# REDUCED TILLAGE ORGANIC CUCURBIT PRODUCTION IN WISCONSIN

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**List of Contents**

# GENERAL OUTLINE

This thesis focuses on reduced tillage production of organic *Cucurbita pepo* winter and summer squash in Wisconsin. Squash is an economically important crop for the Upper Midwest, including for organic producers in Wisconsin specifically. However, cucurbit growers face several challenges, including pest, weed, and disease management, and typically rely on plastic mulch and repeated tillage for weed control. Cover crop-based reduced tillage (CCBRT) production systems have shown promise as a management system that can mitigate the environmental damage from repeated tillage. In addition, CCBRT systems may have secondary benefits for pest and disease management. However, adoption of CCBRT management for cucurbit production has been limited, largely because of the potential for negative impacts on yield and variable results for pest and disease management. In this thesis we introduce this context for reduced tillage cucurbit production and assess potential systems for both summer and winter squash management.

Chapter 1 presents a literature review that includes information on the economic importance of squash production, issues with typical organic squash production including weed control, tillage and pest management, and offers background on prior research on CCBRT systems more broadly, and in vegetable cropping systems specifically, including potential implications for cucurbit production. Chapter 2 outlines an experiment carried out to assess organic acorn squash production in roller-crimped cereal rye mulch, in contrast with straw mulch and full tillage in aisles, and in combination with several in-row management strategies. Results for weed control, pest management, and yield are presented. Chapter 3 outlines a second experiment conducted to assess organic zucchini squash production in plasticulture systems with living mulches between rows, contrasted to full cultivation and straw mulch control treatments. Results for this experiment also include weed control, pest management, and yield, as well as soil coverage by cover crop canopy.

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# CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW OF REDUCED TILLAGE ORGANIC CUCURBIT PRODUCTION

## *INTRODUCTION*

### *Importance of* Cucurbita pepo *squash production*

Squash represents a diverse set of horticultural classes in the genus *Cucurbita*. *Cucurbita pepo* is a particularly diverse species with an ancient association with humans in the Americas (Kumar, 2016). It includes market types of both winter squash, typically consumed as the mature fruit and often stored over long periods, and summer squash, typically consumed fresh as the immature fruit, with minimal storage capacity (Paris, 1996; Kumar, 2016). The species is both economically and culturally important (Kumar, 2016). The most popular group of summer squash is zucchini, which is a relatively recent market class but has undergone particularly intensive breeding and has become the most widely grown (Paris, 1996). *Cucurbita pepo* winter squashes are equally diverse as summer squash, and one common market class is the acorn squash type (Kumar, 2016).

In 2021, United States squash production totaled 6.91 million cwt, a 3% increase from 2020, while the total acreage planted in either winter or summer squash was estimated at 43,800 acres - a significant amount of vegetable acreage, despite a 5% reduction from the previous year. Squash is also an economically significant crop in the US, with a total value of over $215 million. The most important state for squash production in the Upper Midwest is Michigan, ranking fourth for both fresh market and processing production (USDA-NASS 2022).

While not a top producer of squash, Wisconsin is still an important production area for cucurbit crops, most notably ranking 7th for cucumber production and in the top 10 states for pumpkins (USDA-NASS 2022). In addition, Wisconsin is one of the top states for certified organic production across crops, ranking second for number of organic farms and fifth for the acreage of certified organic land (USDA-

NASS 2020). In the 2019 Organic Survey, which was a census of all US certified organic farms with 16,585 total respondents, 170 Wisconsin farms reported over 248 acres of certified organic squash production totaling 24,497 cwt and valued at over $1.2 million (USDA-NASS, 2020). Sales of organic vegetables are growing nationally, with a steep increase of 27% from 2016 to 2019. Certified organic vegetable production in Wisconsin has also been increasing (Silva et al., 2021). Wisconsin ranks 8th nationally in overall organic sales, growing 5.2% from 2016 to 2019 to a value of $269 million, with a commensurate increase in the number of certified organic farms, from just over 1,300 in 2015 to over 1,500 in 2021, and the amount of certified organic acreage in the state, growing 12.6% from 2016 to a total of nearly 251,000 acres (USDA-NASS, 2020; Silva et al., 2021).

### *CHALLENGES IN ORGANIC CUCURBIT PRODUCTION – WEED CONTROL*

Weed management can be a major constraint to successful production of organic crops, including vegetables (Moynihan, 2010; Jenkins and Ory, 2016). Although cucurbit crops are relatively fast growing and weed suppressive, they often suffer from direct competition with weeds (Johnson and Mullinix, 1998). In addition, weeds in cucurbit crops can have indirect negative effects through their interactions with insect and disease pests. For example, several weed species are known alternative hosts for *Phytophthora capsici* (French-Monar et al., 2006), an economically significant disease that can significantly impact yield, and at least study has found the weedy ground cover in organic production can exacerbate the presence of insect pests (Cranshaw et al., 2001). In a 2010 survey of organic farmers conducted by the Minnesota Department of Agriculture, weed control ranked among the top three ‘very important’ research priorities (Moynihan, 2010).

To manage weeds in cucurbit crops, most organic growers rely heavily on either mechanical cultivation or black plastic mulches, both of which entail considerable economic and biological costs. For example, a recent survey of 105 organic farmers in Michigan revealed that the mean number of tillage passes in winter squash production was 6.5 per season, with some growers tilling as many as 15 times (Lowry and Brainard, 2019). Although some tillage is seen as critical to successful organic cucurbit production, excessive tillage is detrimental to soil physical and biological properties (Grandy and Robertson, 2006; Franzlubbers, 2002; Awadhwal and Thierstein, 1985). A 2016 survey of organic growers in Michigan representing 970 acres of certified organic crop production identified development of reduced tillage practices, integration of cover crops into fertility and weed management, and identification of effective cucumber beetle management as top research priorities for cucurbit crops, illustrating the need for additional research (personal communication, Hayden and Brainard, 2016).

In plastic mulch systems in particular, erosion and runoff potential can be exacerbated because the plastic mulch focuses runoff into the aisles between beds, which are often managed as bare soil with cultivation or herbicide (Arnold et al., 2004; Rice et al., 2004). The manufacture and disposal of plastic mulch also increases the carbon footprint and environmental impact (He et al., 2018). Despite potential drawbacks, use of plastic mulch in organic production systems has increased over time and will continue to be commonplace due to important benefits such as effective weed control, increased soil temperature and moisture retention, and weed control in the planting row, all of which often contribute to higher yield (Kasirajan and Ngouajio, 2012). Notably, other mulch options or open strip tillage do not have the same level of benefits for factors such as increased soil temperature (Nair et al., 2015). Fortunately, previous research has shown that some of the immediate environmental impacts of runoff and erosion can be mitigated by living cover in between plastic beds (Arnold et al., 2004).

### *COVER CROP-BASED REDUCED TILLAGE (CCRBT) – AN ALTERNATIVE TO FULL TILLAGE*

Thoughtful integration of cover cropping shows promise for successfully managing weeds while minimizing the economic and environmental costs associated with tillage (Osterholz et al., 2020). Previous research has recognized the valuable role cover crops can play in long-term weed management, including reducing the seedbank while providing other indirect benefits (Jenkins and Ory, 2016; Osterholz et al., 2020). In fact, cover crop-based reduced tillage (CCBRT) practices have become more common over time, particularly in row crops, and with an emerging definition of the strategic integration of cover crops into a cash crop rotation with the specific goal of suppressing weeds while reducing soil disturbance (Silva and Delate, 2017; Vincent-Caboud et al., 2019).

Cover crops can suppress weeds through direct competition (Hiltbrunner et al., 2007; Bezuidenhout et al., 2012; Brust et al., 2014) or through their residues which can suppress weed emergence through physical (mulch) effects, release of allelochemicals, changes in nutrient dynamics, or influences on pathogens (Sarrantonion and Gallandt 2003; Teasdale et al., 2012; Teasdale and Mohler, 2000). Potential for weed suppression can be difficult to assess in the field, but soil canopy coverage is often taken as an indicator of light competition and thus some measure of weed suppression (Place et. al, 2011). Cover crops can also have a wide range of benefits for soil health and water quality by reducing erosion and increasing organic matter (Luo et al., 2010; Reicoskey and Forcella, 1998; Sarrantonion and Gallandt, 2003; De Baets et al., 2011; Ryder and Fares, 2008).

Although cover crops are used extensively in organic production (USDA-NASS, 2020), adoption as a full-season weed control strategy has been limited, and cover crops are usually terminated and incorporated prior to planting the cash crop (Magdoff and van Es, 2009). Shorter growing seasons in temperate climates (Snapp et al., 2005), and diverse, complex, and high value rotations on vegetable farms complicate integration of cover crops (Sarrantonio, 1992) into tillage-intensive production systems of northern cucurbit growers. However, despite the difficulty of incorporating these cover crops into intensively managed systems, the 2019 Organic Survey showed that over 7,500 USDA certified organic farms incorporated the use of green manures, and nearly 6,000 used some method of reduced tillage - an increase of over 22% since 2014 (USDA NASS, 2020). Previous surveys also indicate a high level of farmer interest in using cover crops to reduce tillage (Moynihan, 2010).

One of the most common cover crops used in CCBRT systems is cereal rye (*Secale cereale* L. ), which is notably characterized by high carbon to nitrogen (N) ratios. The high carbon to nitrogen ratio contributes to N immobilization, which boosts weed suppression but can also reduce N available to the cash crop, potentially resulting in reduced yields (Clark et al., 1994; Van Den Bossche et al, 2009; Chehade et al., 2019; Tarrant et al., 2020).  In organic row crop systems, using a roller-crimper has shown to be an effective method of cover crop termination, allowing the cash crop to be planted while maintaining enough surface biomass to contribute to weed suppression (Smith et al., 2011; Delate et al., 2012; Mirsky et al., 2012; Silva, 2014; Jokela and Nair, 2016; Silva and Delate 2017). Such integrations of cover crops into the cash cropping cycle are critical given the difficult nature of integrating cover crops into vegetable rotations (Sarrantonio, 1992), and the unique benefits afforded by full season cover crops (Deguchi et al., 2012).

### *RYE-BASED REDUCED TILLAGE PRODUCTION OF VEGETABLE CROPS*

If successful in a vegetable system, crimped cover crops could provide a more scalable alternative to other organic mulches such as straw, and an option for reducing the intensive tillage seen in cucurbit production specifically. However, studies of organic reduced tillage vegetable systems have shown variable results, including those using living mulch or terminated over-wintered cover crops such as rye. Some studies have shown there is potential for equal or higher yields (e.g. Creamer et al., 1996; Campiglia et al., 2010; Volmer et al., 2010; Forcella et al., 2015; Lounsbury and Weil 2015; Jokela and Nair, 2016), but some results also indicate reduced tillage systems can reduce yields (e.g. Delate et al., 2012; Leavitt et al., 2014; Forcella et al., 2015; Pfeiffer et al., 2016; Bietila et al., 2016; Jokela and Nair, 2016).

In reduced tillage cucurbit systems specifically, studies have shown potential for weed suppression utilizing a crimped rye mulch to suppress weeds (Brainard et al., 2013; Leavitt et al., 2011; Forcella et al., 2015). Some studies found equivalent or improved yields for some cucurbits grown in crimped rye (Hoyt, 1999; Forcella et al., 2015). Studies in organic crimped rye soybean systems (e.g. Smith et al., 2011; Silva et al., 2014) indicate that a threshold of 8-9 Mg $ha^{-1}$ is necessary to obtain satisfactory weed suppression without supplementary weed control, and the effectiveness of that range of biomass is reinforced in the study described in Chapter 2 of this thesis. Unfortunately, that amount of biomass can be difficult to produce in Northern climates for vegetable growers (Brainard et al. 2013). It can also be hard to adequately assess whether there is enough biomass or competition potential for the cover crop to adequately suppress weeds, and tools such as effective roller-crimpers are not widely available at a small enough scale to make them a feasible option for many diversified vegetable producers. Hollow cylinder chevron blade roller-crimpers rely on weight to effectively crimp, and thus require relatively large tractors with adequate horsepower to operate; testing the efficacy of smaller crimper types, such as those that mount on a walk-behind tractor or do not rely solely on weight as a crimping mechanism, would assess the adaptability of the system to small scale vegetable production. New crimper designs for walk-behind tractors have been developed by the USDA-Agricultural Research Service, and may be just as effective as larger chevron blade roller-crimpers (Kornecki and Reyes, 2020).

Adoption of rye-based CCBRT systems within cucurbit production may be higher in conventional systems, with one study from Maryland in 2007 suggesting 70% of conventional pumpkin production in the state utilized no-till planting through cover crop residues (Everts, 2007). However, use of crimped rye for cucurbit production has been met with mixed success or negative results in many studies (e.g. Leavitt et al., 2011). For instance, Forcella et al compared conventionally cultivated and crimped rye systems in Western Minnesota and found that cucumber (*Cucumis sativus L.*) yields were comparable, pumpkin

(*Cucurbita pepo* L.) yields were 25% lower in rye, and watermelon (*Citrullus lanatus*) yields were 75% lower in rye (Forcella et al., 2015). There are many factors that may contribute to lower yield in reduced tillage vegetable systems, including lower soil temperature, which can slow nitrogen mineralization and growth rates (Delate et al., 2003; Mochizuki et al., 2008; Leavitt et al., 2011), lower nutrient availability (Jokela and Nair, 2016), or insufficient weed suppression and subsequent competition with the cash crop (Vincent-Caboud et al., 2019).

One option for mitigating potential for lower yield in reduced tillage systems is more precise management of nutrient dynamics, which can include fertigation or sidedressing (Delate et al., 2008; Schellenberg et al., 2009; Jokela and Nair, 2016), or optimization of legume cover crops for improved nitrogen cycling (Ginakes and Grossman, 2021). Another approach is to implement a strip tillage management system, which can warm soil temperatures comparably to conventional tillage systems (Licht and Al-Kaisi, 2005), although typically not as much as plastic mulch (Nair et al., 2015; Bai et al., 2015). strip tillage systems thus have the potential to combine intensive cover cropping practices and reduced soil disturbance, while improving yields compared to full NT systems (Thomas et al., 2001), although some studies show no benefit (Nair et al., 2015; Jokela et al 2016).

In some cases, strip tillage systems have specific benefits such as promotion of nitrogen mineralization and the support of microbial populations through the incorporation of high-carbon residue (Brainard et al., 2013). In one case in a conventional pumpkin production system, the use of strip tillage in combination with a crimped rye/hairy vetch mixture increased the number of marketable fruits by reducing pathogen incidence (Everts, 2007). In another case in a conventional production system, similar benefits were seen through suppression of weeds (Ogatu, 2004). However, despite the potential benefits of reduced tillage and strip tillage systems for cucurbit growers, adoption has been limited in part because of a lack of development of best practices for reliably producing comparable yields to full tillage systems, and a lack of information on accompanying insect and weed management (Walters et al., 2011, Brainard et al, 2013).

A more typical method for managing the in-row zone is the use of mulches, which are important tools for weed control in organic systems, because they facilitate management of the in-row area that be difficult or impossible to cultivate mechanically as the cash crop matures, while hand-weeding can be time-intensive and expensive (Bietila et al., 2017; Pfeiffer et al., 2016). In-row mulches can also provide other benefits such as water retention, reduced spread of soil-borne diseases, alteration of microclimate, and protecting available soil N from leaching (Kasirajan and Ngouajio, 2012; Schonbeck and Evanylo, 1998; Tarara, 2000). Both plastic mulch and straw mulch are commonly used options (Schonbeck and Evanylo, 1998).

### *LIVING MULCH SYSTEMS FOR BETWEEN-ROW MANAGEMENT IN VEGETABLE PRODUCTION*

Organic growers manage weeds between straw or plastic mulch beds in different ways, including various combinations of cultivation, mowing, living cover crops, and/or dead mulches. Crops grown with plastic mulch may be well suited to the integration of living mulches, because the zone of exclusion provided by the plastic mulch could make the cash crop more resistant to competitive inhibition from living mulches (Tarrant et al., 2020).

Adoption of living mulch between plastic-mulched beds offers a unique opportunity to integrate cover crops into vegetable systems, not only because a cash crop can be grown concurrently with a full season cover crop, but also because the benefits of plastic mulch can be maintained (Tarrant et al., 2020). Full season cover crops utilized as living mulches may also have benefits distinct from terminated cover crop mulches, such as promoting arbuscular mycorrhizal colonization and enhancing nutrient uptake (Deguchi et al., 2012). In addition, tools for management of living mulch plasticulture systems, such as mowers, are often more accessible than roller-crimpers, high residue cultivators, or other tools for cover crop-based reduced tillage management.

Choice of living mulch species is important to maximize weed control benefits of living mulches while minimizing risks associated with competition (Tarrant et al., 2020; Ginakes and Grossman, 2021). For instance, clovers are a common choice because the ability to fix atmospheric N could make them more adaptable and less likely to compete for N (Hartwig and Ammon, 2002; Tarrant et al., 2020). However, clovers also tend to be slower growing and less competitive against summer annual weeds (MacLaren et al., 2019). Tarrant et al. tested nine living mulch treatments and found that all living mulch treatments reduced weed biomass, and that weed biomass was negatively correlated with living mulch biomass. However, they also observed that weed biomass dominated all treatments except teff (*Eragostis tef* (Zuccagni) and pointed out that higher biomass cover crops also require more frequent management and have more potential for competition with the cash crop (Tarrant et al., 2020).

In addition, Tarrant et al. found that all treatments risked competition with potential cash crops by lowering soil inorganic nitrogen and moisture levels within the plastic mulched beds (Tarrant et al., 2020). However, specific management such as root pruning may reduce potential for competition (Båth et al., 2007). Mowing has also been shown to reduce root biomass in correlation with above ground biomass reductions (Liu and Huang, 2002), and may be more accessible for small-scale growers than mechanical root pruning. For instance, Hinds and Hooks found that zucchini yields were suppressed in a living mulch system with sunn hemp (*Crotalaria juncea* L.) cut at 45 cm, but when the sunn hemp was cut to 20cm zucchini yields were not significantly different or were greater in the living mulch treatment than bare ground (Hinds and Hooks, 2016). Overall, studies on living mulch cucurbit production systems have shown variable results, with some suggesting equivalent or higher yields than conventional tillage systems may be possible (Hinds and Hooks, 2016; Kahl et al., 2019; Sportelli et al., 2022), including one limited study incorporating the use of plastic mulch (Nelson and Gleason, 2018), while the same and other studies have shown negative or variable impacts on yield (Hinds and Hooks 2016; Nyoike and Liburd, 2010).

### *CHALLENGES IN ORGANIC CUCURBIT PRODUCTION – PEST MANAGEMENT*

Mulch choice can also affect pest pressure. Two major pests of cucurbits in the Upper Midwest, USA include striped cucumber beetle (*Acalymma trivittatum*) and squash bug (*Anasa tristis*). Cucumber beetles overwinter as adults and can kill seedlings with aggressive early season feeding. They can also vector bacterial wilt, which can cause mortality of mature plants. The adults are typically found feeding on leaves, flowers, and fruit, while larvae feed on roots. Cucumber beetle eggs are laid at the base of cucurbit plants (Haber et al., 20, and thus heavily mulched production tends to suppress cucumber beetle populations (Snyder et al, 2019). In contrast, squash bugs lay their eggs on the underside of leaves, so additional mulches or weedy production systems may provide a range of habitat and protection from predators without suppressing their ability to lay eggs (Doughty et al., 2016).

Since chemical control options for organic growers are limited, and cucumber beetles have the potential to develop resistance, organic growers must rely on cultural and mechanical controls, such as rotation, exclusion, and intercropping to reduce pest pressure (Haber et al., 2021; Doughty et al., 2016). Unfortunately, conditions on organic farms (such as weedy ground cover or straw mulch) may be conducive to squash bugs (Cranshaw et al 2001). So, while straw mulch may suppress cucumber beetle populations (Snyder, 2019), it may increase squash bug pressure by providing places to hide (Cranshaw et al., 2001). Roller-crimped rye mulches may create a similarly heterogenous cover structure conducive to squash bug infestations. In fact, compared to cultivated ground even black plastic mulch may harbor larger populations of squash bugs (Cartwright et al 1990), where they are frequently observed hiding in planting holes (Doughty et al 2016). However, the pest management drawbacks of plastic mulch may be outweighed by other associated benefits. A 2019 study by Skidmore et al. showed higher pest pressure in plasticulture systems as compared to bare ground strip tillage but found that plasticulture still outyielded the strip tillage treatment (Skidmore et al., 2019).

Some studies have shown that living mulch can exacerbate pest issues (Reid and Klotzbach, 2013), while others have shown variable or positive effects on pest levels (Amirault and Caldwell 1998; Grasswitz 2013; Hinds and Hooks 2016; Nyoike and Liburd 2010). For instance, Kahl et al. found that cucumber (*Cucumis sativus* L.) interplanted with red clover (*Trifolium pratense* L.) had increased counts of natural enemies and lower counts of cucumber beetles and melon aphid (*Aphis gossypii*) pressure, although spotted cucumber beetle (*Diabrotica undecimpunctata howardi)* had a variable response (Kahl et al., 2019). Grasswitz found a similar negative response to interplanting for cucumber beetles, but saw no effect on squash bug presence (Grasswitz, 2013). while Nyoike and Liburd also found increased natural predator populations in a buckwheat (*Fagopyrum esculentum* Moench) living mulch, which likely contributed to the lower pest levels they observed in living mulch treatments (Nyoike and Liburd, 2009).

Reducing tillage in between-row areas through mowed living cover crops or straw mulches has the potential to contribute to soil health parameters and other agroecosystem services, such as limiting cucumber beetle movement, but may be antagonistic with other key components of successful cucurbit production, such as squash bug pressure and yield. While increased vegetation diversity generally increases beneficial predatory arthropod populations and can reduce pest pressure (Andow, 1991), including specifically for cucumber beetles (Bach, 1980), results have been variable over time. For instance, Quinn et al. (2016) recently found equal or greater populations of natural predators in mulched treatments as compared to conventionally tilled systems in acorn squash production.

## *KNOWLEDGE GAPS AND RESEARCH DIRECTIONS*

CCBRT systems in vegetable production have shown clear promise for conserving soil health and playing a role in long term weed management. However, results for pest pressure and, most critically, yield have been variable across different reduced tillage systems and vegetable crops, including for cucurbits specifically. More research is needed to continue refining systems specific to each crop and market class, which will help lead to the development of best practices that growers can be confident in adopting for such an economically important and widely grown class of crops. To address these needs, a project funded by the USDA-NIFA Organic Research and Education Initiative in cooperation between University of Wisconsin-Madison and Michigan State University was developed to assess the impact of reduced tillage production on yield, pest pressure, and weed management for two common *Cucurbita pepo* squash crops in the region, acorn winter squash and zucchini summer squash.

As part of this project, one experiment was carried out that investigated the use of roller-crimped rye as an aisle mulch, contrasted to more conventional straw mulch and fully cultivated options, for production of organic acorn winter squash. The experiment sought to expand on previous research on cover crop-based weed management in a strip till system, exploring the interplay between aisle and row treatments. Specifically, yield in the rolled-rye system was compared with the more common straw mulch or bare cultivation systems to see if row mulch would affect how well the aisle mulch systems performed. We chose aisle treatments of full tillage cultivated ground, straw mulch, and crimped rye. To investigate which strip tillage and mulch combination might improve yield, we chose row treatments of plastic mulch, straw mulch, and bare cultivated ground. We tested the null hypotheses that there would be no effect from or interaction between aisle mulch and row mulch and year in explaining yield, plant survival, and insect counts. We also tested the null hypothesis that there would be no significant effect from or interaction between aisle or row mulch type and year on weed counts or weed management time, which would indicate that the mulch treatments performed the same throughout the season. Data collected included vegetable yield, plant survival rate, weed counts and management time, and cucumber beetle and squash bug counts.

As a second part of this project, another experiment investigated the use of different living mulch treatments in the production of organic zucchini squash. This study expands on previous research on cover crop-based weed management in a plasticulture system, since assessments of living mulch cucurbit plasticulture systems specifically are limited and have shown variable results or evaluated a limited set of parameters (e.g. Nelson and Gleason, 2018; Ginakes and Grossman, 2021), and results that might inform crucial pest management practices have been from systems with living mulch only, lacking the critical production component of black plastic mulch (Kahl et al., 2019; Grasswitz, 2013; Nyoike and Liburd, 2009). We specifically address the effects of aisle mulch treatment on yield, weed and pest pressure, and weed management time. We tested the null hypotheses that there would be no effect from aisle mulch in explaining yield, plant survival, or percent cover. We also tested the null hypothesis that there would be no significant effect from or interaction between aisle and date on weed counts, pest counts, or weed management time, which would indicate that the mulch treatments performed the same throughout the season. We chose aisle treatments of full tillage cultivated ground, straw mulch, Dutch white clover, annual ryegrass, and a mix of Dutch white clover and annual ryegrass. Data collected included marketable and unmarketable fruit yield, plant survival rate, weed counts and management time, cucumber beetle and squash bug and egg counts, and percent cover of soil.

To drive adoption of these CCBRT systems that have a range of environmental benefits, researchers need to address the conflicting results of prior studies by testing further refinements of the production systems. In addition, despite the economic importance of organic cucurbit crops in Wisconsin approaching $1.2 million annually, and a nationally notable concentration of organic farms, very little regional research is available for researchers and extension agents to draw on when making recommendations to growers. This project has sought to address some of these knowledge gaps by taking an additional step of refinement in CCBRT production systems, including testing different in-row mulch options for crimped-rye based systems for winter squash production, which have often resulted in reduced yields in prior studies, in addition to different living mulch species and combinations for organic summer squash production, which is typically managed with plasticulture systems. The following thesis will help to further refine cucurbit CCBRT systems for growers, and recommendations by extension agents in the Upper Midwest.

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# CHAPTER 2: IN-ROW MANAGEMENT STRATEGIES FOR COVER-CROP BASED REDUCED TILLAGE ORGANIC SQUASH PRODUCTION IMPACT MARKETABLE YIELD, PEST PRESSURE, AND WEED COUNTS AND MANAGEMENT TIME

## ABSTRACT

Cover crop-based reduced tillage (CCBRT) systems provide multiple benefits, including potential to reduce spread of soil-borne pathogens, minimize erosion, and decrease weed pressure. Despite benefits, adoption has been limited, in part due to inconsistent weed suppression and yields. In 2018 and 2019, CCBRT practices for organic acorn winter squash (*Cucurbita pepo* L.) production were assessed in Wisconsin on certified organic land. Combinations of different between-row (aisle) and in-row mulches were compared to attempt to identify reduced tillage combinations that effectively manage weeds while resulting in yields comparable to full tillage production. Aisle treatments included roller-crimped cereal rye (*Secale cereale* L.) mulch, straw mulch and cultivated bare ground, and in-row treatments included plastic mulch, ground straw mulch, and cultivated ground. Weed and pest counts, weed management time, and yields were compared between treatments. Plots managed with rye and straw in the aisles had significantly less weed pressure as compared to cultivated aisle treatments, although rye required more weed management time than ground straw mulch. In addition, rye resulted in lower marketable yield and higher proportion unmarketable fruit in 2018, with rot the most common cause of unmarketability, possibly due to a 25cm rain event two weeks prior to harvest. Total fruit plant$^{-1}$ was also negatively impacted by rye mulch, although yield data showed there was only a significant row mulch × aisle mulch interaction for marketable fruit m$^{-1}$, and yield in plots with crimped rye mulch in the aisle were not significantly affected by the type of in-row mulch. Pressure from squash bugs (*Anasa tristis*) was also higher in high residue treatments (straw in aisles or rows, rye in aisles, and plastic in rows). Our results support previous evidence that crimped rye can be an effective mulching strategy to reduce weed

pressure, with more efficient application than traditional straw mulch, but that crimped rye systems may have negative implications for yield and pest pressure regardless of in-row management, and potentially depending on environmental factors such as rainfall or soil moisture, indicating that more research is needed to refine the production system.

## INTRODUCTION

Weed management is consistently cited as a significant obstacle for organic farmers (Moynihan, 2010; Jenkins and Ory, 2016). Cover crops have been recognized as a valuable tool in the “many little hammers” approach to creating long-term organic production plans that lower the weed seedbank while providing additional ecological benefits (Liebman and Gallandt, 1997; Baraibar et al., 2018; Wauters et al., 2021). Cover crops can support weed management through direct competition, the creation a physical barrier through crop residues, the release of allelochemicals, and the alteration of soil nutrient dynamics (Hiltbrunner et al., 2007; Bezuidenhout et al.,2012; Brust et al., 2014; Sarrantonio and Gallandt 2003; Teasdale et al., 2012; Teasdale and Mohler, 2000). Beyond their weed suppressive benefits, cover crops also improve soil health and water quality by reducing erosion and increasing organic matter (Luo et al., 2010; Reicoskey and Forcella, 1998; Sarrantonio and Gallandt, 2003; De Baets et al., 2011; Kaspar et al., 2011; Ryder and Fares, 2008).

Cover crop-based reduced tillage (CCBRT) encompasses a suite of practices which strategically integrate cover crops into a cash crop rotation with the goal of suppressing weeds while reducing soil disturbance (Vincent-Caboud et al., 2019). These practices frequently integrate the use of a roller-crimper to create an in-situ mulch of killed cover crop residue into which the cash crop can be planted, providing a thick layer of biomass allowing for season-long weed suppression without the need for tillage and cultivation (Smith et al., 2011; Delate et al., 2012; Mirsky et al., 2012; Silva, 2014; Silva and Delate 2017). While much of the research regarding CCBRT has been conducted with grain crops, an increasing number of studies have evaluated this system for organic vegetable production. The performance of CCBRT in organic vegetable systems has varied widely depending on the vegetable crop, cover crop, and environment (Lounsbury et al., 2020; Forcella et al., 2015; Chehad et al., 2019). In certain circumstances, the practice has resulted in equivalent or greater vegetable yields than those obtained from more typical organic systems using mechanical weed management (e.g. Creamer et al., 1996; Campiglia et al., 2010; Volmer et al., 2010; Lounsbury and Weil 2015; Jokela and Nair, 2016; Sportelli et al., 2022), while other studies, the system resulted in reduced yields (e.g. Delate et al., 2012; Leavitt et al., 2014; Bietila et al., 2016; Jokela and Nair, 2016).

Reduced yields under CCBRT management can often be attributed to several factors, including insufficient weed suppression and competition of the cover crop with the cash crop, such as for nitrogen (Vincent-Caboud et al., 2019). Slow nitrogen mineralization rates associated with lower soil temperatures can limit available nitrogen at key phases of crop growth within CCBRT systems (Leavitt et al., 2011). Some of the most commonly used cover crops found in CCBRT management, such as cereal rye (*Secale cereale* L.), are characterized by high carbon to nitrogen (N) ratios at maturity, which can lead to N immobilization, especially if cover crop residue remains on the soil surface rather than incorporated into the soil (Clark et al., 1994; Salon, 2012; Van Den Bossche et al, 2009; Chehade et al., 2019). The effects of these phenomena can be seen in several CCBRT vegetable studies. For example, in Iowa, organic bell pepper yields under CCBRT management were comparable in one season, but lower during the second year, with the differences being attributed to differences in temperature and nutrient availability in soil under no-till management (Jokela and Nair, 2016). This phenomenon may have also been a factor in the performance of CCBRT systems in the Northeastern US, where organic cabbage yields were reduced 21% and temperatures under rye mulch were 2– 3°C lower than bare soil, although other factors such as stunting due to rye allelopathy may have also impacted final yields of the crop (Mochizuki et al., 2008).

Leavitt et al. (2011) also suggested that lower temperatures in CCBRT treatments led to lower yields for organic tomato, pepper, and zucchini in Minnesota.

Strip tillage has been presented as an alternative management approach to mitigate the potential yield losses related to the adoption of CCBRT practices, including in organic vegetable systems (Luna et al. 2012; Mochizuki et al. 2007; Bietila et al., 2017; Leavitt et al., 2011; Delate et al., 2012, Ginakes and Grossman 2021). With strip tillage management, primary tillage and associated cover crop incorporation is restricted to the in-row planting zone, with the aisles between the rows remaining undisturbed. strip tillage systems have the potential to combine the weed management benefits of intensive cover cropping practices with soil-building and reduced soil disturbance, while reducing risk of yield loss compared to full NT systems (Thomas et al., 2001; Brainard et al 2013).

Strip tillage systems can promote plant growth and yields through quicker warming of soil temperatures comparable to conventional tillage systems but not as great as with the use of plastic mulch (Licht and Al-Kaisi, 2005; Tillman et al., 2015). Further, strip tillage management allows for the incorporation of high-carbon crop residues with the planting zone, which supports microbial populations and promotes N mineralization (Brainard et al. 2013). With the implementation of CCBRT practices in conventional systems, the use of strip tillage into rolled-crimped cereal rye and a rye/hairy vetch mixture successfully suppressed weeds during the production of conventionally managed pumpkin, resulting in an equivalent marketable number of fruit as compared to plants grown without the use of rolled mulches (Ogatu, 2004).

This study expands on previous research on organic CCBRT management for cucurbit systems using strip tillage strategies, evaluating both in-row management of the tilled strips and between row (aisle) management strategies. Whole plot row mulch treatments representing possible strip tillage options included plastic mulch, straw mulch and bare cultivated ground, while split plot aisle mulch treatments included full tillage cultivated ground, straw mulch and crimped rye. Data collected included vegetable yield, plant survival rate, weed counts and management time, and cucumber beetle and squash bug counts.

## MATERIALS AND METHODS

### *Site and treatment descriptions*

Field trials were conducted at the University of Wisconsin's West Madison Agricultural Research Station (Verona, WI, USA) from September 2017 to September 2019. Two adjacent areas of certified organic land (43.0734, -89.5474 and 43.0744, -89.5465) were used for the experiment, both of which had been previously planted with a three-year old alfalfa stand and managed in accordance with the United States Department of Agriculture National Organic Program (USDA-NOP) regulations (Office of the Federal Register, 2017). Soil types were Batavia and Troxel silt loams, with organic matter content of 3.3% in 2018 and 2.9% in 2019, and pH 6.6 in 2018 and 7.2 in 2019. The experiment was established as a split-plot randomized complete block design with three replications, with row mulch as the whole-plot factor and aisle mulch as the strip-plot factor (Appendix A, Supplemental Figure 1). Each subplot had 10 plants. Whole plot, row mulch factors included a cultivated control, black plastic mulch, and ground straw mulch applied at a rate of 33625 kg ha$^{-1}$. Strip plot, aisle mulch treatments included cereal rye crimped at anthesis with a roller-crimper (I&J Manufacturing, Gap, PA), ground winter wheat straw mulch applied at a rate of 33625 kg ha$^{-1}$, and a cultivated control.

### *Field activities*

Field activities are summarized in Table 1. Cereal rye was seeded in the entire study area with a Landoll grain drill (Landoll Corporation, Marysville, KS) at a rate of 250.96 kg ha$^{-1}$ on September 25, 2017 and September 27, 2018, 2-3 weeks following the termination of a three-year alfalfa stand with a

Brillion Super Soil Builder Disk Chisel (Brillion Iron Works, Brillion, WI). The following spring, cultivated and straw mulched treatments were terminated when the cereal rye reached 0.25m in height. Planting rows were strip tilled on 2.74m centers within roller-crimped treatment plots using 900DRT Husqavarna walk-behind rototiller (Husqvarna Group, Stockholm, Sweden) to a 1.22 m width. In all treatment plots containing ground straw or cultivation, the cereal rye cover crop was mowed using a rotary mower followed by tillage using a Case IH JX65 tractor with 65 horsepower (Case IH, Racine, WI) with a PTO driven Land Pride RTA3576 tiller with a 1.83m working width (Land Pride, Salinas, KS). One tillage event was adequate to terminate the rye in 2018, but a second tilling was required in 2019. Rye biomass was measured at anthesis immediately prior to crimping by clipping above ground growth in two 0.25 $m^2$ sections, immediately adjacent to each rye plot but outside of the study area, so as not to affect weed pressure within plot. Biomass samples were then placed in a heated air dryer (54°C) at WMARS for 14 days and weighed. Remaining cereal rye within the rye aisle treatments was terminated by roller-crimping at anthesis, with the 4.57m roller-crimper (I&J Manufacturing, Gap, PA).

Fertilizer was applied by hand within planting strips according to University of Wisconsin-Extension recommendations (Laboski and Peters, 2019) based on soil test results, including 134.5kg $ha^{-1}$ of N, followed by an additional shallow pass with the rototiller to incorporate fertilizer. Drip irrigation, plastic and straw mulches were applied by hand following final rye termination. Three-week old ‘Honey Bear F1’ acorn squash (*Cucurbita pepo*) transplants grown in 50 cell trays were hand transplanted at 0.61m in-row and 2.74m between-row spacing one week after crimping, in both years. Drip irrigation placed under mulch was applied as needed throughout the season.

In both rows and aisles, weeds were categorized as broadleaf or grass weeds and counted within two randomly placed 0.25 $m^2$ quadrats within 24hrs prior to timed manual weeding (n=18 per treatment at each date). Straw and plastic mulch treatments were weeded by hand, and cultivated treatments were managed with stirrup hoes supplemented by additional hand weeding close to plants. Total weeding time (for a single person) required for weed management after the planting of the cash crops was recorded separately for each row and aisle treatment at each weeding event (n=9 per treatment at each date). Cucumber beetle, squash bug egg clusters, and adult squash bugs per plant were counted as close to a weekly basis as possible (n=90 per treatment at each date). Squash was harvested at maturity, assessed visually by the condition of fruit peduncles and plant senescence in combination with projected days to maturity. In each plot, the final plant count was recorded, and all mature squash of marketable size were harvested and sorted as marketable or non-marketable as determined by visible evidence of rot, insect damage, surface blemishes, or being misshapen. Immature fruit (as assessed by very small size and green peduncles) were not counted.

*Table 1: Summary of field activities.*

| Date (2017) | Date (2018) | Date (2019) | Activity |
|---|---|---|---|
| September 25 | September 27 | | 'Aroostock' rye seeding (4 bu / acre) |
| | May 17, June 14 | May 15, May 30, June 11 | Tilling planting strips and control plots to terminate cover crop or incorporate fertilizer |
| | June 6 | June 6 | Rye biomass |
| | June 7 | June 7 | Termination of rye plots by crimping |
| | June 14 | June 11 | Application of fertilizer |
| | June 14 | June 12 | Application of straw and plastic mulches |
| | June 14 | June 14 | Winter squash transplanting |
| | July 18 and 25; August 8, 20 and 31st; September 7 | July 16, 23, and 28; August 6, 13, 20, and 27 | Insect counts |
| | July 17 and 25; August 8 and 20 | July 3, 12, and 23; August 7 and 28 | Weed counts |
| | July 17; August 8 and 20 | July 3, 12, and 23; August 7 and 28 | Timed weed management |
| | September 13 | September 3 | Harvest |

## *Data analysis*

Data were analyzed in R (R.app GUI 1.73 (7892 Catalina build), S. Urbanek & H.-J. Bibiko, © R Foundation for Statistical Computing, 2020). ANOVAs were done using the lme() function in the "nlme" package (Pinheiro 2022) using the following model:

$$\mathrm{Y_{ijkl}} = \mu + \mathrm{A_i} + \mathrm{B_{j(i)}} + \mathrm{WP_k} + \delta_{\mathrm{k(ji)}} + \mathrm{SP_l} + \mathrm{(AWP)_{ik}} + \mathrm{(ASP)_{il}} + \mathrm{(AWPSP)_{ikl}} + \epsilon_{\mathrm{ijkl}}$$

where $Y_{ijkl}$ is the observation for the *i*th year, *j*th block, *k*th row mulch (whole plot) treatment, and *l*th aisle mulch (subplot) treatment, $A_i$ is the fixed effect of the *i*th year (*i*=2018, 2019), $B_{j(i)}$ is the random effect of the *j*th block nested within the *i*th year (*j*=1, 2, 3), $WP_k$ is the fixed effect of the *k*th whole plot row mulch treatment (*k* = cultivated, straw, plastic), $\delta_{k(ji)}$ is the random effect of the whole plot error term nested within the *j*th block within the *i*th year, $SP_l$ is the fixed effect of the *l*th subplot aisle mulch treatment (*l* = cultivated, straw, rye), $(AWP)_{ik}$ is the effect of the interaction between the *i*th year and *k*th aisle mulch, $(ASP)_{il}$ is the effect of the interaction between the *i*th year and *l*th row mulch, $(AWPSP)_{ikl}$ is the effect of the interaction between the *i*th year and *k*th aisle mulch and *l*th row mulch, and $\epsilon_{ijkl}$ is the residual error associated with the observation for the *i*th year, *j*th block, *k*th row mulch (whole plot) treatment, and *l*th aisle mulch (subplot) treatment.

Pest data, weed management time, weed counts, and survival data were analyzed following the same procedure. However, pest counts and weed management time were transformed to cumulative counts, with only the final cumulative count analyzed. Weed counts and weed management time were analyzed with either the whole plot or subplot terms as appropriate, not both, and thus did not include the whole plot error term or associated interactions, so in-row weeding data was only associated with row mulch effects, and aisle weeding data was only associated with aisle mulch treatments. Pest and weed counts also included an additional subsampling error term $\gamma_{m(k(ji))}$ which was the random effect of the *m*th subsample (*m*=1…10 where 10 is the number of plants per plot checked for pests, or where *m*=1, 2 subsamples for weed counts).

Normality and equality of variances were checked visually with standardized residuals vs fitted value plots and normal QQ plots respectively (R Core Team 2022). Right skewed count data for individual models (i.e. an entire given variable for a single model) were transformed with log(*x* + 1) when necessary to improve assumptions of normality and equality of variances. Pest count data could not be fully transformed to meet assumptions, but due to relative robustness of the F-test to deviations from normality and equal variances F-tests were performed anyway. Left skewed plant survival data was transformed with an arcsin(sqrt(*x*)) transformation. When ANOVA F-tests were significant, Tukey's Multiple Comparisons Procedure was used to compare treatment means and develop significance groupings using the emmeans() function in the "emmeans" package, which is also how estimated marginal means for tables were obtained. When two-way interactions between main effects were found, pairwise comparisons for the simple main effect were made for each level of the other factor, again using the emmeans() function with a Tukey adjustment. All figures are shown with non-transformed data though significance groupings are based on transformed data when applicable.

## RESULTS AND DISCUSSION

### *WEATHER*

**Table 2:** Weather data collected at UW-Madison Arboretum Weather Station (~6 miles from study site).

| Time Period | Total precipitation in cm (deviation from 40 yr average) | Average daily temperature in ºC (deviation from 40 yr average) | GDDU 50 (deviation from 40 yr average) |
|---|---|---|---|
| October 2017 - February 2018 | 27.89 (+2.02) | -0.7 (+0.49) | 182 (+77) |
| March - May 2018 | 33.07 (+7.71) | 7.41 (-0.13) | 463 (+128) |
| June - Sept 2018 | 86.11 (+41.28) | 20.57 (+0.95) | 2286 (+238) |
| October 2018 - February 2019 | 37.24 (+11.37) | -1.13 (+0.06) | 86 (-19) |
| March - May 2019 | 24.05 (-3.53) | 7.45 (-0.09) | 259 (-76) |
| June - Sept 2019 | 58.90 (+14.07) | 20.28 (+0.66) | 2164 (+116) |

Winter and spring precipitation leading into the 2018 season was slightly greater than average, with close to average temperatures and the accumulation of more growing degree day units (GDDU) than normal. In contrast, winter conditions prior to the 2019 production season were colder and wetter than average, with a cooler and drier than average spring. Both 2018 and 2019 saw greater summer rainfall than average, with a single rain event in late August of 2018 releasing over 25cm of rain within 24 hours at the study site. Weed data was ended after that extreme rainfall event. (MRCC, 2021)

**Table 3:** Yield, quality, and survival data in both years by mulch treatment. Estimated marginal means averaged across the level of block and year are shown. Untransformed data is shown in the table but significance groupings according to a p-value adjustment for pairwise comparisons following the Tukey method are based on transformed data where applicable. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at P < 0.05. Lowercase letters indicate significance groupings for the whole plot effect of row mulch treatments within one aisle mulch treatment, and uppercase letters indicate significance groupings for the whole plot effect of row mulch across aisle mulch treatments, or the sub plot effect of aisle mulch across row mulch treatments. Significance groupings for the simple main effects of aisle mulch within row mulch treatments are not shown: cultivated aisles yielded significantly higher than rye aisles when paired with hay mulch in rows, and cultivated also yielded higher than hay aisle mulch when paired with plastic in rows.

| **Aisle mulch** | **Row mulch** | **Total fruit $m^{-1}$** | **Mar. fruit $m^{-1}$** | **Proportion Unmark. Fruit** | **Unmark. fruit $m^{-1}$** | **Total fruit $plant^{-1}$** | **Marketable fruit $plant^{-1}$** | **Proportion Plant Survival** |
|---|---|---|---|---|---|---|---|---|
| Cultivated | Straw | 10.29 | 6.48 | 0.36 | 3.66 | 8.92 | 5.11 | 0.80 |
| | Black plastic | 8.50 | 5.85 | 0.32 | 2.11 | 7.48 | 4.58 | 0.72 |
| | Cultivated | 9.25 | 5.93 | 0.32 | 2.57 | 6.82 | 3.93 | 0.93 |
| Simple main effect across row mulch | Cultivated aisle average | 8.87 | 6.09 A | 0.33 B | 2.78 B | 6.70 B | 4.54 A | 0.82 |
| Roller-crimped rye | Straw | 10.59 | 3.83 | 0.58 | 5.71 | 9.17 | 3.01 | 0.77 |
| | Black plastic | 6.71 | 3.91 | 0.45 | 3.01 | 6.20 | 3.05 | 0.72 |
| | Cultivated | 11.78 | 5.93 | 0.44 | 4.84 | 8.14 | 3.78 | 0.97 |
| Simple main effect across row mulch | Rye aisle average | 9.08 | 4.56 B | 0.46 A | 4.52 A | 6.77 B | 3.28 B | 0.82 |
| Straw | Straw | 11.43 | 5.30 ab | 0.53 | 6.12 | 9.58 | 3.84 | 0.85 |
| | Black plastic | 6.76 | 3.77 b | 0.47 | 3.47 | 8.58 | 4.34 | 0.55 |
| | Cultivated | 11.73 | 7.30 a | 0.38 | 4.32 | 7.87 | 4.57 | 0.97 |
| Simple main effect across row mulch | Straw aisle average | 10.10 | 5.46 AB | 0.49 A | 4.64 A | 7.93 A | 4.25 A | 0.79 |
| **Row Mulch** | Straw | 10.37 A | 5.20 | 0.49 | 5.17 A | 7.96 A | 3.98 | 0.81 B |
| Simple main effect across aisle mulch | Black plastic | 7.37 B | 4.51 | 0.41 | 2.86 B | 6.85 AB | 3.99 | 0.66 B |
| | Cultivated | 10.30 A | 6.39 | 0.37 | 3.91 AB | 6.58 B | 4.09 | 0.96 A |
| **Treatment Effects** | Row mulch | F=9.28, p<0.01 | F=2.54, ns | F=1.79, ns | F=9.70, p<0.01 | F=5.04, p<0.05 | F=0.03, ns | F=11.54, p<0.01 |
| | Aisle mulch | F=2.10, ns | F=10.54, p<0.001 | F=7.71, p<0 .01 | F=8.65, p<0.01 | F=5.62, p<0.05 | F=10.54, p<0.001 | F=0.19, ns |
| | Row × aisle | F=2.03, ns | F=2.98, p<0.05 | F=0.53, ns | F=0.17, ns | F=1.56, ns | F=2.69, p<0.1 | F=1.38, ns |
| | Year | F=12.59, p<0.05 | F=5.22, p<0.1 | F=0.09, ns | F=0.21, ns | F=13.97, p<0.05 | F=2.62, ns | F=0.15, ns |
| | Year × aisle | F=0.64, ns | F=2.87, p<0.1 | F=3.83, p<0.05 | F=2.61, p<0.1 | F=0.33, ns | F=6.47, p<0.01 | F=0.26, ns |
| | Year × row | F=0.89, ns | F=1.58, ns | F=1.67, ns | F=0.91, ns | F=1.32, ns | F=2.81, ns | F=0.24, ns |
| | Year × row × aisle | F=0.46, ns | F=0.14, ns | F=0.09, ns | F=0.32, ns | F=0.27, ns | F=0.34 ns | F=0.71, ns |

## *YIELD AND PLANT SURVIVAL*

While the rye treatment yielded equivalent total fruit m-1 to the cultivated treatment, rye produced lower yields with respect to marketable fruit m-1 and a higher proportion and count of unmarketable fruit than cultivated aisles, regardless of row mulch (Table 3, Figure 1). The amount of marketable fruit plant$^{-1}$ produced by cultivated aisles was similar to straw-mulched aisles but yield in terms of total fruit plant$^{-1}$ was lower. Across aisle mulch treatments, plastic rows produced fewer total fruit m$^{-1}$ than rows mulched with straw or cultivated rows, likely due to the low survival rate observed in plastic rows (Figure 2). With a lower number of unmarketable fruit, plastic rows produced yields of marketable fruit comparable to that of the rows mulched with straw despite the reduced number of total fruit, although the trend was towards lower marketable yields. Treatments utilizing straw produced greater total fruit yield in rows on a m$^{-1}$ basis, and greater

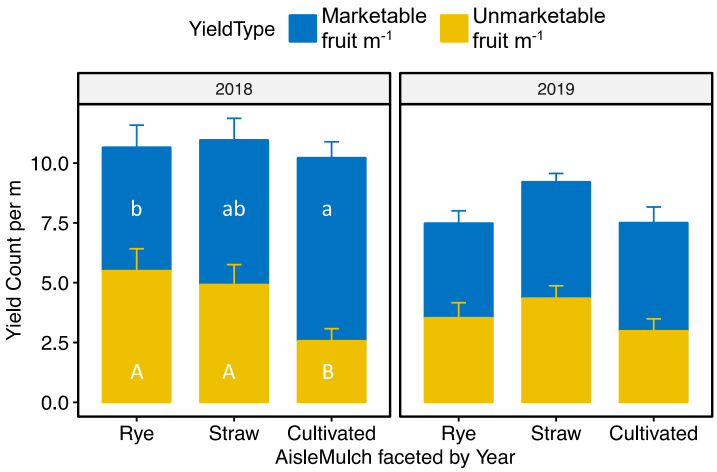

*Figure 1: Yield counts m-1 by aisle mulch and year. There was a significant year × aisle mulch interaction with differences in 2018 driving the overall significance of aisle mulch. Lowercase letters indicate significance groupings for marketable fruit m-1 and uppercase letters indicate significance groupings for unmarketable fruit m$^{-1}$and proportion unmarketable fruit; groups with the same letter (or no letter) were not significantly different across row mulch treatments within the same year at $P < 0.05$.*

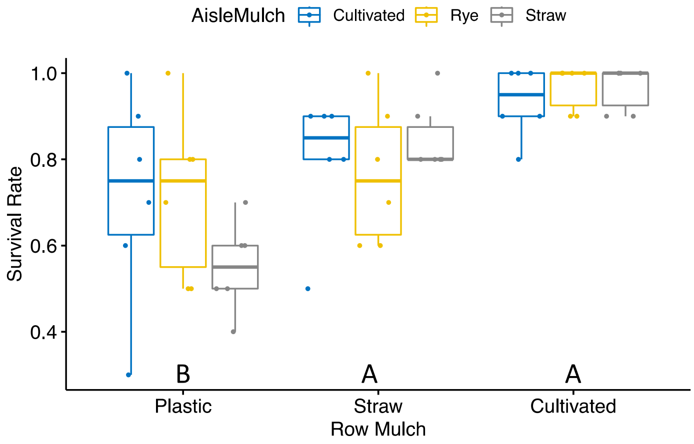

*Figure 2: Survival rate by aisle mulch across years. Rows with plastic mulch had a lower survival rate than rows managed with cultivation or straw mulch. Uppercase letters indicate significance groupings for row mulches; groups with the same letter (or no letter) were not significantly different across years and aisle mulch treatments at $P < 0.05$.*

yields in both rows and aisles on a plant$^{-1}$ basis but did not result in better marketable fruit yields due to producing more unmarketable fruit than cultivated treatments.

A significant row mulch × aisle mulch interaction was observed for marketable fruit m$^{-1}$ (Figure 3). The use of straw mulch within the row resulted in higher yields when coupled with cultivated aisles as compared to rye aisles (Figure 3A). Within rows with the plastic mulch treatment, higher yields were observed for plots with cultivated aisles as compared to straw or rye in the aisle (Figure 3A). No significant differences were observed for row mulch treatments utilizing cultivated or rye aisles. However, within straw-mulched treatments, the marketable fruit yield utilizing cultivated rows was double that of treatments utilizing plastic rows (Figure 3B). Whenever rows were cultivated yield was similar regardless of the combination with straw, rye or cultivation in the aisle. Similarly, whenever aisles were cultivated, there were equivalent yields regardless of row mulch treatment.

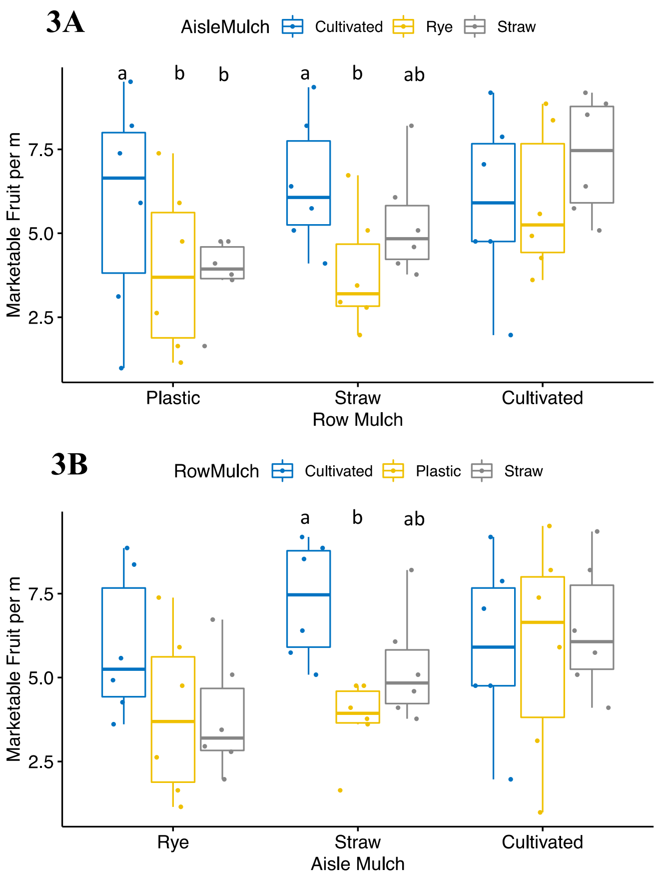

*Figure 3:. There was a significant row mulch × aisle mulch interaction for marketable fruit m$^{-1}$ across years. 3A: Lowercase letters indicate significance groupings for aisle mulch within a given row mulch group. 3B: Row mulch significance groupings within a given aisle mulch group. Treatments with the same letter (or no letter) were not significantly different across within a row (3A) or aisle (3B) mulch treatment and across years at $P < 0.05$.*

Differences in marketability were driven by a significant year × aisle mulch interaction, with clearly higher proportions of unmarketable fruits for both straw mulched aisles and crimped rye in 2018, the year the field flooded prior to harvest, and no significant differences in 2019 (Figure 1; Appendix A, Supplementary Tables 1 and 2). Similarly, a year × aisle mulch interaction was observed for marketable fruit plant$^{-1}$ (Appendix A, Supplementary Figure 2). In both years, rot was the most common cause of fruit being deemed unmarketable, followed by rodent damage. The predominant cause of plant death was squash vine borer (*Melittia cucurbitae*) in 2018 and verticillium wilt (*Verticillium dahliae*) and fusarium crown and fruit rot (*Fusarium solani* f. sp. *cucurbitae*) in 2019. Initial symptoms were diagnosed by the UW-Madison Plant Disease Diagnostic Clinic, and subsequent disease symptoms were diagnosed visually according to association with the characteristics from initial samples.

While the primary yield declines in this study appeared to be caused by the 2018 rain event and subsequent fruit rot, the crimped rye treatments also produced fewer total fruit plant$^{-1}$ than treatments with straw mulch in the aisle, suggesting there may also be other mechanisms impacting yield. Given that N immobilization with rye cover crops has been documented, supplementary nutrient application may be an option for limiting yield losses. While aisle mulch treatment was not associated with survival in this study, and thus yield plant$^{-1}$ may be useful in assessing potential for yield in the absence of the high incidence of fruit rot observed in this study, the row mulch treatments were clearly associated with survival, and thus yield m$^{-1}$ is likely the more useful metric for assessing the impacts of row mulch management.

Previous research suggests that supplementary fertilization could improve vegetable yields in reduced tillage systems, but studies largely focus on either fertigation or sidedressing (e.g. Schellenberg et al., 2009; Jokela and Nair, 2016). Future studies assessing the benefits of supplementary fertilizers should compare approaches and rates within a single study. Choosing cover crop species or mixes that include the benefit of nitrogen fixation from legumes, and optimizing management to maximize nitrogen cycling may also be an option for reducing the potential for yield declines (Ginakes and Grossman, 2021).

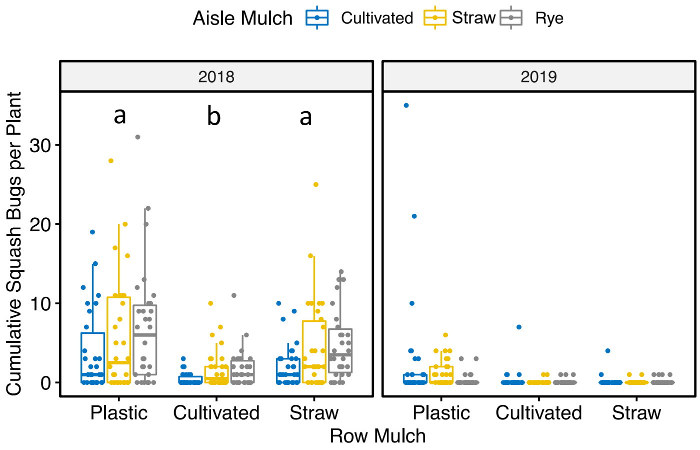

*Figure 4: Cumulative squash bug counts per plant by row and aisle mulch, faceted by year. There were significant year × aisle mulch and year × row mulch interactions, with differences in 2018 driving the overall significance of row mulch, and a crossover interaction with straw mulched rows performing similar to plastic mulch in 2018 but similar to cultivated rows in 2019. Lowercase letters indicate significance groupings for row mulch across aisle mulch treatments within the same year, and uppercase letters indicate significance groupings for aisle mulch across row mulch treatments in 2018; groups with the same letter were not significantly different at P < 0.05.*

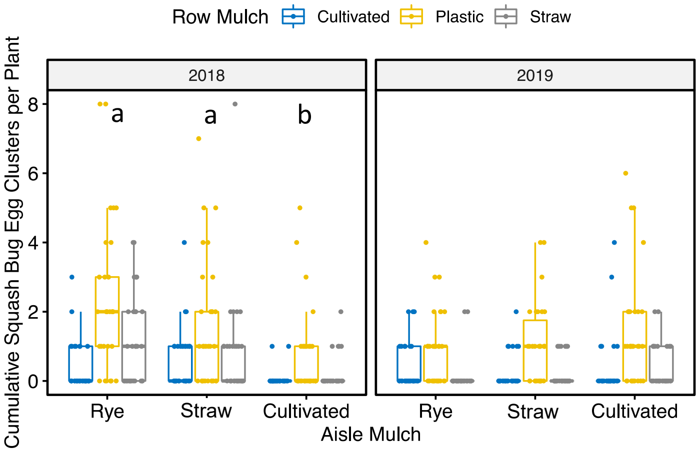

*Figure 5: Cumulative squash bug egg cluster counts per plant by aisle and row mulch, faceted by year. There was a significant year × aisle mulch interactions, with differences in 2018 driving the overall significance of aisle mulch. Lowercase letters indicate significance groupings for aisle mulch across row mulch treatments within the same year, and uppercase letters indicate significance groupings for row mulch across years and aisle mulch treatments; groups with the same letter were not significantly different at P < 0.05.*

## *INSECT PEST PRESENCE*

### *Striped cucumber beetle*

Striped cucumber beetle counts were very low overall, especially in 2018, and the only clear effect was from year (Table 4; Appendix A, Supplementary Table 3).

### *Squash bug adults*

Significant aisle mulch × year and row mulch × year interactions were observed in explaining squash bug pressure due to lower counts in 2019, with overall effects driven primarily by 2018 (Figure 4). The simple main effect of year was also significant due to the low counts in 2019. Both aisle and row mulches were only significant in 2018. Rows with straw and plastic mulch had higher numbers than cultivated rows across aisle mulch levels, while cultivated aisles also resulted in lower numbers than the mulched treatments of ground straw or rye aisles across row mulch levels.

Overall, cultivated treatments resulted in lower populations compared to other mulches, and across all aisle mulch treatments rows with plastic mulch consistently resulted in the highest counts.

**Table 4:** Average cumulative cucumber beetle, squash bugs and egg cluster counts by aisle mulch treatment. Untransformed data is shown in the table but significance groupings are based on transformed data where applicable. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at P < 0.05. Lowercase letters indicate significance groupings for the simple main effect of row mulch treatments within one aisle mulch treatment, and uppercase letters indicate significance groupings for the simple main effect of aisle mulch across row mulch treatments or row mulch across aisle mulch treatments.

| **Aisle type** | **Row Mulch** | **Cumulative Cucumber Beetles per Plant** | **Cumulative Squash Bugs per Plant** | **Cumulative Egg Clusters per Plant** |
|---|---|---|---|---|
| Cultivated control | Ground straw | 0.67 | 1.18 | 0.22 |
| | Black plastic | 0.53 | 3.33 | 1.07 |
| | Cultivated | 0.80 | 0.37 | 0.28 |
| | Cultivated aisle average | 0.67 | 1.63 | 0.52 B |
| Roller-crimped rye | Ground straw | 1.03 | 2.50 | 0.62 |
| | Black plastic | 0.77 | 3.58 | 1.62 |
| | Cultivated | 0.78 | 0.95 | 0.40 |
| | Rye aisle average | 0.86 | 2.34 | 0.88 A |
| Ground Straw | Ground straw | 102 | 2.25 | 0.52 |
| | Black plastic | 0.73 | 3.43 | 1.32 |
| | Cultivated | 0.70 | 0.87 | 0.43 |
| | Straw aisle average | 0.82 | 2.18 | 0.76 AB |
| Row type | Ground straw rows | 0.91 | 1.98 B | 0.47 B |
| | Black plastic rows | 0.68 | 3.45 A | 1.33 A |
| | Cultivated rows | 0.76 | 0.73 B | 0.35 B |
| **Treatment Effects** | Row mulch | F=1.93, ns | F=16.01, p<0.01 | F=19.48, p<0.001 |
| | Aisle mulch | F=1.34, ns | F=2.06, ns | F=4.85 p<0.05 |
| | Year | F=264.19, p<0.0001 | F=60.39, p<0.01 | F=1.86, ns |
| | Row × aisle | F=1.03, ns | F=0.34, ns | F=0.25, ns |
| | Aisle × year | F=2.58, p<0.1 | F=6.72, p<0.001 | F=12.39, p<0.001 |
| | Row × year | F=0.61, ns | F=5.10, p<0.05 | F=0.87, ns |
| | Aisle × row × year | F=0.61, ns | F=0.41, ns | F=1.78, ns |

### *Squash bug egg clusters*

A significant aisle mulch × year interaction explained cumulative squash bug egg cluster counts per plant (Figure 5). The simple main effects of row mulch and aisle mulch were also significant across years. Similar to results for squash bug adults, cultivated treatments had lower egg cluster counts. For row mulches, ground straw performed similarly to cultivation, with lower counts than plastic. In aisles rye resulted in higher egg cluster counts as compared to cultivation.

Results regarding both squash bug adults and their egg clusters are consistent with observations reported by Doughty et al., (2016) who suggested that squash bugs will often be found in the planting holes of plastic mulches, a behavior that could make it difficult for a grower to effectively apply pesticide when needed. Cranshaw et al. (2001) also showed increased damage to pumpkin by squash bugs when using straw or plastic mulches. While the effect of row mulches was clear, the results of our two-year study showed inconsistent effects of aisle mulching (either as crimped rye or ground straw) on squash bugs, with 2018 demonstrating greater squash bug pressure with aisle mulching, and 2019 showing no clear effect. Habitat provided by mulches may benefit cash crops by promoting within-field natural enemy activity and biological control (Tonhasca and Byrne 1994, Langellotto and Denno 2004, Bryant et al. 2013, Hinds and Hooks 2013). However, our results indicated that the habitat could also benefit pests. In general, pest abundance on the squash was relatively low in our experimental field during the study period, which may have contributed to the variable response between years.

## *WEED POPULATIONS*

### *Aisle weed counts and management time*

Cultivated aisles resulted in the highest total, broadleaf, and grass weed counts and required the greatest weed management time inputs (Table 5). Rye aisles resulted in fewer weeds and required less weed management time as compared to cultivated treatments but had significantly more weeds and took longer to manage than straw mulch (Figure 6). There was a significant aisle mulch × year interaction for all weed related data points due primarily to changes in significance level in pairwise comparisons between aisle mulches because of generally higher weed counts in 2019 than 2018, with the exception of higher broadleaf weed counts in 2018 (Appendix A; Supplementary Table 4). There were no significant crossover interactions, except for rye and straw aisle mulches being similar in 2019 for grass weeds. Broadleaf and grass weeds differed in 2018 and 2019 within cultivated aisle treatments, but not total weeds, as more broadleaf weeds were present in 2018 and more grass weeds in 2019. Overall, year was significant for both broadleaf and grass weed counts because of the higher counts in 2018 and 2019 respectively.

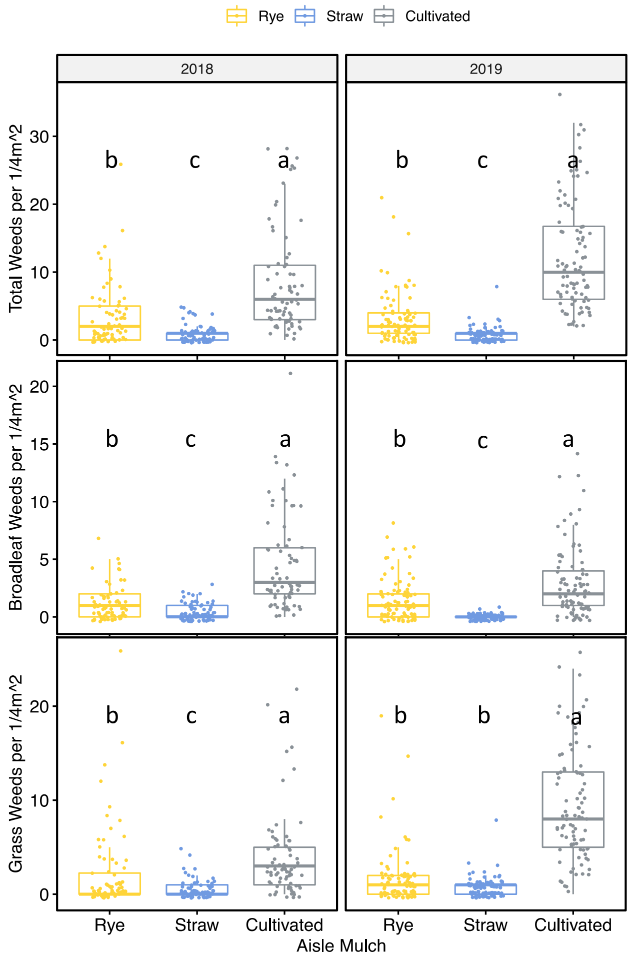

*Figure 6: Total (top), broadleaf (middle), and grass(bottom) weed counts per .25*$m^2$*, faceted by year. There was a significant year × aisle mulch interaction for all three weed types, primarily due to heavier broadleaf weed pressure in 2018 and heavier grass weed pressure in 2019. Lowercase letters indicate significance groupings for aisle mulch across within a given year; groups with the same letter were not significantly different at* $P < 0.05$*.*

The effectiveness of the cereal rye treatment with respect to weed suppression was likely influenced by heavy mulch residue created by the rye cover crop. One key factor affecting successful weed suppression of CCBRT systems is the cover crop biomass at termination; cover crop biomass on the soil surface should reach 8–9 Mg ha$^{-1}$ to obtain satisfactory weed suppression without additional weed control methods, which can include time-consuming and labor-intensive hand-weeding to rescue the vegetable crop from excessive yield loss (Smith et al., 2011; Mirsky et al., 2012; Bietila et al., 2017). In the two years of the study, the biomass of cover crop produced reached or nearly reached the threshold needed for adequate weed suppression (mean biomass of 11,756 kg $ha^{-1}$ in 2018 and 7866 kg $ha^{-1}$ in 2019).

While the use of CCBRT techniques in this study did result in fewer weeds as compared to management with cultivation, a small number of weeds were still present in the field throughout the production season. In organic production, crop canopy cover is another important tool for continued weed suppression (Hoad et al., 2012). Variety trials conducted within CCBRT management systems could further optimize the system towards complete elimination of weed seed production; for example, the cultivar in this trial was a semi-bush type, and vining cucurbit cultivars providing greater ground cover which could further contribute to weed suppression, especially during years where cover crop biomass might be lower than the ideal range.

The weed suppression provided by the CCBRT approach translated into fewer weeding hours required for crop management as compared to cultivation. Despite the decreased yields observed in 2018 using the metric of marketable fruit, this approach could be still considered advantageous to farmers, as labor needs across the entire farm during the peak production times of mid-summer can be limiting, and the opportunity costs of not having the ability to use that labor elsewhere on the farm (e.g., harvesting crops or attending a market), as well as the actual costs of the labor, may justify the tolerance of the lower yields.

### *Row weed counts and management time*

Overall, weed counts and management time were higher in cultivated rows than in those mulched with either straw or plastic. Similar to aisle weed counts, a significant effect of year was observed with respect to broadleaf and grass weed counts due to higher counts in 2018 and 2019 respectively, and a significant row mulch × year interaction for cultivated rows was observed due to those higher counts. A crossover interaction for row weed counts was also observed; straw and plastic mulches were equivalent for total and grass weed counts in 2018, but plastic had higher counts than straw in 2019. This interaction was likely due to the overall increased prevalence of grass weeds in 2019, exacerbated by the difficulty of managing weeds at the shoulders of the beds with plastic mulch where exposed soil was present, whereas the in-row straw mulch extended to the rye or straw mulches in aisles.

**Table 5:** Weed counts and management time in 2018 and 2019 relative to row and aisle mulch treatments. Untransformed data is shown in the table but significance groupings are based on transformed data where applicable. Columns with the same letter were not significantly different across mulch treatments within the same year at P < 0.05 in either aisles or rows.

| **Mulch type** | **Weeding time (hrs/ha)** | **Total weed ct per ¼ m$^2$** | **Broadleaf ct per ¼ m$^2$** | **Grass ct per ¼ m$^2$** |
|---|---|---|---|---|
| Cultivated aisle | 841 a | 10.43 a | 3.73 a | 6.69 a |
| Rye aisle | 523 b | 3.28 b | 1.31 b | 1.97 b |
| Straw | 206 c | 0.86 c | 0.23 c | 0.64 c |
| **Aisle Treatment Effects** | | | | |
| Aisle mulch | F=95.39, p<0.0001 | F=155.12, p<0.0001 | F=133.05, p<0.0001 | F-127.36, p<0.0001 |
| Year | F=70.31, p<0.01 | F=1.14, ns | F=5.54, p<0.1 | F=7.71, p<0.05 |
| Aisle × year | F=15.11, p<0.001 | F=3.73, p<0.05 | F=8.01, p<0.01 | F=13.86, p<0.0001 |
| Straw row | 119 b | 0.28 b | 0.12 b | 0.16 b |
| Plastic row | 140 b | 0.72 b | 0.20 b | 0.52 b |
| Cultivated row | 704 a | 8.57 a | 3.64 a | 4.94 a |
| **Row Treatment Effects** | | | | |
| Row mulch | F=108.53, p<0.0001 | F=370.90, p=<0.0001 | F=135.55, p<0.0001 | F=192.29, p<0.0001 |
| Year | ns | ns | F=11.55, p<0.05 | F=12.03, p<0.05 |
| Row × year | ns | F=6.03, p<0.01 | F=20.52, p<0.0001 | F=14.72, p<0.0001 |

Mulching with straw resulted in adequate weed suppression and increased the total fruit yield, while avoiding the problems of plastic mulch with respect to increased squash bug pest pressure. Thus, applying straw mulch within the tilled planting strip may be a better option than black plastic for growers adopting CCBRT practices for cucurbit production. Anecdotally, the straw mulch was also easier to apply in combination with rye than it was to dig the plastic mulch in by hand since conventional mulch-layers could not deal with the heavy residue at the edge of the tilled strip.

## CONCLUSIONS

The primary goal of this study was to evaluate the impact of strip tillage management with CCBRT practices for organic squash production. The data derived from this work demonstrated that the use of CCBRT practices with strip tillage techniques in organic cucurbit systems has the potential to produce overall yields comparable to that of standard organic cucurbit production practices using cultivation, with total fruit $m^{-1}$ equivalent between approaches in both years and marketable fruit comparable in 2019. This supports the suggestions of previous research that strip tillage in CCBRT systems can be a viable alternative to full tillage systems (Forcella et al, 2015; Tillman et al., 2015; Jokela and Nair, 2016). However, reduced marketable fruits $plant^{-1}$ and $m^{-1}$ were observed in 2018 as a result of increased rates of unmarketable fruit in that year, likely influenced by the record-breaking rain event that released 25cm in less than 24 hours two weeks prior to harvest.

In general, a stronger effect from row mulch than aisle mulch on total yield $m^{-1}$ was observed in our study. Cultivated rows had higher yields than mulched rows, again pointing to the sensitivity of these systems to environmental conditions. These system × environment interaction indicate the need for further study of disease and pest dynamics within CCBRT systems as driven by different environmental conditions. Despite the potential for reduced yields, all treatments generally produced well relative to the advertised marketable yield $plant^{-1}$ for the variety used (All American Selections, 2009).

CCBRT systems provide the notable benefit of resilience in the face of extreme rainfall events through protecting the soil and reducing erosion. However, while soil is protected under wet conditions, our study indicated that trade-offs may exist with respect to the system exacerbating disease pressure. While some research has investigated disease dynamics in CCBRT systems for cucurbits (e.g. Maglione et al., 2022), it is crucial that such research also simultaneously integrates the assessment other agronomic impacts such as yield quantity and weed management in order to form a more holistic picture of system performance.

Overall, rolled-crimped management strategies for organic cucurbit management were demonstrated to be a valuable tool for organic vegetable farmers in the upper Midwestern US. However, our research did highlight that questions remain as to the interaction between specific management choices and environmental conditions and the resulting agronomic impacts; providing answers to these questions will reduce risk for growers and drive further adoption of this practice. Thus, future research should focus on understanding the more nuanced management aspects of the system, including the identification of cultivars adapted to reduced tillage systems, supplementary fertilization methods that might result in more reliable yields, and longer term studies that explore disease and pest dynamics (such as the potential for cover crop species to provide alternate hosts for diseases, residue to increase fruit rot incidence by maintaining higher soil moisture, and predator populations and predation of common pests).

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# CHAPTER 3: LIVING MULCH PLASTICULTURE SYSTEMS FOR ORGANIC ZUCCHINI (CUCURBITA PEPO L.) PRODUCTION

## ABSTRACT

Living mulch systems can provide multiple agronomic and ecosystem benefits, including reducing erosion and decreasing weed and pest pressure. However, inconsistent yields and lack of best practices for weed and pest management have contributed to its lack of adoption by farmers. In 2018 and 2019, living mulch practices for organic zucchini (*Cucurbita pepo* L.) production were assessed in Southern Wisconsin on certified organic land. Living mulches of Dutch white clover (*Trifolium repens*), annual ryegrass (*Lolium multiflorum*), and a mix of Dutch white clover and annual ryegrass were compared with full tillage cultivated ground and straw mulch controls for effect on yield, marketability, weed and pest counts, and weed management time. Mixed species living mulch, cultivated, and straw mulch treatments yielded consistently higher than clover treatments, while ryegrass had variable results. There was no difference in the number of squash bug (*Anasa tristis*) egg clusters, but clover treatments had fewer adult squash bugs, with ryegrass and mixed species living mulches also trending lower. There were also lower counts of striped cucumber beetles (*Acalymma trivittatum*) in living mulch treatments . Ryegrass and mixed species living mulches were generally more weed suppressive than clover and cultivated aisles, although living mulch treatments mostly had more weeds than straw mulched aisles, apart from comparable suppression of grass weeds for ryegrass in 2019. Weed management time took longer for living mulch treatments than straw, while cultivated treatments took longer to manage than all other treatments in 2019 and longer than ryegrass and straw in 2018. Despite higher weed counts in clover than in cultivated aisles in 2019, all living mulches took less time for weed management than cultivation, indicating that managing living mulches

with mowing can be more efficient than hand cultivation even with very high weed counts. Our results support previous evidence that the right choice of living mulch species may reduce pest and weed pressure but reinforces the evidence that living mulch systems can negatively impact yield.

## INTRODUCTION

Weed management is a critical challenge facing organic farmers and is consistently cited as a priority for further research (Moynihan, 2010; Jenkins and Ory, 2016). To manage weeds in vegetable crops, organic growers rely heavily on both mechanical cultivation and plastic mulches (Brown and Gallandt, 2018; Jabbour et al., 2013). Plastic mulches can be used to prevent weed emergence within the planting row where mechanical and hand weeding may be difficult if not impossible once the crop establishes. In addition to their weed suppressive benefits, plastic mulches provide other positive aspects to the production systems, including increased soil temperature and moisture retention, which often contributes to higher yield (Kasirajan and Ngouajio, 2012; Steinmetz et. al, 2016). However, plastic mulch systems also present management challenges, including exacerbation of erosion due to water runoff into the aisles between beds, which are usually managed as bare soil with cultivation or herbicide (Arnold et al., 2004; Rice et al., 2004).

Environmental impacts of runoff and erosion can be mitigated in plastic mulch systems by planting living cover crops between the plastic-covered beds (Arnold et al., 2004). The use of cover crops between rows can also reduce long term weed seedbank while providing additional ecological services (Liebman and Gallandt, 1997; Baraibar et al., 2018; Wauters et al., 2021). Cover crops can suppress weeds through direct competition (Hiltbrunner et al., 2007; Bezuidenhout et al., 2012; Brust et al., 2014) and by generating residues which can suppress weed emergence through physical (mulch) effects, release of allelochemicals, and changes in nutrient dynamics (Sarrantonio and Gallandt 2003; Teasdale et al., 2012; Teasdale and Mohler, 2000). Full season cover crops utilized as living mulches may also have benefits unique from terminated cover crop mulches, such as promoting arbuscular mycorrhizal colonization and enhancing nutrient uptake (Deguchi et al., 2012).

While cover crops are used extensively in organic production (USDA-NASS, 2019), they are typically terminated and incorporated prior to planting the cash crop (Magdoff and van Es, 2009). Shorter growing seasons in temperate climates, coupled with diverse, complex, and high value rotations on vegetable farms, further complicate integration of cover crops into tillage-intensive production systems of northern cucurbit grower (Snapp et al., 2005; Sarrantonio, 1992). The use of living mulches between plastic-mulched beds provides an opportunity to integrate cover crops into vegetable systems, as the cash crop can be grown concurrently with a full season cover crop while maintaining the benefits of the plastic mulch within a targeted planting zone (Tarrant et al., 2020).

Adoption of living mulch-based reduced tillage vegetable systems has been limited partly because of variable or negative effects on yield (Butler, 2012; Law et al., 2006; Reid, 2015; Warren et al, 2015; Pfeiffer et al., 2016; Hinds and Hooks 2016), although other studies have shown positive results (e.g. Sportelli et al., 2022). The unique interactions of each cash crop and cover crop contributes to the variability in observed results, creating challenges in the development of robust best practices for the diversity of crops produced by organic vegetable growers (Walters et al., 2011; Brainard et al, 2013). Living mulch studies focused on cucurbit production have shown inconsistent impacts on yields, with some indicating potential for equivalent or higher yields (Nelson and Gleason, 2018; Kahl et al., 2019) and others showing negative or variable impacts (Hinds and Jooks, 2016; Nyoike and Liburd, 2010).

Choice of living mulch species is important to maximize weed control benefits of living mulches while minimizing risks associated with competition (Tarrant et al., 2020). Clovers are a common choice as their ability to fix atmospheric N provides fertility benefits and reduces the risk of N competition with the cash crop (Hartwig and Ammon, 2002). However, clovers also tend to be slower growing and less competitive against summer annual weeds (MacLaren et al., 2019). Tarrant et al. tested nine living mulch species and combinations and found that all living mulch treatments reduced weed biomass, with weed biomass negatively correlated with living mulch biomass. In addition, Tarrant et al. found that all treatments had the potential to compete with cash crops by lowering soil inorganic nitrogen and moisture levels within the plastic mulched beds (Tarrant et al., 2020). However, specific management such as root pruning, which reduces the depth and biomass of living roots, may reduce potential for competition (Båth et al., 2007). The drastic removal of above ground biomass caused by mowing may be reciprocated with corresponding reductions in root biomass, and thus reduce competition potential (Liu and Huang, 2002). For instance, Hinds et al (2016) found that zucchini yields were reduced in a living mulch system with sunn hemp (*Crotalaria juncea* L.) grown to a height of 45 cm, but when the sunn hemp was managed to a height of 20cm, zucchini yields were equivalent or greater in the living mulch treatment than bare ground.

Mulch choice can also affect pest pressure. Two major pests of cucurbits in the Upper Midwest, USA include striped cucumber beetle (*Acalymma trivittatum*) and squash bug (*Anasa tristis*). Since chemical control options for organic growers are limited, organic growers must integrate cultural and mechanical methods, such as rotation, exclusion, and intercropping, in addition to allowable chemical controls to both effectively manage pest pressure and mitigate the risk of insecticide resistance (Haber et al., 2021; Doughty et al., 2016).

Some studies have shown that living mulch can exacerbate pest issues (Reid and Klotzbach, 2013), while others have shown variable or beneficial effects on pest levels (Amirault and Caldwell 1998; Grasswitz 2013; Hinds and Hooks, 2016; Nyoike and Liburd 2010). For instance, Kahl et al. (2019) found that cucumber (*Cucumis sativus* L.) interplanted with red clover (*Trifolium pratense* L.) had increased counts of natural enemies and lower counts of cucumber beetles and reduced melon aphid (*Aphis gossypii*) pressure, although spotted cucumber beetle (*Diabrotica undecimpunctata howardi*) had a variable response. Grasswitz et al. (2013) found a similar negative response to interplanting for cucumber beetles, but saw no effect on squash bug presence, while Nyoike and Liburd (2009) also found increased natural predator populations in a buckwheat (*Fagopyrum esculentum* Moench) living mulch.

This study expands on previous research on living mulches in a plasticulture system. We specifically address the effects of aisle mulch treatment on yield, weed and pest pressure, and weed management time. We tested the null hypotheses that there would be no effect from aisle mulch in explaining yield, plant survival, or percent cover. We also tested the null hypothesis that there would be no significant effect from or interaction between aisle and date on weed counts, pest counts, or weed management time, which would indicate that the mulch treatments performed the same throughout the season. We chose aisle treatments of full tillage cultivated ground, ground straw mulch, Dutch white clover, annual ryegrass, and a mix of Dutch white clover and annual ryegrass. Data collected included marketable and unmarketable fruit yield, plant survival rate, weed counts and management time, cucumber beetle and squash bug and egg counts, and percent cover of soil.

## MATERIALS AND METHODS

### *SITE AND TREATMENT DESCRIPTIONS*

Field trials were conducted at the University of Wisconsin West Madison Agricultural Research Station on Batavia and Troxel Silt Loams from September 2017 to September 2019. Two areas of certified organic land (43.0734, -89.5474 and 43.0744, -89.5465) were used for the experiment (following the termination of a third-year alfalfa stand) and managed in accordance to the United States Department of Agriculture National Organic Program (USDA-NOP) regulations (Office of the Federal Register, 2017). Soil organic matter was 3.3% in 2018 and 2.9% in 2019, and pH was 6.6 in 2018 and 7.2 in 2019. The experiment was established as a randomized complete block design with four replications, 8 plants per plot, and additional guard rows in between data rows to separate living mulch treatments (Appendix B, Supplementary Figure 1). Aisle mulch treatments included a cultivated control, ground straw mulch at a rate of ~31 T ha$^{-1}$, Dutch white clover (*Trifolium repens*) seeded at a rate of 24.64 kg ha$^{-1}$, annual ryegrass (*Lolium multiflorum*), seeded at a rate of 101.66 kg ha$^{-1}$, and a mix of the two seeded at a rate of 15.57 kg ha$^{-1}$ Dutch white clover and 31.37 kg ha$^{-1}$ annual ryegrass.

### *FIELD ACTIVITIES*

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Cereal rye (*Secale cereale*) rye was seeded throughout the entire study area with a Landoll grain drill (Landoll Corporation, Marysville, KS) at a rate of 127 kg ha$^{-1}$ on September 25, 2017 and September 27, 2018, 2-3 weeks following the termination of a third-year alfalfa stand with a Brillion Super Soil Builder Disk Chisel (Brillion Iron Works, Brillion, WI). The following spring, rye was terminated through tillage with a Case IH JX65 tractor with 65 horsepower (Case IH, Racine, WI) with a PTO driven Land Pride RTA3576 tiller with a 1.83m working width (Land Pride, Salinas, KS). One tillage event was adequate to terminate the rye in 2018, but a second tillage event was required in 2019. Fertilizer was broadcast applied according to University of Wisconsin-Extension recommendations (Laboski and Peters, 2019) based on soil test results and was incorporated with an additional rototilling. Plastic mulch (1.22m wide) and drip irrigation was applied in planting strips with a Mechanical Transplanter Model 85 mulch layer (Mechanical Transplanter Company, Holland, MI), ground winter wheat straw mulch was applied by hand for check plots and living mulch treatments were seeded by hand and lightly incorporated by raking. Three-week-old 'Dunja F1' zucchini summer squash (*Cucurbita pepo*) transplants grown in 50 cell trays were hand transplanted at 0.61m in-row and 2.44m between-row spacing. Drip irrigation placed under the mulch was applied as needed throughout the season.

**Table 1:** Summary of field activities

| **Date (2017)** | **Date (2018)** | **Date (2019)** | **Activity** |
|---|---|---|---|
| September 25 | September 27 | | Aroostock' rye cover crop seeding (2 bu / acre) |
| | May 17 | May 15 | Terminate rye cover crop |
| | May 17 | May 17 | Application of fertilizer |
| | May 17 | May 21 | Additional Tillage |
| | May 17 | May 23 | Application of plastic and straw mulches |
| | May 18 | May 23 | Seed living mulches |
| | June 6 | June 7 | Transplant |
| | July 18 and 25; August 8 and 20 | July 9 16, 23, and 29; August 6 and 13 | Insect counts |
| | July 17 and 25; August 8 | June 27; July 8, 16 and 28 | Weed counts |
| | July 17 and 25; August 8 | June 27; July 8, 16 and 28 | Timed weed management |
| | - | July 31 | Apply pyrethrin pesticide (Pyganic ®) |
| | July 5, 17, 18, and 23; August 2nd, 8, 13, 15, 20 and 27. | July 9, 11, 15, 18, 22nd, 24, 26, 29, and 31; August 1, 3, 5 and 9 | Harvests |

Weeds were categorized as broadleaf or grass weeds and counted within four randomly placed 0.25 $m^2$ quadrats (two each side of the data row, n=16 per treatment at each date) within 24 hrs prior to timed manual weeding. Weeds were removed manually within the ground straw treatment and with stirrup hoes supplemented by additional hand weeding on the shoulders of beds to avoid tearing plastic within the cultivated treatment. Living mulch treatments were managed by mowing with a Simplicity 13.5hp walk-behind brush hog (Simplicity Manufacturing, Port Washington, WI) with a 15cm blade height, supplemented by additional hand weeding to avoid weeds reaching reproductive maturity. Total weeding time (for a single person) required for weed management after the planting of the cash crops was recorded separately for each treatment at each weeding event (n=4 per treatment at each date). Weeding data was taken either when weed pressure necessitated weeding, as determined by weeds approaching flowering or being above 30cm, or when ryegrass or mixed species living mulches needed mowing, as determined by rygrass being above 30cm. Cucumber beetle, squash bug egg clusters, and adult squash bugs per plant were counted as close to a weekly basis as possible (n=32 per treatment at each date).

Squash was harvested when fruit had reached marketable maturity at 15+ cm, averaging every 6 days in 2018 and every 2.5 days in 2019. In each plot, the plant stand count was recorded and all squash of adequate size were harvested and sorted by quality as marketable or non-marketable. Fruit was counted as unmarketable if it showed visible evidence of rot, insect damage, surface blemishes, or was misshapen. Fruit was counted as marketable if firm and had smooth, unblemished skins. Due to early season squash bug pressure in 2019, pyrethrin (PyGanic®,Sumitomo Chemical, Chuo City, Tokyo, Japan) was applied once on July 31.

### *DATA ANALYSIS*

Data was analyzed in R (R.app GUI 1.4 "Juliet Rose" (df86b69e, 2021-05-24), © R Foundation for Statistical Computing, 2021). ANOVAs for data such as yield, marketability, survival, weed management time, and pest counts were done using the lme() function in the "nlme" package (Pinheiro 2022) using the following model:

$$\mathrm{Y_{ijk}} = \mu + \mathrm{A_i} + \mathrm{B_{j(i)}} + \mathrm{M_k} + \delta_{\mathrm{k(ji)}} + \mathrm{SP_l} + \mathrm{(AM)_{ik}} + \epsilon_{\mathrm{ijk}}$$

where $Y_{ijkl}$ is the observation for the *i*th year, *j*th block, and *k*th aisle mulch treatment, $A_i$ is the fixed effect of the *i*th year (*i*=2018, 2019), $B_{j(i)}$ is the random effect of the *j*th block nested within the *i*th year (*j*=1, 2, 3), $\mathrm{M_k}$ is the fixed effect of the *k*th aisle mulch treatment (*k* = cultivated, straw, clover, ryegrass, or mix), $\mathrm{(AM)_{ik}}$ is the effect of the interaction between the *i*th year and *k*th aisle mulch and $\epsilon_{\mathrm{ijk}}$is the residual error associated with the observation for the *i*th year, *j*th block, and *k*th aisle mulch treatment.

Pest counts, harvest counts, and weed management time were transformed to cumulative counts per plot, with only the final cumulative count analyzed to meet assumptions of independent observations and improve assumptions of normality and equality of variance. Analysis for weed counts included an additional subsampling error term $\gamma_{m\mathrm{(kjil)}}$ which was the random effect of the *m*th subsample where *m*=1, 2, 3, 4 subsamples for weed counts. Since survival rate was not associated with aisle mulch treatment yield $\mathrm{m}^{-1}$ analyses also included a covariate of stand count, $\beta X_{ijk}$ where $\beta$ is the slope of the covariate of stand count $X$ within the *i*th year, *j*th block, and *k*th aisle mulch treatment.

Normality and equality of variances were checked visually with standardized residuals vs fitted value plots and normal QQ plots respectively (R Core Team 2022). Right skewed weed count data for each ANOVA for a given dependent were transformed with log($x$ + 1) when necessary to improve assumptions of normality and equality of variances. When ANOVA F-tests were significant, Tukey's Multiple Comparisons Procedure was used to compare treatment means and develop significance groupings using the emmeans() function in the "emmeans" package, which is also how estimated marginal means for tables were obtained. When two-way interactions between main effects were found, pairwise comparisons for the simple main effect were made for each level of the other factor, again using the emmeans() function with a Tukey adjustment. All figures are shown with non-transformed data though significance groupings are based on transformed data when applicable.

## RESULTS

### *WEATHER*

**Table 2:** Weather data collected at UW-Madison Arboretum Weather Station (~6 miles from study site).

| **Time period** | **Total precipitation in cm (deviation from 40 yr average)** | **Average daily temperature in ºC (deviation from 40 yr average)** | **GDDU 50 (deviation from 40 yr average)** |
|---|---|---|---|
| October 2017 - February 2018 | 27.89 (+2.02) | -0.7 (+0.49) | 182 (+77) |
| March - May 2018 | 33.07 (+7.71) | 7.41 (-0.13) | 463 (+128) |
| June - Sept 2018 | 86.11 (+41.28) | 20.57 (+0.95) | 2286 (+238) |
| October 2018 - February 2019 | 37.24 (+11.37) | -1.13 (+0.06) | 86 (-19) |
| March - May 2019 | 24.05 (-3.53) | 7.45 (-0.09) | 259 (-76) |
| June - Sept 2019 | 58.90 (+14.07) | 20.28 (+0.66) | 2164 (+116) |

The winter and spring months leading into the 2018 growing season experienced slightly more precipitation than average and close to average temperatures with the accumulation of more growing degree day units (GDDU) than normal, providing an environment conducive to greater cereal rye biomass accumulation as compared to 2019, which experienced a particularly cold, wet winter and a cool, dry spring. Both 2018 and 2019 experienced more rainfall than average, with a single rain event in late August of 2018 releasing over 25cm of rain within 24 hours at the study site. (MRCC, 2021)

## *SURVIVAL, VEGETABLE YIELD AND QUALITY*

### *Plant survival*

Average survival rates across both years ranged between 81% for straw mulch and 92% mixed species living mulch treatments, but was not significantly impacted by aisle mulch treatment, year, or an interaction between the two (Table 3).

**Table 3:** Cumulative yield, fruit quality, and survival data by aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at $P < 0.05$. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch treatments, with a p-value adjustment using the Tukey method for comparing a family of estimates.

| **Aisle Mulch** | **Proportion Plant Survival** | **Marketable Fruit per m** | **Total Fruit per m** | **Unmark. Fruit per m** | **Proportion Unmark.** | **Marketable Fruit per Plant** | **Total Fruit per Plant** |
|---|---|---|---|---|---|---|---|
| Cultivated | 0.86 | 15.0 ab | 22.93 ab | 7.94 | 0.26 | 8.29 a | 12.8 |
| Straw | 0.81 | 16.0 a | 23.95 a | 7.96 | 0.29 | 8.13 a | 12.1 |
| Clover | 0.83 | 11.7 b | 19.84 b | 8.18 | 0.28 | 5.69 b | 10.6 |
| Ryegrass | 0.84 | 11.8 b | 20.06 ab | 8.26 | 0.31 | 6.04 b | 10.8 |
| Mix | 0.92 | 12.5 ab | 20.57 ab | 8.10 | 0.23 | 6.58 ab | 11.1 |
| **Treatment Effects:** | | | | | | | |
| Cov: Stand Ct | NA | F=21.13, p<0.0001 | F=20.35, p<0.001 | F=2.05, ns | NA | NA | NA |
| Aisle Mulch | F=0.48, ns | F=3.16, p<0.05 | F=3.77, p<0.05 | F=0.08, ns | F=0.22, ns | F=5.85, p<0.01 | F=2.60, p<0.1 |
| Year | F=2.23, ns | F=23.67, p<0.01 | F=32.47, p<0.01 | F=16.32, p<0.01 | F=10.55, p<0.05 | F=153.24, p<0.0001 | F=195.51, p<0.0001 |
| Aisle × Year | F=0.94, ns | F=2.09, ns | F=1.01, ns | F=0.54, ns | F=0.66, ns | F=2.38, p<0.1 | F=1.39, ns |

### *Overall yield*

Because variation in the proportion of plants that survived was observed which would affect yield $m^{-1}$, but aisle mulch treatments themselves did not affect this proportion, the proportion of plants surviving was used as a covariate, which had a significant effect on both cumulative marketable fruit and total fruit, but not on unmarketable fruit.

Year influenced all yield response variables (Appendix B, Supplementary Table 1). Aisle mulch affected marketable and total fruit m$^{-1}$ but did not affect unmarketable fruit counts m$^{-1}$ or the proportion of fruit that were unmarketable (Figure 1). Aisle mulch was also significant for marketable fruit plant$^{-1}$ but not total fruit plant$^{-1}$ (Figure 2). On a m$^{-1}$ basis, straw mulch treatments outyielded clover treatments for both marketable and total fruit, and the ryegrass treatment for marketable fruit. On a plant$^{-1}$ basis, both the straw mulch and cultivated treatments yielded more marketable fruit than clover or ryegrass treatments, while the mixed species living mulch treatment was similar to both groups.

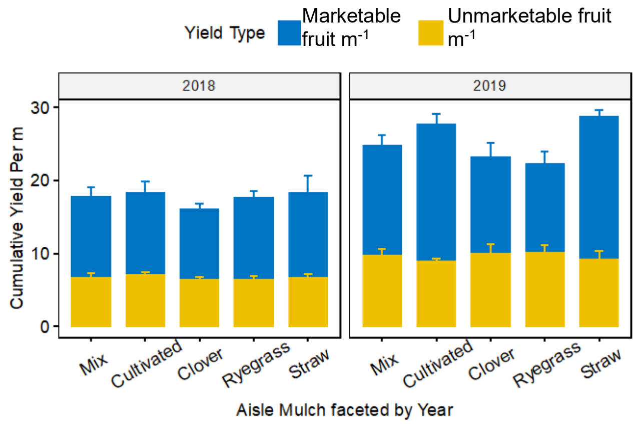

*Figure 1: Yield m$^{-1}$. Aisle mulch differences were significant across years for both marketable and total fruit, but there was no interaction between mulch and year. Number of fruit deemed unmarketable was not affected by aisle mulch. There were higher fruit counts in 2019 than in 2018.*

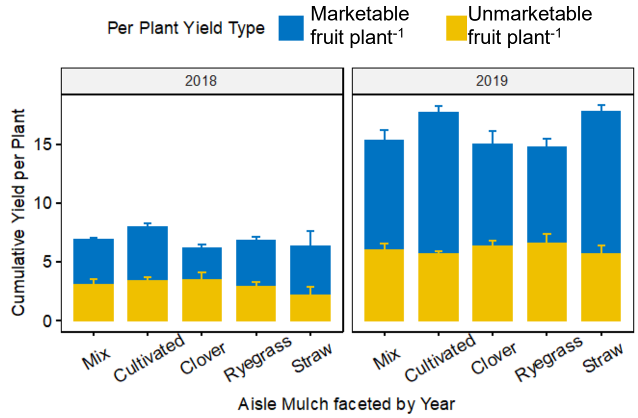

*Figure 2: Yield plant$^{-1}$. Marketable fruit per plant was affected by aisle mulch, but total fruit and number of fruit deemed unmarketable were not.*

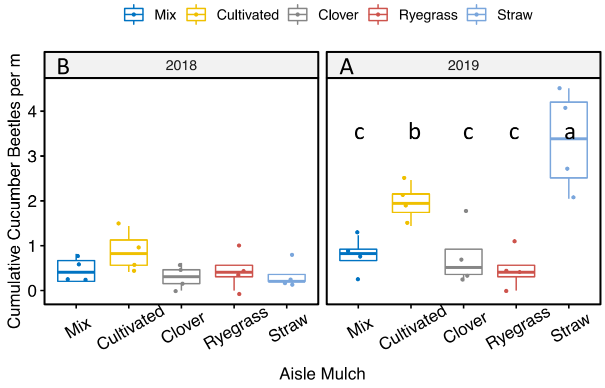

*Figure 3: Cumulative cucumber beetle counts m$^{-1}$. In 2019 there was a significant effect from aisle mulch. Treatments with the same lowercase letter (or no letter) were not significantly different within the same year at $P < 0.05$, while uppercase letters indicate groupings for year across mulch treatments.*

## *INSECT PEST PRESSURE*

### *Striped cucumber beetle*

There was a significant year × mulch interaction for cumulative number of cucumber beetles m$^{-1}$ (Table 4 for overall results; Appendix B, Supplementary Table 2 for results by year). Although cucumber beetle pressure was

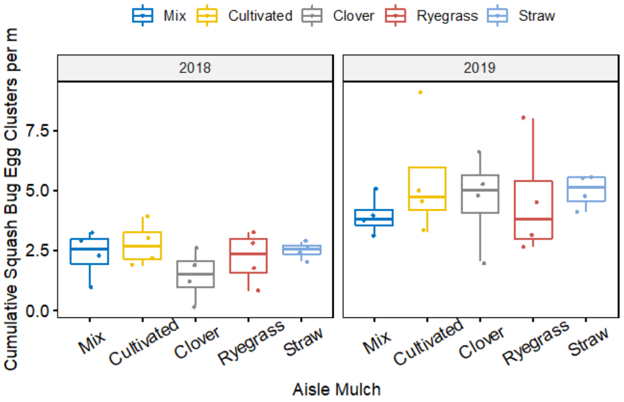

*Figure 4: Cumulative egg cluster counts m$^{-1}$ were affected by year but not aisle mulch. Years with the same uppercase letter were not significantly different across mulch treatments at $P < 0.05$.*

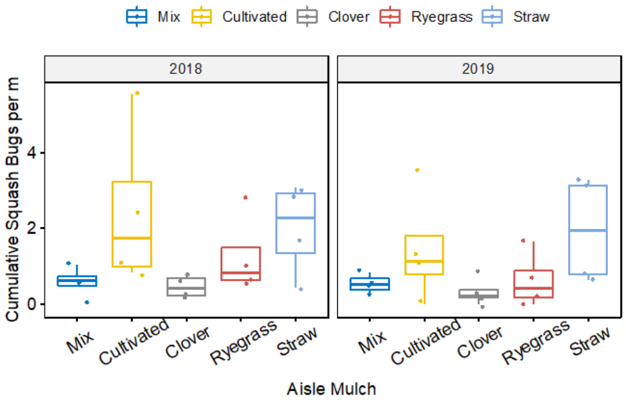

*Figure 5: Cumulative squash bug counts m$^{-1}$ were affected by aisle mulch, but not year. Treatments with the same lowercase letter (or no letter) were not significantly different across years at $P < 0.05$.*

negligible in 2018 and there were no differences between treatments, clear differences were evident during the 2019 season (Figure 3). Cultivated and straw mulch treatments resulted in higher cucumber beetle counts m$^{-1}$ than the clover or ryegrass treatments, while the mixed species living mulch treatment resulted in lower cucumber beetle counts as compared with the straw mulch treatment but was not different from other living mulch treatments.

**Table 4:** Final cumulative counts of striped cucumber beetle, squash bugs and egg clusters in 2018 and 2019 by aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at $P < 0.05$. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch treatments, with a p-value adjustment using the Tukey method for comparing a family of estimates.

| **Aisle Mulch** | **Cumulative cucumber beetles per m** | **Cumulative egg clusters per m** | **Cumulative squash bugs per m** |
|---|---|---|---|
| Cultivated | 1.41 ab | 4.10 | 1.95 a |
| Straw | 1.85 a | 3.74 | 1.97 a |
| Clover | 0.54 c | 3.08 | 0.38 b |
| Ryegrass | 0.46 c | 3.38 | 0.95 ab |
| Mix | 0.62 bc | 3.15 | 0.54 ab |
| **Treatment Effects:** | | | |
| Aisle mulch | F=9.93, p<0.001 | F=0.69, ns | F=4.26, p<0.01 |
| Year | F=30.12, p<0.01 | F=28.40, p<0.01 | F=1.66, ns |
| Aisle × Year | F=9.18, p<0.001 | F=0.32, ns | F=0.30, ns |

### *Squash bug eggs and adults*

The cumulative number of egg clusters m$^{-1}$ was not affected by aisle mulch, although significantly more egg clusters were observed in 2019 as compared to 2018 (Figure 4). In contrast, the number of adult squash bugs m$^{-1}$ was affected by aisle mulch but not year (Figure 5), with clover having lower counts as compared to straw or cultivated treatments. Both ryegrass and mixed species cover crop treatments were not different from either group.

## *MULCHES AND WEED POPULATIONS*

### *Weed counts and management time*

A significant year × aisle mulch interaction explained the amount of total, broadleaf, and grass weeds (Table 5 for overall results; Figure 6; Appendix B, Supplementary Table 3 for results by year). Across both years, the straw mulch resulted in lower weed counts than other treatments, with the exception of performing similarly to ryegrass for grass weeds. For total and grass weeds, the clover resulted in greater weed numbers than all other treatments, and the cultivated treatment resulted in greater weed numbers than ryegrass and mixed species living mulch treatments. Broadleaf weed numbers were similar among all treatments except straw mulch.

**Table 5:** Least square means of cumulative weed counts and management. Columns with the same letter were not significantly different across mulch treatments within the same year at □ = 0.05. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch, with results averaged across blocks, dates, and samples and a p-value adjustment using the Tukey method for comparing a family of estimates.

| **Aisle Mulch** | **Total Weed Ct (per .25m$^2$)** | **Grass Weed Ct (per .25m$^2$)** | **Broadleaf Weed Ct (per .25m$^2$)** | **Total Weeding Time (hrs/ha)** | **Living Mulch Percent Cover** |
|---|---|---|---|---|---|
| Cultivated | 8.88 b | 5.82 b | 3.04 a | 264.3 a | - |
| Straw | 0.48 d | 0.23 d | 0.20 b | 82.8 c | - |
| Clover | 12.49 a | 9.27 a | 3.22 a | 238.6 b | 90.34% a |
| Ryegrass | 2.72 c | 0.85 cd | 1.88 a | 134.0 c | 59.12% c |
| Mix | 3.00 c | 1.13 c | 1.88 a | 198.9 b | 78.96% b |
| **Treatment Effects**: | | | | | |
| Aisle Mulch | F=98.60, p<0.0001 | F=121.03, p<0.0001 | F=24.14, p<0.0001 | F=53.36, p<0.0001 | F=54.87, p<0.0001 |
| Year | F=49.49, p<0.0001 | F=47.95, p<0.001 | F=18.55, p<0.01 | F=52.21, p<0.0001 | F=9.20, p<0.05 |
| Aisle × Year | F=7.93, p<0.001 | F=20.04, p<0.0001 | F=4.32, p<0.01 | F=38.43, p<0.0001 | F=19.39, p<0.001 |

Despite its notably higher weed numbers, the clover treatment required less time for weed management than cultivated aisles. The mixed species living mulch required a similar amount of weed management time as compared to the clover treatment, despite having fewer weeds. Straw mulch and ryegrass required less weed management time than all other groups (Figure 7).

Differences in weed management time relative to the quantity of weeds may have been influenced by different field crews in different years, although during a specific weed management event, the same crew member always weeded the entirety of a given block across treatments.

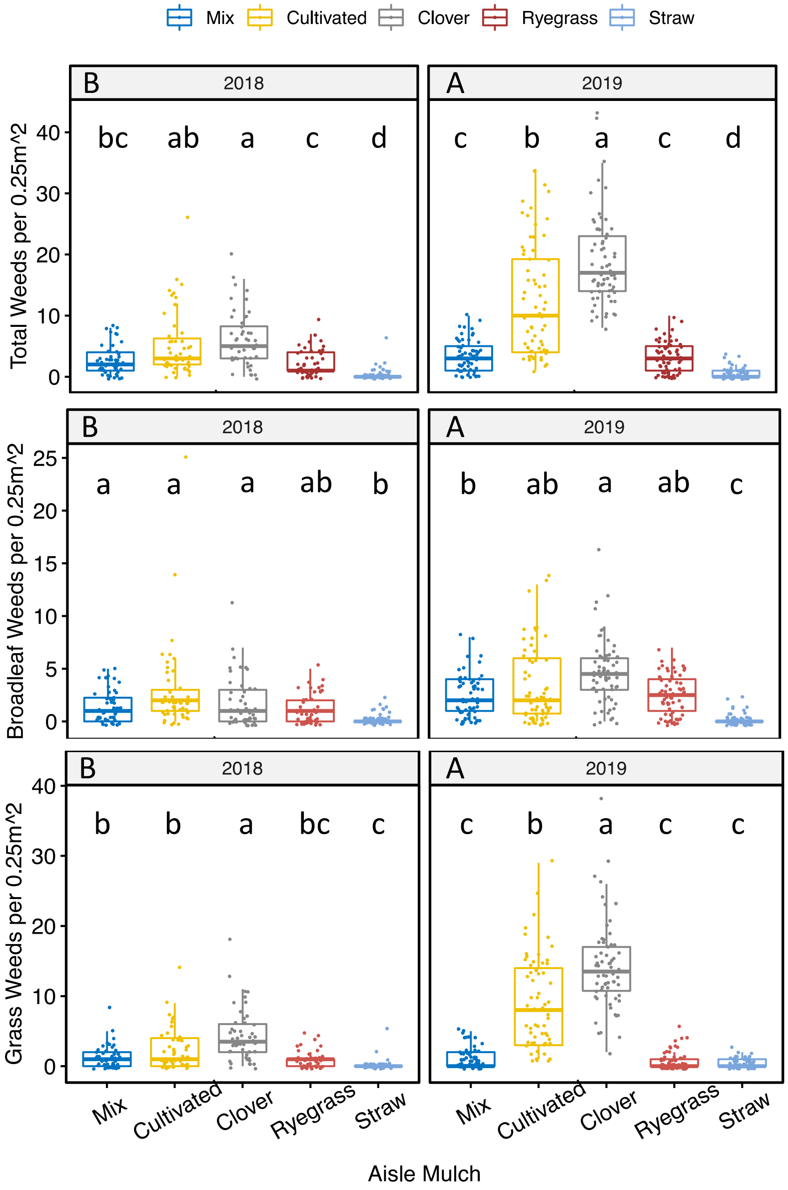

*Figure 6: Total (top), broadleaf (center), and grass (bottom) weed counts per 0.25m² across dates and subsamples. There was a significant aisle mulch × year interaction both years for all three weed types, with higher weed counts and more stark differences between treatments in 2019. Clover generally ranked highest, followed by cultivated aisles, while mixed species and ryegrass living mulch treatments often had weed suppression similar to the straw mulch control. Lowercase letters indicate significance groupings within a given year and weed response variable, while uppercase letters indicate significance groupings for years across aisle mulch treatments. Groups that share the same letter are not significantly different at P<0.05.*

*Percent soil coverage by living mulch*

A significant year × aisle mulch interaction was observed for living mulch percent cover (Figure 8). Whereas in 2018 ryegrass had significantly lower coverage than both other living mulch treatments and the mixed species living mulch in turn had lower coverage than the clover treatment, in 2019 only the mixed species had less coverage than the clover treatment, and the ryegrass was not different from either group. Overall, percent cover was lower in 2018 than 2019, and across both years clover clearly had the best soil coverage at 90%, while the mixed species living mulch had lower cover at 79% and ryegrass averaged the lowest coverage at 59%.

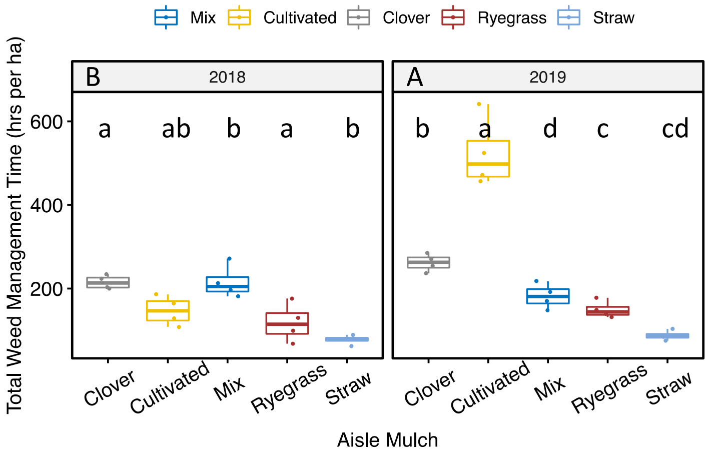

*Figure 7: Cumulative weed management time. There was a significant year × aisle mulch interaction, with the higher weed counts in 2019 leading to much larger increases in weed management time for cultivated aisles as compared to other treatments, and thus changing both rankings and statistical groupings. Lowercase letters indicate significance groupings for mulch treatment within a given year. Treatments that share the same letter are not significantly different at P<0.05.*

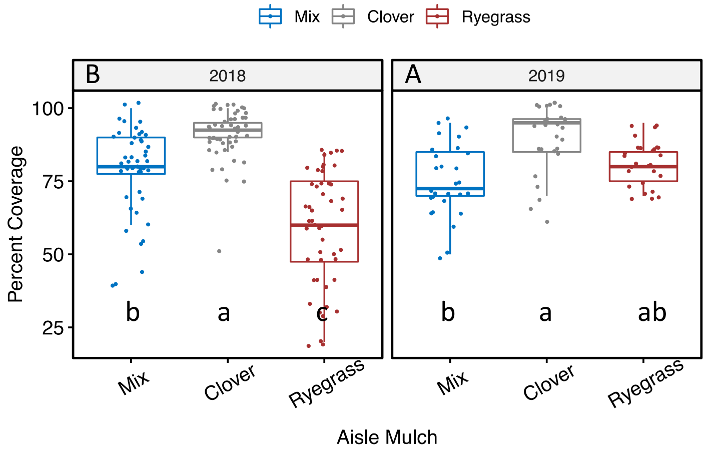

*Figure 8: Percent cover of living mulch treatments at each date. There was a significant aisle mulch × year interaction. Lowercase letters indicate significance groupings for mulch treatments within a given year, while uppercase letters indicate significance groupings for year across mulch treatments. Treatments that share the same letter are not significantly different at P<0.05.*

## DISCUSSION

Previous research demonstrated variable or negative impacts on yield when cucurbit species were produced using living mulch systems (Hinds and Hooks 2016; Nyoike and Liburd, 2010), although some limited results demonstrated a mitigation of yield losses when plastic mulch was laid within the planting row (Nelson and Gleason 2018; Kahl et al., 2019).

Our results reinforce the risk of reduced yield in living mulch systems, with lower marketable yield in treatments using clover and annual ryegrass as a living mulch as compared to managing the aisles using cultivation or straw mulch. However, using the mixture of annual ryegrass and clover performed comparably to the more standard management practices of cultivation and straw mulch. Management practices to reduce the potential for competition between cover crops and cash crops, such as the regular mowing of living mulches to a height of 15 cm (Båth et al., 2007; Hinds et al, 2015), and the management of the planting strip using plastic mulch (Nelson and Gleason, 2018), did not fully mitigate reduced yields in our study. While low mowing has the potential to result in reduced competition or mitigate cash crop yield loss (Liu and Huang, 2002; Hinds et al, 2015), future studies could compare mowing with mechanical root pruning, which has also been suggested as a way to reduce living mulch competition with cash crops (Båth et al., 2007).

Our results supported previous studies suggesting potential benefits of living mulches for reducing pest pressure (Nyoike and Liburd, 2009; Kahl et al., 2019; Grasswitz et al., 2013). However, our results should be interpreted in the context of low overall pest pressure. In contrast to Grasswitz's observation that living mulch systems resulted in greater squash bug pressure as compared to standard management, our results showed no clear differences between management approaches for the numbers of squash bug eggs. However, the lower numbers of adults resulting from the use of living mulch cover crops observed in our study could be due to increased natural predators in living mulch systems (Grasswitz et al., 2013; Nyoike and Liburd, 2009; Kahl et al., 2019). We are not aware of previous studies on living mulch that investigated predator populations alongside pests within a plasticulture system. Given the prevalence of plastic mulch for producers, future studies could investigate whether the same mechanism of increased predator populations might be responsible for reduced pest pressure in plasticulture systems with living mulch.

Our results also support previous research indicating that clover does not adequately suppress weeds during the establishment year (MacLaren et al., 2019; Tarrant et al, 2020). Soil coverage by the cover crop, a potential indicator of light competition (Place et al., 2011), did not appear to be the significant driver of reduced weed counts in our study, given that clover resulted in a higher percent coverage than ryegrass or the mixed species treatments but still had higher weed counts. The clover treatment also had a consistently lower yield m$^{-1}$. As compared with the cultivated control, ryegrass reduced weed counts both years, but still yielded fewer marketable fruit. The mixed species performed best out of the living mulch treatments, with weed control comparable to ryegrass and yields equivalent to the cultivated and straw mulch controls.

The use of annual ryegrass and an annual ryegrass/clover mix resulted in better weed suppression as compared to a clover cover

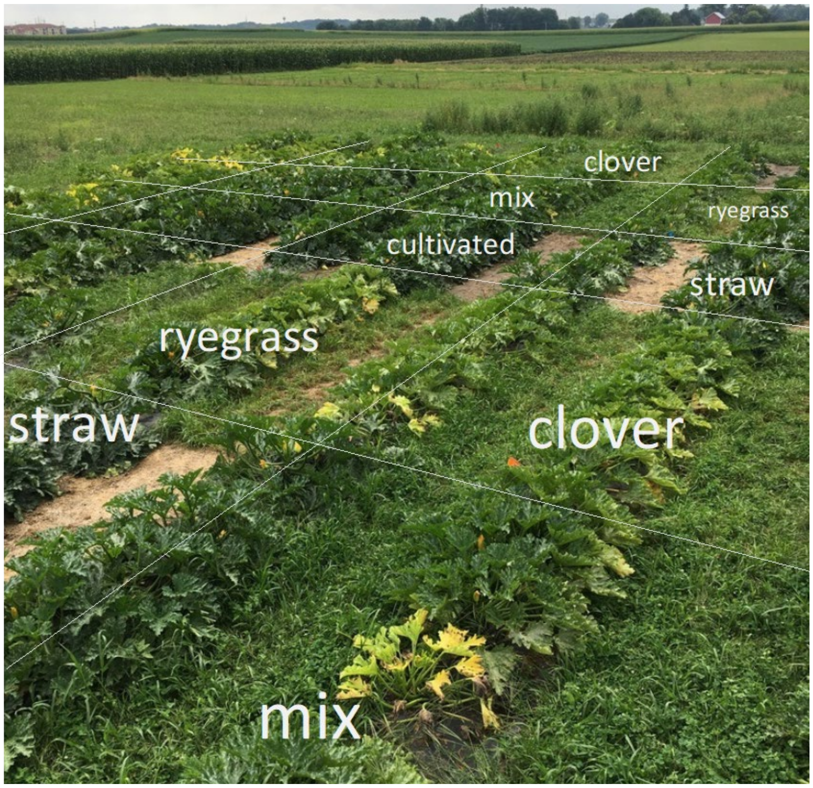

*Figure 9: In 2019 many living mulch plots exhibited visible chlorosis. Note that the particularly stunted and yellowed plant in the foreground mixed species living mulch plot was afflicted with fusarium wilt, whereas in many other living mulch plots the plants were yellowing without any particular disease identifiable as the cause.*

crop alone, Results from Tarrant et al. (2020) suggest that both ryegrass and clover have the potential to reduce soil nitrate and moisture within the cash crop row relative to cultivated controls, supporting the negative impacts on yields observed in both treatments in our study. Anecdotally, chlorosis was visible in living mulch treatments in 2019 (Figure 9), suggesting that nutrient competition between cash and cover crops may have contributed to reduced yields.

Given the equivalent proportions of unmarketable fruit, benefits for pest control, and even comparable weed control in ryegrass as compared to straw mulch, future studies could address the potential of nutrient and water resource competition as a possible driver of reduced marketable fruit yields in living mulch cucurbit systems. Analyzing nutrient and water status of both cash crop and cover crops and testing supplementary fertilizer, such as has been done in other crops (e.g. Fracchiolla et al., 2020 or Warren et al., 2015), may help understand the role of cover crop competition in reducing cash crop yield.

In one of the two years of our study, managing the aisle as bare ground required significantly longer weed management time as compared to managing the aisles using any of the cover crop treatments. Similar to the observation of Butler et al. (2013) that a single mowing event is not adequate to eliminate some weed species' reproductive capacity, the greatest proportion of the weed management time required for living mulch treatments was in additional hand weeding to remove weeds not terminated completely by the mower. Anecdotally, most of the hand weeding required was found outside of the mower management zone, either below the mower deck, or at the shoulders of the bed underneath the more mature cash crop canopy encroaching into the aisle. However, all treatments were weeded completely clean at each weeding event to create equivalent conditions between the living mulch treatments and the bare cultivated control. In a more practical circumstance, farmers may have a higher tolerance for weed pressure, in which case simply mowing the living mulch treatments may suffice.

Clover had higher weed counts than cultivated aisles in 2019, yet required less management time, indicating the use of mowing as a management tool in living mulch treatments likely hindered weed growth, thus contributing to reduced impact of higher weed counts in 2019 as compared with 2018. Despite significantly higher weed counts in 2019 as compared to 2018 across all mulch treatments, only the cultivated treatment took longer for weed management in the second year, whereas straw and living mulches had equivalent management times between years. Our results suggest that alongside traditional organic and plastic mulches, living mulch managed with mowing has potential to mitigate some of the increased management time associated with very weedy conditions, whereas in less weedy conditions they may take longer to manage than traditional options like straw mulch or cultivation.

This study contributes to our further understanding of effects of living mulch on weed and pest pressure, with the system demonstrating potential for agroecosystem benefits but variable impacts on cash crop yield. Further research over multiple years, across multiple environments and with additional crops will contribute to our understanding of the system's performance across organic vegetable farms. While pest pressure was low during both years of our study, production environments experiencing greater pest pressure may benefit more from the use of living mulches. However, to reduce the risk associated with the adoption of these practices, future research should address potential economic and management considerations such as weed management thresholds, supplementary weed management methods. It is also important to investigate the competition potential between cover crops and cash crops, and how nutrient status and yield respond to supplementary fertilizer.

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# FINAL CONCLUSIONS

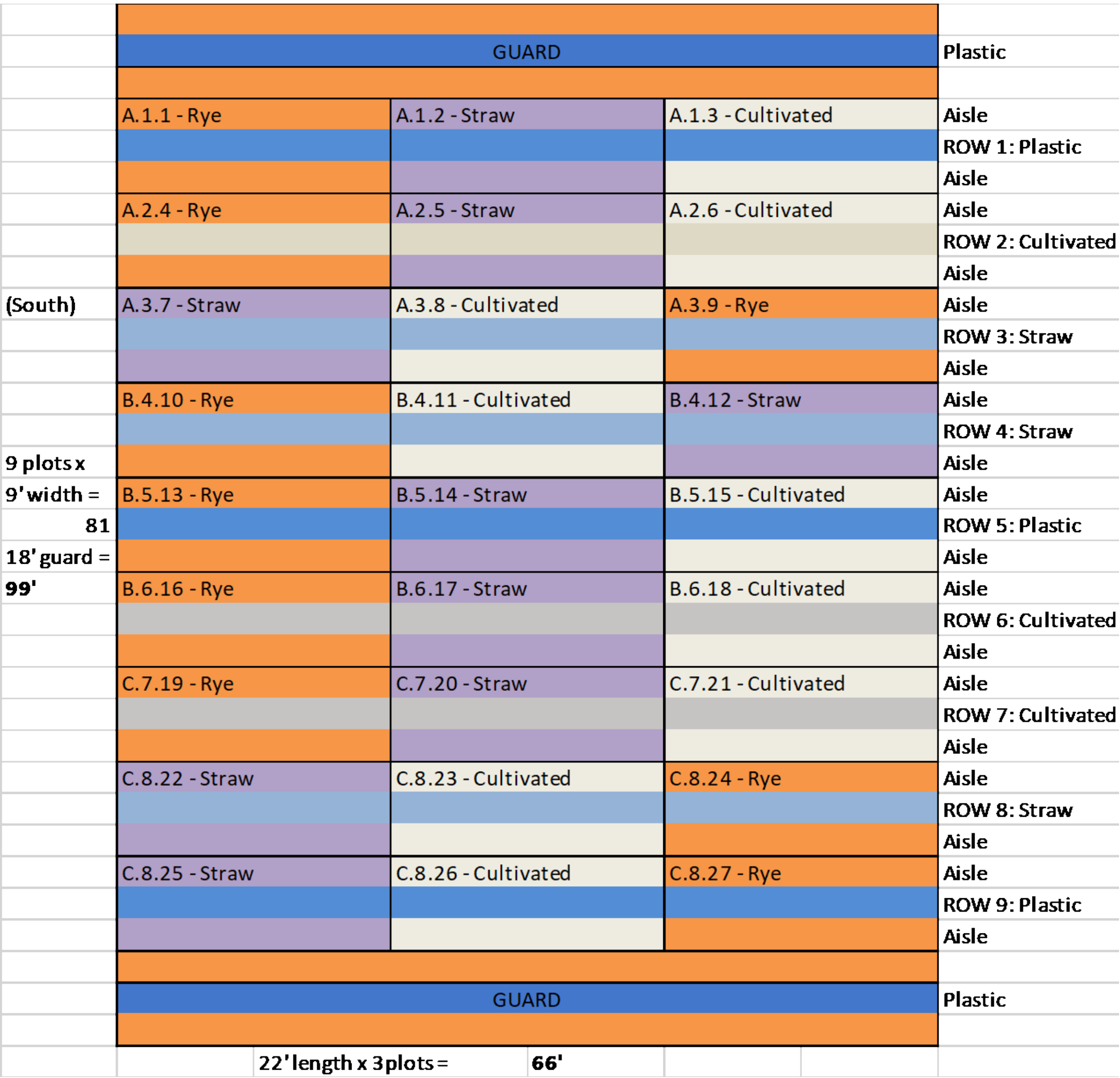
The objective of this project was to investigate in more detail reduced tillage methods that apply to organic cucurbit production in Wisconsin specifically and the upper Midwest more broadly. To pursue this goal, we investigated two different production systems: first, a winter squash production system with different aisle and row mulches, including fall-planted cereal rey for roller-crimping, which has been used effectively in the production of Midwest field crops; second, a zucchini plasticulture system with different spring-planted cover crops as living mulches compared to conventional tillage and straw mulch.

In the crimped rye experiment there were variable results, and the reduced yields observed primarily during the 2018 production season may have been due to the unprecedented flood that impacted the study site. However, as extreme rain events become more common in the Upper Midwest it is important to capture a diversity of environments before growers can have confidence in adopting these alternative production systems. The rye system may also have impacts on pest management, with increased pressure from squash bugs observed in mulches with higher residue – although the highest pest pressure was observed in the plastic mulch, where there was also the highest plant mortality rate. On the other hand, the crimped rye system showed promise for weed suppression with much more efficient application than traditional straw mulches and the potential for additional ecological benefits. The successful weed suppression and variable results for yield – notably with equivalent yield to control mulches when paired with cultivated rows – indicates that with more research these reduced tillage production systems could be optimized for vegetable production with competitive yields.

In the zucchini plasticulture systems with living mulches we saw no increase in proportion of fruit deemed unmarketable or impact on plant survival, and reduced pest counts, yet also found lower yield for some living mulches, particularly consistent with clover. In addition, clover proved to have poor weed suppression, and even had consistently higher grass weed counts than the cultivated treatment. In contrast, the mixed species living mulch was not significantly different in yield from control treatments, despite ranking lower, and maintained the pest and weed control benefits seen in the other two living mulch treatments. Our results offer results that will be informative for growers and researchers alike as living mulch plasticulture systems are adopted and studied more widely.

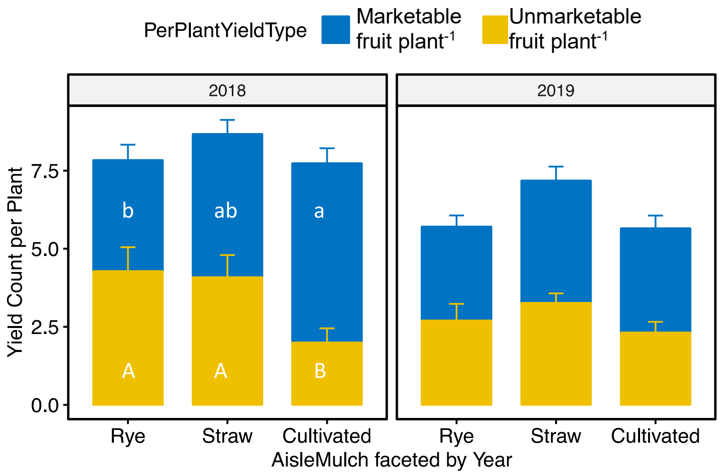
Chlorosis was visible in living mulch treatments in 2019, suggesting that nutrient competition between cash and cover crops may have contributed to reduced yields. The high carbon concentration of the crimped rye may also have caused N immobilization that contributed to reduced yields. Future studies on CCBRT systems for organic vegetable production should assess nutrient status of both cash crops and cover crops to understand how nutrient cycling is changing or contributing to yield. In addition, beneficial insects should be studied alongside pests. It is not only the end results, but the mechanisms behind them which might be most informative to future researchers and the development of best practices for growers. Lastly, it is critical that future studies continue to try a range of management tools and methods to make these systems accessible to growers of all scales, whether that means different mowers for living mulches or small-scale crimpers for walk-behind tractors. There is certainly potential for competitive cucurbit production in CCBRT systems, but more work needs to be done to refine the systems.

# APPENDIX A: CHAPTER 1 SUPPLEMENTARY MATERIALS



| | | | | |
|---|---|---|---|---|
| | | | | |
| | GUARD | | | **Plastic** |
| | | | | |
| | A.1.1 - Rye | A.1.2 - Straw | A.1.3 - Cultivated | **Aisle** |
| | | | | **ROW 1: Plastic** |
| | | | | **Aisle** |
| | A.2.4 - Rye | A.2.5 - Straw | A.2.6 - Cultivated | **Aisle** |
| | | | | **ROW 2: Cultivated** |
| | | | | **Aisle** |
| **(South)** | A.3.7 - Straw | A.3.8 - Cultivated | A.3.9 - Rye | **Aisle** |
| | | | | **ROW 3: Straw** |
| | | | | **Aisle** |
| | B.4.10 - Rye | B.4.11 - Cultivated | B.4.12 - Straw | **Aisle** |
| | | | | **ROW 4: Straw** |
| **9 plots x** | | | | **Aisle** |
| **9' width =** | B.5.13 - Rye | B.5.14 - Straw | B.5.15 - Cultivated | **Aisle** |
| **81** | | | | **ROW 5: Plastic** |
| **18' guard =** | | | | **Aisle** |
| **99'** | B.6.16 - Rye | B.6.17 - Straw | B.6.18 - Cultivated | **Aisle** |
| | | | | **ROW 6: Cultivated** |
| | | | | **Aisle** |
| | C.7.19 - Rye | C.7.20 - Straw | C.7.21 - Cultivated | **Aisle** |
| | | | | **ROW 7: Cultivated** |
| | | | | **Aisle** |
| | C.8.22 - Straw | C.8.23 - Cultivated | C.8.24 - Rye | **Aisle** |
| | | | | **ROW 8: Straw** |
| | | | | **Aisle** |
| | C.8.25 - Straw | C.8.26 - Cultivated | C.8.27 - Rye | **Aisle** |
| | | | | **ROW 9: Plastic** |
| | | | | **Aisle** |
| | | | | |
| | GUARD | | | **Plastic** |
| | | | | |
| | **22' length x 3 plots =** | **66'** | | |

***Supplementary Figure 1:*** *Split plot RCBD layout with three replications, row mulch as the whole plot factor and aisle mulch as the split plot factor. 2018 layout is shown here, while 2019 was similar with both rows and aisles randomized differently.*



*Supplementary Figure 2: Marketable fruit per plant by aisle mulch and year. There were no differences in 2019, but in 2018 cultivated aisles had a higher yield than aisles with crimped rye. Cultivated aisles also had fewer unmarketable fruit per plant. Lowercase letters indicate significance groupings for marketable fruit and uppercase letters indicate significance groupings for unmarketable fruit and proportion unmarketable fruit across row mulches; groups with the same letter (or no letter) were not significantly different across row mulch treatments within the same year at P < 0.05.*

**Supplementary Table 1:** Yield, quality and survival data in 2018 by aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at P < 0.05. Lowercase letters indicate significance groupings for the simple main effect of row mulch treatments within one aisle mulch treatment, and uppercase letters indicate significance groupings for the simple main effect of aisle mulch across row mulch treatments. Significance groupings for the simple main effect of row mulch treatments across aisle mulch treatments not shown.

| **Aisle mulch** | **Row mulch** | **Total fruit m$^{-1}$** | **Mar. fruit m$^{-1}$** | **Unmark. fruit m$^{-1}$** | **Total fruit plant$^{-1}$** | **Mark. fruit plant$^{-1}$** | **Proportion Unmark.** | **Proportion Plant Survival** |
|---|---|---|---|---|---|---|---|---|
| Cultivated control | Ground straw | 11.15 | 7.98 | 3.17 | 8.92 | 6.56 | 0.26 | 0.77 |
| | Black plastic | 6.56 | 6.94 | 2.41 | 7.48 | 5.29 | 0.28 | 0.77 |
| | Cultivated | 10.17 | 8.04 | 2.13 | 6.82 | 5.37 | 0.20 | 0.93 |
| | Cultivated aisle average | 10.23 | 7.66 | 2.57 | 7.74 | 5.74 A | 0.25 B | 0.82 |
| Roller-crimped rye | Ground straw | 11.65 | 4.37 | 7.27 | 9.17 | 3.24 | 0.62 | 0.80 |
| | Black plastic | 7.38 | 3.72 | 3.66 | 6.20 | 2.73 | 0.55 | 0.73 |
| | Cultivated | 12.96 | 7.38 | 5.58 | 8.14 | 4.70 | 0.41 | 0.97 |
| | Rye aisle average | 10.66 | 5.16 | 5.50 | 7.84 | 3.56 C | 0.53 A | 0.83 |
| Ground straw | Ground straw | 12.58 | 5.80 | 6.78 | 9.58 | 4.42 | 0.53 | 0.80 |
| | Black plastic | 7.05 | 3.50 | 3.94 | 8.58 | 3.94 | 0.54 | 0.53 |
| | Cultivated | 10.33 | 8.86 | 4.05 | 7.87 | 5.40 | 0.31 | 0.80 |
| | Straw aisle average | 10.97 | 6.05 | 4.92 | 8.68 | 4.59 B | 0.46 A | 0.78 |
| Row Mulch Across Aisle Mulch Treatments | Ground straw | 11.79 | 6.05 | 5.74 | 9.22 | 4.74 | 0.47 | 0.79 |
| | Black plastic | 8.06 | 4.72 | 3.34 | 7.42 | 3.99 | 0.45 | 0.68 |
| | Cultivated | 12.01 | 8.09 | 3.92 | 7.61 | 5.16 | 0.31 | 0.97 |

**Supplementary Table 2:** Yield, quality and survival data in 2019 by aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at $P < 0.05$. Lowercase letters indicate significance groupings for the simple main effect of row mulch treatments within one aisle mulch treatment, and uppercase letters indicate significance groupings for the simple main effect of aisle mulch across row mulch treatments. Significance groupings for the simple main effect of row mulch treatments across aisle mulch treatments not shown.

| **Aisle mulch** | **Row mulch** | **Total fruit $m^{-1}$** | **Mar. fruit $m^{-1}$** | **Unmark. fruit $m^{-1}$** | **Total fruit $plant^{-1}$** | **Mark. fruit $plant^{-1}$** | **Proportion Unmark.** | **Proportion Plant Survival** |
|---|---|---|---|---|---|---|---|---|
| Cultivated control | Ground straw | 9.13 | 4.98 | 4.16 | 6.69 | 3.65 | 0.45 | 0.83 |
| | Black plastic | 6.56 | 4.76 | 1.80 | 5.80 | 3.88 | 0.35 | 0.67 |
| | Cultivated | 6.84 | 3.83 | 3.01 | 4.47 | 2.49 | 0.43 | 0.93 |
| | Cultivated aisle average | 7.51 | 4.52 | 2.99 | 5.66 | 3.34 | 0.41 | 0.80 |
| Roller-crimped rye | Ground straw | 7.44 | 3.28 | 4.16 | 6.38 | 2.77 | 0.54 | 0.73 |
| | Black plastic | 6.45 | 4.10 | 2.35 | 5.29 | 3.38 | 0.36 | 0.70 |
| | Cultivated | 8.58 | 4.48 | 4.10 | 5.45 | 2.86 | 0.46 | 0.97 |
| | Rye aisle average | 7.49 | 3.96 | 3.54 | 5.71 | 3.00 | 0.45 | 0.80 |
| Ground straw | Ground straw | 10.28 | 4.81 | 5.47 | 7.02 | 3.26 | 0.53 | 0.90 |
| | Black plastic | 7.05 | 4.05 | 3.01 | 7.76 | 4.74 | 0.41 | 0.57 |
| | Cultivated | 10.33 | 5.74 | 4.59 | 6.76 | 3.74 | 0.44 | 0.93 |
| | Straw aisle average | 9.22 | 4.87 | 4.36 | 7.18 | 3.92 | 0.46 | 0.81 |
| Row Mulch Across Aisle Mulch Treatments | Ground straw | 8.95 | 4.36 | 4.59 | 6.70 | 3.23 | 0.51 | 0.82 |
| | Black plastic | 6.69 | 4.30 | 2.39 | 6.29 | 4.00 | 0.37 | 0.64 |
| | Cultivated | 8.58 | 4.68 | 3.90 | 5.56 | 3.00 | 0.45 | 0.94 |

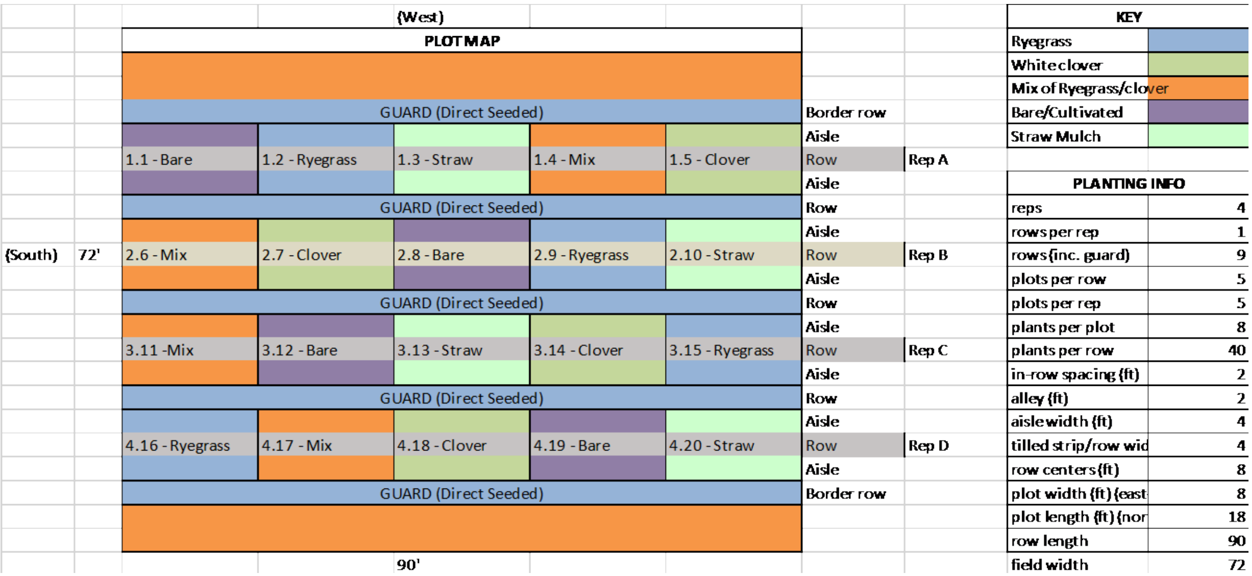
**Supplementary Table 3:** Average cumulative cucumber beetle, squash bugs and egg cluster counts, 2018 and 2019 by aisle and row mulch treatment. Columns with the same letter (or no letter) were not significantly different within the same year at $P < 0.05$. Lowercase letters indicate significance groupings for the simple main effect of row mulch treatments within one aisle mulch treatment, and uppercase letters indicate significance groupings for the simple main effect of aisle mulch across row mulch treatments, or the simple main effect of row mulch treatments across aisle mulches.

| | | 2018 | | | 2019 | | |
|---|---|---|---|---|---|---|---|
| **Aisle type** | **Row Mulch** | **Cucumber beetles per plant** | **Squash bugs per plant** | **Squash bug egg clusters per plant** | **Cucumber beetles per plant** | **Squash bugs per plant** | **Squash bug egg clusters per plant** |
| Cultivated control | Ground straw | 0.10 | 2.20 | 0.20 | 1.23 | 0.17 | 0.37 |
| | Black plastic | 0.17 | 3.83 | 0.73 | 0.90 | 2.83 | 1.40 |
| | Cultivated | 0.13 | 0.40 | 0.07 | 1.47 | 0.33 | 0.37 |
| | Cultivated aisle average | 0.13 | 0.72 B | 0.33 B | 1.20 | 0.28 | 0.71 |
| Roller-crimped rye | Ground straw | 0.13 | 4.87 | 1.10 | 1.93 | 0.13 | 0.13 |
| | Black plastic | 0.07 | 6.83 | 2.30 | 1.47 | 0.33 | 0.93 |
| | Cultivated | 0.07 | 1.80 | 0.40 | 1.50 | 0.10 | 0.40 |
| | Rye aisle average | 0.09 | 1.26 A | 1.27 A | 1.63 | 0.12 | 0.49 |
| Ground straw | Ground straw | 0.23 | 4.43 | 0.83 | 1.80 | 0.07 | 0.20 |
| | Black plastic | 0.03 | 5.70 | 1.60 | 1.43 | 1.67 | 1.03 |
| | Cultivated | 0.10 | 1.67 | 0.63 | 1.30 | 0.07 | 0.23 |
| | Straw aisle average | 0.12 | 1.04 AB | 1.02 A | 1.51 | 0.21 | 0.49 |
| Row Mulch Across Aisle Mulch Treatments | Ground straw | 0.16 | 3.83 A | 0.71 | 1.66 | 0.12 | 0.23 |
| | Black plastic | 0.09 | 5.46 A | 1.54 | 1.27 | 1.44 | 1.12 |
| | Cultivated | 0.10 | 1.29 B | 0.33 | 1.42 | 0.17 | 0.33 |

**Supplementary Table 4:** Weed counts and management time in 2018 and 2019 relative to row and aisle mulch treatments. Columns with the same letter were not significantly different across mulch treatments within the same year at $P < 0.05$ in either aisles or rows.

| | 2018 | | | | 2019 | | | |
|---|---|---|---|---|---|---|---|---|
| **Mulch type** | **Weeding time (hrs/ha)** | **Total weed ct per ¼ $m^2$** | **Broadleaf ct per ¼ $m^2$** | **Grass ct per ¼ $m^2$** | **Weeding time (hrs/ha)** | **Total weed ct per ¼ $m^2$** | **Broadleaf ct per ¼ $m^2$** | **Grass ct per ¼ $m^2$** |
| Cultivated aisle | 84.30 a | 8.53 a | 4.60 a | 3.93 a | 117.62 a | 12.33 a | 2.87 a | 9.47 a |
| Rye aisle | 40.69 b | 3.40 b | 0.56 b | 2.29 b | 80.13 b | 3.16 b | 1.50 b | 1.66 b |
| Straw aisle | 31.41 c | 0.97 c | 0.27 c | 0.54 c | 22.34 c | 0.76 c | 0.022 c | 0.73 b |
| Straw row | 26.51 b | 0.39 b | 0.22 b | 0.17 b | 13.76 b | 0.17 c | 0.011 b | 0.16 c |
| Plastic row | 26.48 b | 0.40 b | 0.17 b | 0.24 b | 19.14 b | 1.03 b | 0.23 b | 0.80 b |
| Cultivated row | 112.84 a | 7.83 a | 4.97 a | 2.86 a | 108.37 a | 9.31 a | 2.30 a | 7.01 a |

# APPENDIX B: CHAPTER 2 SUPPLEMENTARY MATERIAL



(West)

**PLOT MAP**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| | GUARD (Direct Seeded) | | | | | Border row | |
| | | | | | | Aisle | |
| | 1.1 - Bare | 1.2 - Ryegrass | 1.3 - Straw | 1.4 - Mix | 1.5 - Clover | Row | Rep A |
| | | | | | | Aisle | |
| | GUARD (Direct Seeded) | | | | | Row | |
| | | | | | | Aisle | |
| (South) 72' | 2.6 - Mix | 2.7 - Clover | 2.8 - Bare | 2.9 - Ryegrass | 2.10 - Straw | Row | Rep B |
| | | | | | | Aisle | |
| | GUARD (Direct Seeded) | | | | | Row | |
| | | | | | | Aisle | |
| | 3.11 -Mix | 3.12 - Bare | 3.13 - Straw | 3.14 - Clover | 3.15 - Ryegrass | Row | Rep C |
| | | | | | | Aisle | |
| | GUARD (Direct Seeded) | | | | | Row | |
| | | | | | | Aisle | |
| | 4.16 - Ryegrass | 4.17 - Mix | 4.18 - Clover | 4.19 - Bare | 4.20 - Straw | Row | Rep D |
| | | | | | | Aisle | |
| | GUARD (Direct Seeded) | | | | | Border row | |
| | | | | | | | |

90'

| KEY | |
|---|---|
| Ryegrass | 🟦 |
| White clover | 🟩 |
| Mix of Ryegrass/clover | 🟧 |
| Bare/Cultivated | 🟪 |
| Straw Mulch | 🟩 |

| PLANTING INFO | |
|---|---|
| reps | 4 |
| rows per rep | 1 |
| rows (inc. guard) | 9 |
| plots per row | 5 |
| plots per rep | 5 |
| plants per plot | 8 |
| plants per row | 40 |
| in-row spacing (ft) | 2 |
| alley (ft) | 2 |
| aisle width (ft) | 4 |
| tilled strip/row wid | 4 |
| row centers (ft) | 8 |
| plot width (ft) (east | 8 |
| plot length (ft) (nor | 18 |
| row length | 90 |
| field width | 72 |

*Supplementary Figure 1: Planting specifications and RCBD with four replications illustrated with the 2019 plot layout. 2018 was similarly laid out with a separate randomization.*

**Supplementary Table 1:** Cumulative yield per m, yield per plant, fruit quality and survival data by year and aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at α = 0.05. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch treatments within a year, with a p-value adjustment using the Tukey method for comparing a family of estimates. Data displayed as estimated Least Square Means.

| Year | Aisle Mulch | Proportion Plant Survival | Marketable Fruit $m^{-1}$ | Total Fruit per $m^{-1}$ | Unmark. Fruit per $m^{-1}$ | Proportion Unmark. | Marketable Fruit per Plant | Total Fruit per Plant |
|---|---|---|---|---|---|---|---|---|
| 2018 | Cultivated | 0.88 | 11.1 | 18.1 | 7.00 | 0.24 | 4.51 | 7.94 |
| | Straw | 0.69 | 13.2 | 20.0 | 6.79 | 0.11 | 4.17 | 6.36 |
| | Clover | 0.75 | 10.6 | 17.7 | 6.47 | 0.17 | 2.73 | 6.20 |
| | Ryegrass | 0.84 | 11.3 | 17.7 | 6.47 | 0.19 | 3.94 | 6.81 |
| | Mix | 0.91 | 10.6 | 17.2 | 6.56 | 0.15 | 3.82 | 6.90 |
| 2019 | Cultivated | 0.84 | 18.8 | 27.7 | 8.88 | 0.29 | 12.07 | 17.37 |
| | Straw | 0.94 | 18.7 | 27.9 | 9.14 | 0.47 | 12.08 | 17.80 |
| | Clover | 0.91 | 12.7 | 22.6 | 9.89 | 0.39 | 8.67 | 15.01 |
| | Ryegrass | 0.84 | 12.3 | 22.4 | 10.06 | 0.44 | 8.15 | 14.75 |
| | Mix | 0.94 | 14.3 | 23.9 | 9.65 | 0.30 | 9.32 | 15.31 |

**Supplementary Table 2:** Final cumulative counts of striped cucumber beetle, squash bugs and egg clusters by year and aisle mulch treatment. Columns with the same letter (or no letter) were not significantly different across mulch treatments within the same year at α = 0.05. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch treatments within a year, with results averaged across blocks and a p-value adjustment using the Tukey method for comparing a family of estimates. Displayed as estimated Least Square Means.

| **Year** | **Aisle Mulch** | **Cumulative CB per m** | **Cumulative SB per m** | **Cumulative EC per m** |
|---|---|---|---|---|
| 2018 | Cultivated | 0.87 | 2.46 | 2.77 |
| | Straw | 0.36 | 1.99 | 2.51 |
| | Clover | 0.31 | 0.46 | 1.49 |
| | Ryegrass | 0.46 | 1.28 | 2.20 |
| | Mix | 0.46 | 0.56 | 2.36 |
| 2019 | Cultivated | 1.95 b | 1.44 | 5.43 |
| | Straw | 3.33 a | 1.95 | 4.97 |
| | Clover | 0.77 c | 0.31 | 4.66 |
| | Ryegrass | 0.46 c | 0.62 | 4.56 |
| | Mix | 0.77 c | 0.51 | 3.95 |

**Supplementary Table 3:** Means of cumulative weed counts and management time by year and aisle mulch treatments. Columns with the same letter were not significantly different across mulch treatments within the same year at α = 0.05. Lowercase letters indicate significance groupings for the simple main effect of aisle mulch treatments within a year, with results averaged across blocks and dates, with a p-value adjustment using the Tukey method for comparing a family of estimates. Significance groupings and data for each date and block level not shown. Data displayed as estimated Least Square Means.

| **Year** | **Aisle Mulch** | **Total Weeding Time (hrs/ha)** | **Total Weed Ct (per 1/4m^2)** | **Broadleaf Weed Ct (per 1/4m^2)** | **Grass Weed Ct (per 1/4m^2)** | **Living Mulch Percent Cover** |
|---|---|---|---|---|---|---|
| 2018 | Cultivated | 147.1 ab | 5.31 b | 2.85 a | 2.46 b | - |
| | Straw | 77.7 b | 0.40 d | 0.23 b | 0.17 c | - |
| | Clover | 215.8 a | 6.13 a | 1.79 a | 4.33 a | 91% a |
| | Ryegrass | 118.5 b | 2.15 c | 1.19 ab | 0.96 bc | 59% c |
| | Mix | 215.4 a | 2.67 c | 1.46 a | 1.21 b | 79% b |
| 2019 | Cultivated | 523.5 a | 12.45 b | 3.23 ab | 9.18 b | - |
| | Straw | 87.8 d | 0.56 d | 0.17 c | 0.39 c | - |
| | Clover | 261.8 b | 18.86 a | 4.66 a | 14.20 a | 90% a |
| | Ryegrass | 149.6 cd | 3.30 c | 2.56 ab | 0.75 c | 81% ab |
| | Mix | 182.0 c | 3.34 c | 2.30 b | 1.05 c | 75% b |