 0	0 ± 0	4.8 ± 1.3a
	2	64	0 ± 0	0 ± 0	3.3 ± 1.1b
	3	64	0 ± 0	0 ± 0	2.0 ± 0.7b

Table 3.5. (cont'd)

2 wk	1	64	0 ± 0	0.3 ± 0.3	3.3 ± 0.9a
	2	64	0 ± 0	0.5 ± 0.5	2.0 ± 0.7b
	3	64	0 ± 0	0 ± 0	2.5 ± 1.5b
4 wk	1	64	0 ± 0	0 ± 0	3.2 ± 0.2a
	2	64	0 ± 0	0 ± 0	0.7 ± 0.7b
	3	64	0 ± 0	0 ± 0	1.8 ± 0.5b
Effects		Stats			
Trap crop planting timing		*P*	-	0.1892	0.1101
		F	-	1.79	2.42
		df	-	2, 24	2, 24
Row no.		*P*	-	0.5759	0.0180
		F	-	0.57	4.77
		df	-	2, 24	2, 24
Trap crop planting timing*row no.		*P*	-	0.6774	0.5449
		F	-	0.58	0.79
		df	-	4, 24	4, 24

[a]Abbreviations: DAP = days after planting, no. = number.
[b]- = No comparisons are available due to the zero occurrence of eggs 57 and 64 DAP.
Different letters indicate significant pairwise differences between treatments within a column and DAP via Tukey-HSD test applied to EMMs ($P < 0.05$).

Table 3.6. Mean (±SE) Colorado potato beetle (CPB) density impacted by trap crop planting timing and main crop row at MRC-24.

		CPB density		
Main effects	DAP[a]	Eggs	Larvae	Adults
Trap crop planting timing		(m^{-1})		
0 wk	50	0 ± 0	58.6 ± 8.5ab	0.1 ± 0.1
2 wk	50	0 ± 0	50.2 ± 6.8b	0.5 ± 0.2
4 wk	50	0 ± 0	79.6 ± 9.3a	0.5 ± 0.1
Row no.				
4	50	0 ± 0	35.7 ± 7.8c	0.5 ± 0.2
5	50	0 ± 0	51.2 ± 11.1bc	0.3 ± 0.2
6	50	0 ± 0	57.6 ± 8.9bc	0.4 ± 0.1
7	50	0 ± 0	47.7 ± 10.7bc	0.2 ± 0.1
8	50	0 ± 0	98.2 ± 11.6a	0.3 ± 0.2
9	50	0 ± 0	86.7 ± 12.5ab	0.6 ± 0.2
Effects	Stats			
Trap crop planting timing	*P*	-[b]	0.0083	0.0579
	F	-	5.26	3.01
	df	-	2, 51	2, 51
Row no.	*P*	-	0.0001	0.6931
	F	-	6.76	0.61
	df	-	5, 51	5, 51
Trap crop planting timing*row no.	*P*	-	0.5360	0.3483
	F	-	0.90	1.15
	df	-	10, 51	10, 51
Trap crop planting timing				
0 wk	57	0 ± 0	0.3 ± 0.1	0.4 ± 0.2
2 wk	57	0 ± 0	1.9 ± 0.7	0.1 ± 0.1
4 wk	57	0 ± 0	3.5 ± 2.7	0 ± 0
Row no.				
4	57	0 ± 0	0.5 ± 0.3	0.1 ± 0.1
5	57	0 ± 0	0.8 ± 0.4	0.3 ± 0.3
6	57	0 ± 0	2.3 ± 1.3	0.3 ± 0.1
7	57	0 ± 0	5.4 ± 5.4	0.3 ± 0.3
8	57	0 ± 0	1.3 ± 0.7	0.1 ± 0.1
9	57	0 ± 0	0.9 ± 0.3	0.1 ± 0.1
Effects	Stats			
Trap crop planting timing	*P*	-	0.3748	0.1146
	F	-	1.00	2.26
	df	-	2, 51	2, 51
Row no.	*P*	-	0.6406	0.8035
	F	-	0.68	0.46
	df	-	5, 51	5, 51
Trap crop planting timing*row no.	*P*	-	0.3978	0.4491
	F	-	1.08	1.00
	df	-	10, 51	10, 51

Table 3.6. (cont'd)

Trap crop planting timing				
0 wk	64	0 ± 0	0 ± 0	2.6 ± 0.4
2 wk	64	0 ± 0	0.3 ± 0.3	2.6 ± 0.4
4 wk	64	0 ± 0	0 ± 0	2.9 ± 0.4
Row no.				
4	64	0 ± 0	0 ± 0	1.7 ± 0.4b
5	64	0 ± 0	0.1 ± 0.1	1.8 ± 0.4b
6	64	0 ± 0	0.5 ± 0.5	2.8 ± 0.6ab
7	64	0 ± 0	0.1 ± 0.1	2.6 ± 0.5ab
8	64	0 ± 0	0 ± 0	3.5 ± 0.6a
9	64	0 ± 0	0 ± 0	4.0 ± 0.5a
Effects	Stats			
Trap crop planting timing	*P*	-	0.3521	0.6883
	F	-	1.07	0.38
	df	-	2, 51	2, 51
Row no.	*P*	-	0.5415	0.0020
	F	-	0.82	4.45
	df	-	5, 51	5, 51
Trap crop planting timing*row no.	*P*	-	0.5116	0.9926
	F	-	0.93	0.23
	df	-	10, 51	10, 51

[a]Abbreviations: DAP = days after planting, no. = number.

[b]- = No comparisons are available due to the zero occurrence of eggs 50, 57, and 64 DAP. Different letters indicate significant pairwise differences between treatments within a column and DAP via Tukey-HSD test applied to EMMs (P < 0.05).

Table 3.7. Cumulative degree days (DD) at each planting date and evaluation timing at the Michigan State University Montcalm Research Center.[a]

	Date	MRC-23[b]
Trap crop planting timing		DD (11°C)
0 wk	May 30	333.5
2 wk	June 13	512.5
4 wk	June 27	738.7
Data collection (DAP)		
47	July 16	1,052.5
55	July 24	1,172.2
62	July 31	1,305.5
69	August 7	1,416.5
78	August 16	1,549.9
	Date	MRC-24
Trap crop planting timing		DD (11°C)
0 wk	May 6	181.4
2 wk	May 20	316.5
4 wk	June 3	481.2
Data collection (DAP)		
50	June 25	868.9
57	July 2	956.2
64	July 9	1,087.7

[a]DD data collected from the Michigan State University Enviroweather network (https://enviroweather.msu.edu) from the weather station within 1 km of the study location.
[b]Abbreviations: MRC-23 = Montcalm Research Center 2023, MRC-24 = Montcalm Research Center 2024, DAP= days after planting.

Table 3.8. Average temperature (°C) in winter months prior to each growing season and cumulative degree days (DD) at the end of each summer month at the Michigan State University Montcalm Research Center.[a]

	Site-year[b]	
Month	MRC-23	MRC-24
	Average temperature (°C)	
November	3.78	3.04
December	-2.11	2.38
January	-1.34	-3.71
February	-2.03	0.91
March	0.95	3.69
	DD (11°C)	
April	101.7	131.3
May	355.5	438.3
June	783.7	939.3
July	1,305.5	1,484.1
August	1,766.8	2,000.4

[a]Temperature and DD data collected from the Michigan State University Enviroweather network (https://enviroweather.msu.edu) from the weather station within 1 km of the study location.
[b]Abbreviations: MRC-23 = Montcalm Research Center 2023, MRC-24 = Montcalm Research Center 2024, DAP= days after planting.

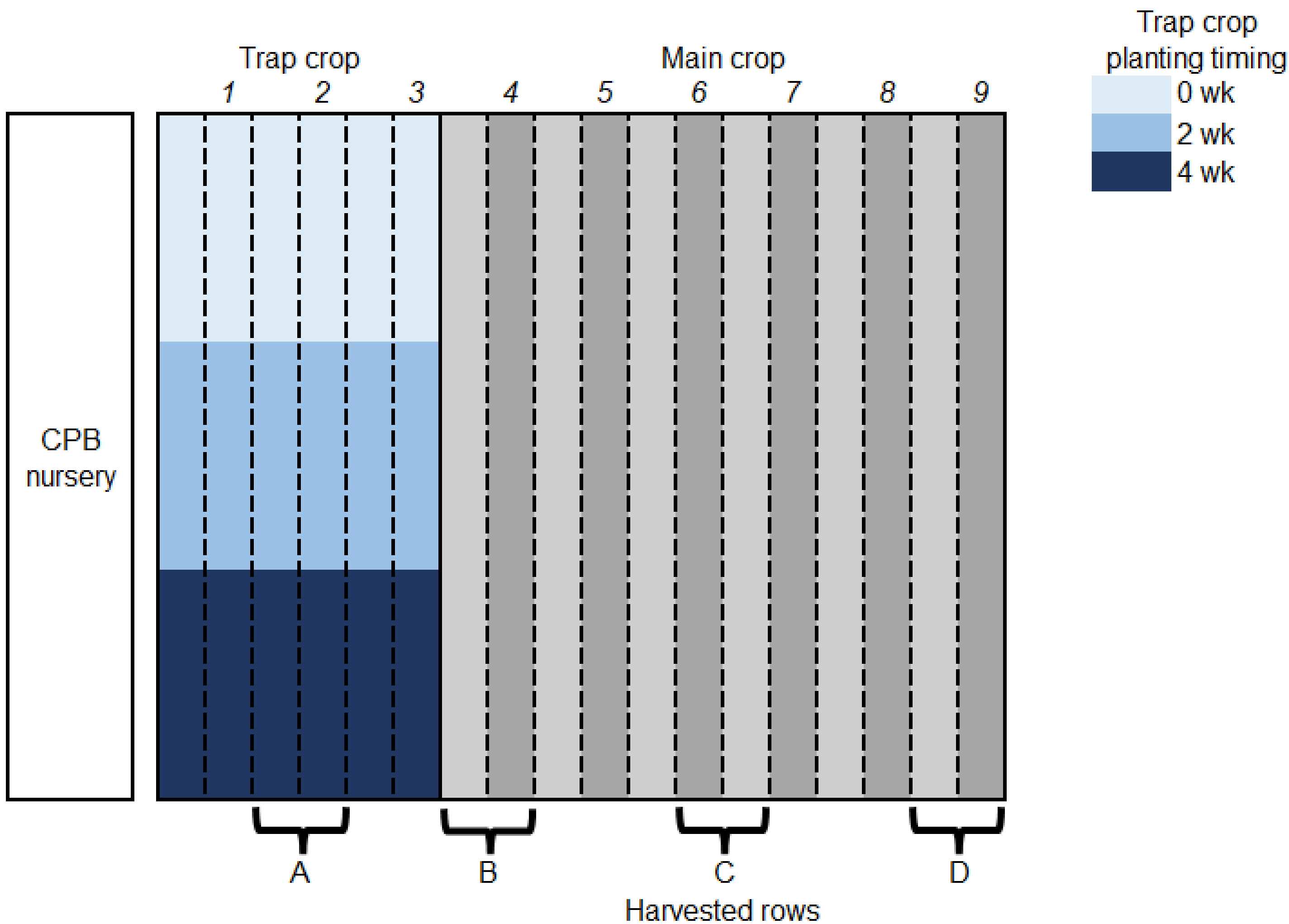

Figure 3.1. Visual representation of one replication of the delayed trap crop study at MRC-23 and MRC-24. Figure represents the layout of field studies with trap crop and main crop plots placed next to the Colorado potato beetle (CPB) nursery. Grey shading separated by dashed lines indicates potato rows with numbers along the top indicating data collection rows. Brackets A, B, C, and D indicate harvested rows.

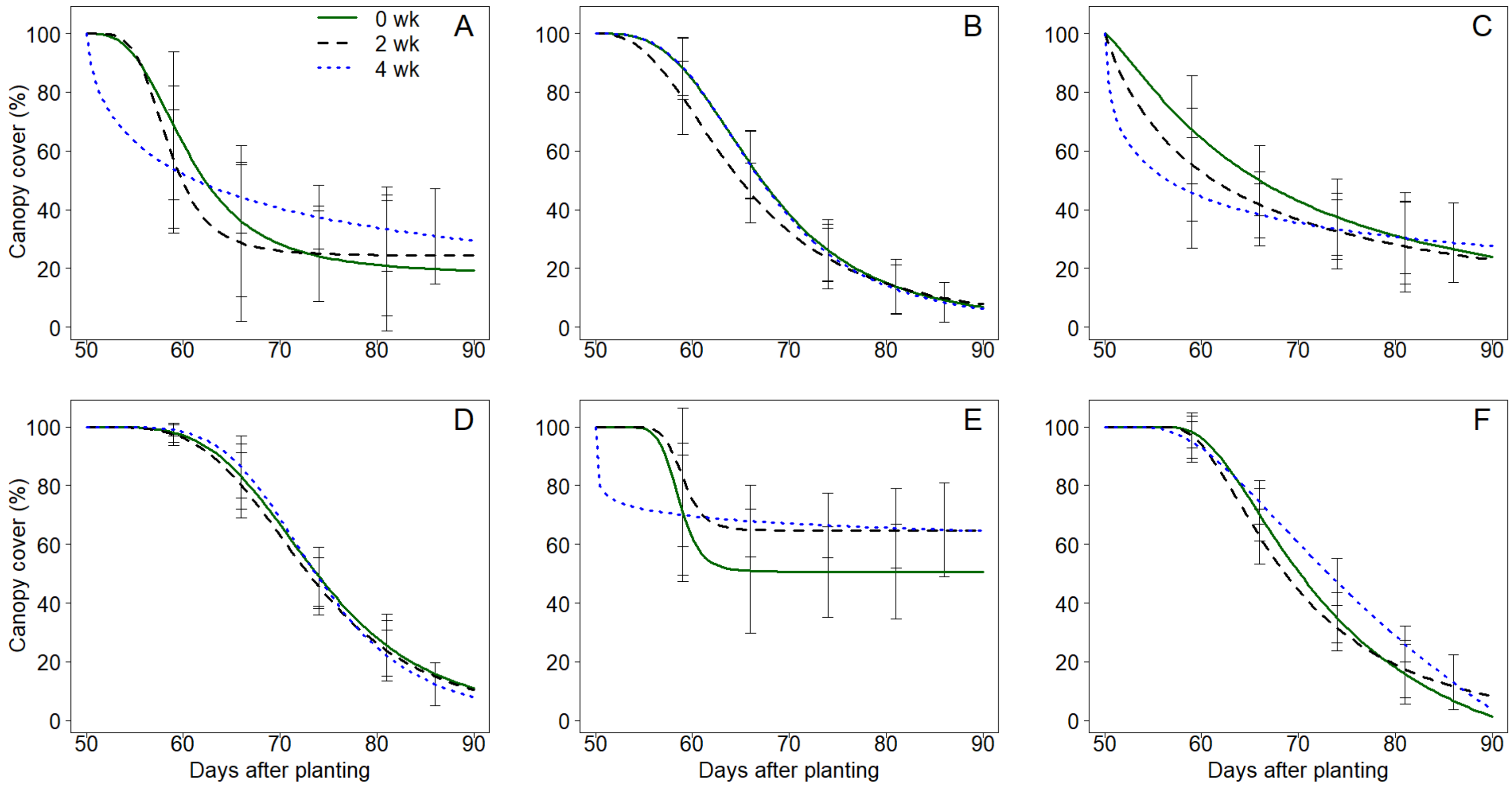

Figure 3.2. Mean (±SE) potato canopy loss impacted by trap crop planting timing at MRC-23 for main crop rows 4 (A), 5 (B), 6 (C), 7 (D), 8 (E), and 9 (F).

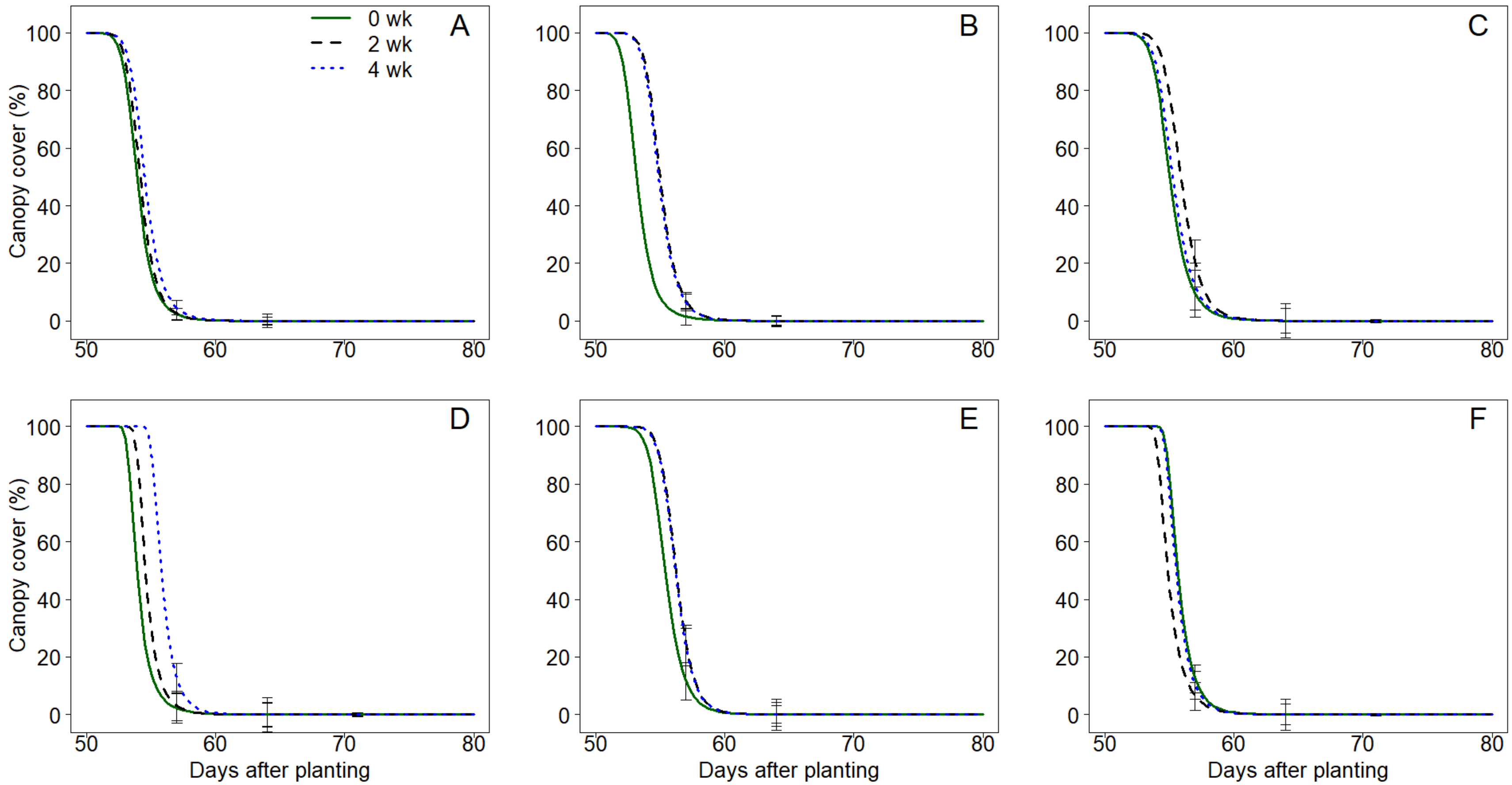

Figure 3.3. Mean (±SE) potato canopy loss impacted by trap crop planting timing at MRC-24 for main crop rows 4 (A), 5 (B), 6 (C), 7 (D), 8 (E), and 9 (F).

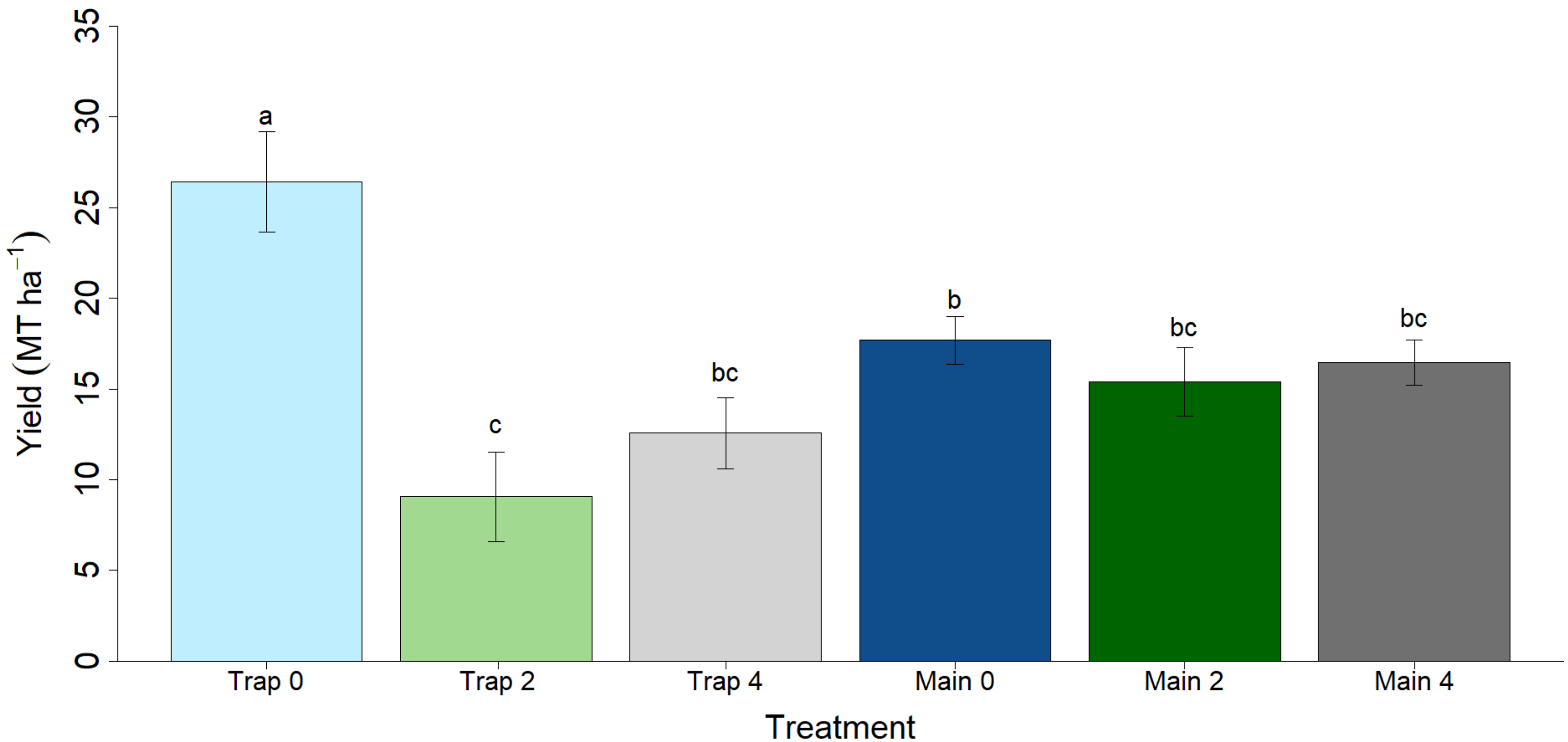

Figure 3.4. Mean (±SE) yield of trap and main crop treatments impacted by trap crop planting timing at MRC-23, averaged across rows. Bars labeled by the same letter are not statistically different for main effect of trap crop planting timing (α =0.05).

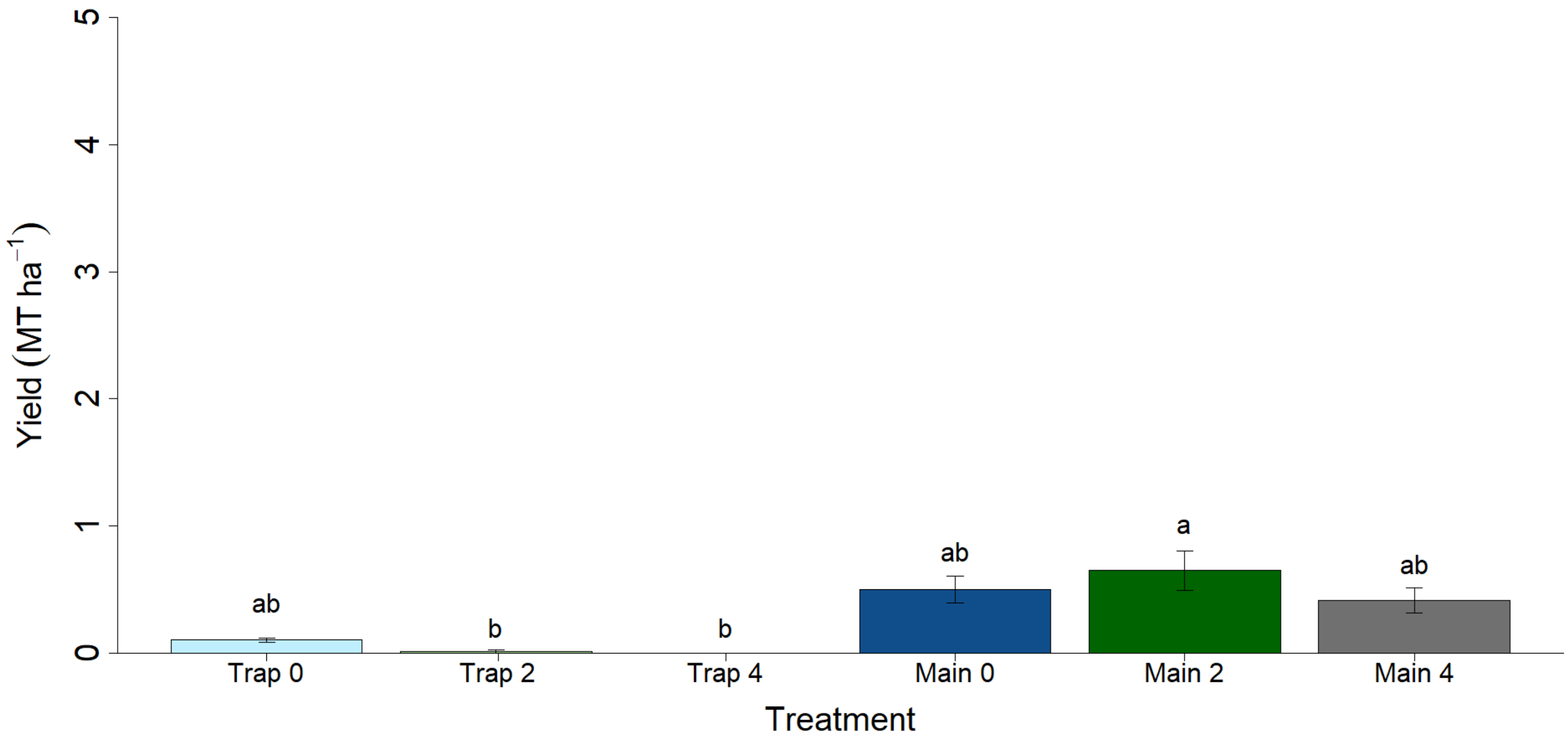

Figure 3.5. Mean (±SE) yield of trap and main crop treatments impacted by trap crop planting timing at MRC-24, averaged across rows. Bars labeled by the same letter are not statistically different for main effect of trap crop planting timing (α =0.05). Note change in y-axis scale relative to MRC-23 (Figure 3.4) due to decreased yield across treatments in MRC-24.