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Evaluating Physical and Cultural Methods to Improve Weed Management in Organic Vegetables

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EVALUATING PHYSICAL AND CULTURAL METHODS TO IMPROVE WEED MANAGEMENT IN ORGANIC VEGETABLES

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A DISSERTATION
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy
(in Ecology and Environmental Sciences)

The Graduate School
The University of Maine
May 2022

Advisory Committee:

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EVALUATING PHYSICAL AND CULTURAL METHODS TO IMPROVE WEED MANAGEMENT IN ORGANIC VEGETABLES

By Rebecca J. Champagne

Dissertation Advisor: Dr. Eric R. Gallandt

An Abstract of the Dissertation Presented
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Effectively managing weeds in organic vegetable production continues to be challenging and costly. Cultivation, often referred to as physical weed control (PWC), is foundational for organic farmers; however, efficacy tends to be low and highly variable. Additionally, some crops are slow to germinate, and thus have poor competitive ability against weeds and high mortality from cultivation. This can result in high costs for hand-weeding labor, abundant seed rain into the soil, and a recurring, often increasing, weed problem. These challenges may be addressed by “stacking” tools to increase weed control efficacy, integrating targeted seedbank management strategies to reduce the germinable weed seedbank, and characterizing crop cultivar early growth traits to better understand crop tolerance to different tool mechanisms.

Chapter one reviews weed management from the perspective of small-scale organic vegetable farms and the unique challenges they face. Weed control objectives, such as minimizing weed seed rain and reducing labor costs, seed- and seedling-focused management like tarping and hand-tool options, and future research needs for small-scale farms are discussed.

Chapter two assesses a weed management systems experiment combining tool stacking with seedbank management and how these practices can affect weed control efficacy and the germinable weed seedbank, respectively. Tool stacking helped increase efficacy and lower weed seedling densities during the growing season, while seedbank management reduced the germinable weed seedbank and contributed to higher crop yields in bush bean and table beet.

Chapter three builds upon the previous chapter by examining how tool stacking can be used with the Terrateck Double Wheel Hoe, a unique hand tool. The effects of single tools and tool stacking on crop mortality and weed control efficacy were examined in bush bean and table beet. Tool stacking increased weed control efficacy in both crops, and although stacking did not result in higher crop mortality in bush bean, table beet mortality was high.

Chapter four assesses the concept of “cultivation tolerance” with nine carrot cultivars, selected to represent large, average, and relatively small plants. Root and shoot characteristics were measured in greenhouse experiments, and carrot mortality and yield from cultivation were measured in field experiments. Few differences in early growth characteristics were found at two-true leaves, and unexpectedly, no differences in cultivar mortality were detected in the field.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
C	Celsius
cm	Centimeter
h	Hour
ha	Hectare
kg	Kilogram
m	Meter
Mg	Megagram
mg	Milligram
min	Minute
PWC	Physical Weed Control
N	Newton
no.	Number
s	Second

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LIST OF EQUATIONS

Equation 1. Expected efficacy of tool stacking:

Two tools:

$$\text{Expected Efficacy (\%)} = 100 – ((X*Y)/100)$$

Three tools:

$$\text{Expected Efficacy (\%)} = 100 – ((X*Y*Z)/10{,}000)$$

Equation 2. Selectivity Ratio:

$$\text{Selectivity Ratio} = \text{\% crop survival} / \text{\% weed survival}$$

CHAPTER 1

WEED MANAGEMENT FOR SMALL-SCALE ORGANIC VEGETABLE FARMS. A REVIEW

Abstract

Weed management continues to be a significant production challenge for organic farmers, especially in vegetable crops that have slow early-season growth and poor competitive ability against weeds. Compounding their weed problems, small-scale organic farmers increasingly face unpredictable labor availability and increasing costs, they are often land-limited, and also tend to have diverse operations, which all make weed management challenging. In this review, we discuss weed management options and future research needs for small-scale, highly-diverse organic vegetable farmers. Management objectives such as optimizing the competitive advantage of crops over weeds, minimizing weed seed rain, and reducing labor costs are a priority. While cultivation with hand tools, hand weeding, and flame weeding are foundational practices, these must be supported by broader ecological strategies to reduce the weed seedbank.

Introduction

Weed management is a major challenge for organic farmers (Jerkins and Ory 2016), and they rely on a great diversity of management practices, variously emphasizing cultivation (physical weed control), seedbank management, and mulching to prevent weed growth (Brown and Gallandt 2019). Early and repeated cultivation provides crops a size advantage and improved competitive ability, but a lack of weed management later in the season results in abundant weed seed rain (i.e., deposition of weed seeds from the mother plant onto the soil surface) and thus a recurring or increasing weed problem over time. Growing a diverse array of crops comes with inherent inefficiencies due to lack of specialization, while small-scale farmers often have limited access to capital, labor, and appropriate tools and supplies, which can all influence the success of their weed management efforts (Hanson et al. 2004; McErlich and Boydston 2013).

For the purpose of this review, we consider small-scale organic farms to be two hectares (five acres) or less in size, relying primarily on hand-weeding and hand tools for weed management. They can also be classified by an annual farm income of less than $350,000 USD gross cash (USDA ERS 2021). Small-scale organic farmers have identified various operational and economic constraints that could affect their farms, and these constraints have the potential to limit weed management efforts and success. Focus groups with organic farmers across the United States have shown that farmers are concerned with labor availability, access to capital, and access to the right equipment (Hanson et al. 2004). Labor for hand-weeding can be quite expensive, and labor may not always be available. Small-scale farms may only have enough capital for one tractor, and some do not have tractors, instead relying on a few different types of hand tools. These farmers must be careful about investing in new equipment. Access to land can limit crop rotation and cover cropping options, reducing opportunities for multiple stresses considered foundational to ecologically- based weed management (Liebman and Gallandt 1997). These farmers are also concerned with the instability of organic price premiums and increased competition from large organic operations that can supply more product in local markets (Hanson et al. 2004). These many challenges can greatly affect operational success, often preventing a farmer from successfully completing tasks such as weed management.

Unfortunately, climate change will likely make weed management even more challenging for these farmers (Birthisel et al. 2021).

Why do some small-scale farmers rely almost exclusively on hand tools and hand weeding, while others use alternative strategies such as tarping, mulching, and flame weeding? Farmer surveys have revealed that a farmer's approach to weed management will likely depend on the density of weeds on their farm and their beliefs about how to manage those densities (Riemens et al. 2010). Mental models constructed from scientist and organic farmer focus groups in the Northeast United States revealed that perceptions about weeds and weed management tend to differ between growers and the scientific community (Jabbour et al. 2014). Farmers are more likely to rely on their own experience and the practices of other farmers to drive their weed management, as opposed to relevant research findings (Jabbour et al. 2014). In a survey of organic farmers in the Midwestern United States, DeDecker et al. (2014) found that farmers utilized on average 15 different weed management techniques in their operations. Of those surveyed, 82% said they preferred other farmers as their source of information for weed management (DeDecker et al. 2014). In the Northwestern United States, organic farmer surveys suggested that number of crops grown, education level, and farmer knowledge about weeds influence the diversity of farmers' weed management programs (Tautges et al. 2016).

The goal of this review paper is to summarize peer-reviewed literature that directly concerns weed management on small-scale organic farms, or research that is applicable to a small scale. A review in this area is needed because small-scale organic farms typically rely on expensive hand labor and continue to battle high densities of weeds, limiting their production. A current review of this nature has not been identified by the authors; additionally, information gaps pertaining to research on hand tools specifically have been identified, which is potentially hindering the weed management efforts of small-scale growers.

Cultivation: Managing Weed Seedlings

Farmers have long relied on "weeding" to reduce weed density thereby maximizing crop yield and quality. Cultivation, sometimes called physical weed control, generally relies on tractor-mounted, walk-behind tool carriers, or wheeled and long-handled tools to slice, uproot or bury small weed seedlings while selectively avoiding crop plants (Gallandt et al. 2018). For the sake of labor efficiency, emphasis should be placed on use of wheeled and long-handled tools, using slower and more laborious hand pulling as a last resort.

Walk-behind Tools

Walk-behind tool carriers or walk-behind tractors, such as mowers, hillers, and rotary plows, are another option for small-scale organic operations, and they have the potential to increase weeding efficiency compared to hand tools because they operate at a working rate independent of weed densities. These tool carriers are pushed by hand and powered by two wheels and a 5 to 14 horsepower engine, making them easy to operate and feasible for use at a small-scale (Pressman 2011). Upfront costs are cheaper than tractor-mounted cultivation tools, and they may provide labor-saving opportunities compared to hand tools and hand weeding due to differences in working rates (Figure 1.1). Some walk-behind carriers, such as the Tilmor Power Ox (Tilmor, Ohio, United States) or the HAK L-Series (HAK Bleiswijk, South Holland, Netherlands), can be equipped with different cultivation tools like finger weeders or hilling discs that normally would only be available to mount on four-wheeled tractors. It is important to note, however, that walk-behind tool carriers require careful tool adjustment and operation compared to hand tools to prevent crop damage and mortality. Additionally, the authors are unaware of any published literature on walk-behind tools such as those mentioned above. Research into the efficacy of these tools would be useful to help farmers make informed tool purchases.

Hand Tools

Although there are a variety of hand tools available for small-scale organic farmers, hand tools tend to have some disadvantages. The design and manufacturing of new tools in the United States has tended to focus on tools for large (>5 acres) operations, such as tools for four-wheel tractors and camera-guidance systems. Additionally, tools appropriate for a small-scale farmer may have to be purchased from a different country, loaned for use, or engineered by the farmer themselves with materials they already own (Pressman 2011). Research on the use and efficacy of hand tools is lacking compared to that of larger-scale, tractor-drawn implements, leaving much of their use to different methods such as trial-and-error or word-of-mouth from other farmers. Additionally, hand tools may lack an appropriate ergonomic design, making an already labor-intensive task more difficult (Kar et al. 2003; Wibowo and Soni 2016). Managing weeds is already a difficult task, and small-scale farmers would benefit from greater research on the tools they rely on.

Small-scale and organic farmers rely on hand tools to remove emerged weeds during the growing season. Hand tools can be broadly classified into four categories: short handle tools, long handle tools, wheel hoes, and walk-behind tool carriers. As with hand weeding, the labor required to remove weeds from the field using hand tools is dependent on the density of weeds, and also the chosen tool. Hand tools should be used on dry, sunny days to decrease the chance of weeds re-rooting, and generally, fields should be weeded every 10-15 days in early summer when most annual weed species are emerging (Fourtier 2014). This can help give the crop a competitive advantage and also deplete the germinable weed seedbank, which can decrease weeding labor in subsequent seasons.

Short handle tools are used while working on the ground close to the crop row and where crops are planted at a high density and care must be taken to carefully weed between plants. They can be used to slice weed shoots from the roots, uproot weeds from the soil, or bury them and create a ridge of soil around the crop. Some short handle tools include hoes, spades, and pronged weeding forks. Short handle tools are commonly used by small-scale subsistence farmers because of low purchasing costs (Sarkar et al. 2015).

Long handle tools are used for the same reason as short handle tools but are designed with longer handles for use while standing up. Tools such as wire weeders, stirrup hoes, and collinear hoes can be used to kill small weeds close to the crop row with minimal soil disturbance (Pressman 2011) (Figure 1.2). According to Eliot Coleman (2018), a farmer will make on average 2,000 strokes of a tool in one hour of weeding labor. Because of this, the weight of a hand tool is important for both the ease and efficiency of weeding, and therefore the labor required to complete the task. Coleman (2018) suggests that a hand tool weigh no more than 680 grams in order for the user to not expend unnecessary energy.

Two different long-handled tools for small-scale rice farms in sub-Saharan Africa were examined by Rodenburg et al. (2015) to determine if the adoption of hand tools could reduce weeding labor relative to standard season-long hand weeding. Hand tools with straight-spikes and twisted-spikes were used in rice 21 and 42 days after transplanting and the time spent using the tools was compared to time spent hand weeding. In this study, a farmer averaged 253 hours of labor per hectare hand weeding; in comparison, the straight-spike tool decreased weeding labor by 32-49% and the twisted-spike tool reduced labor by 32-56% (Rodenburg et al. 2015).

Wheel hoes, which include a wheel and a hoe blade attached to a frame, are often used to cultivate between crop rows and up to the side of the crop (Pressman 2011) (Figure 1.3). They are available with different wheel diameters and blade widths and are operated by the use of a push-pull motion while moving between crop rows (Coleman 2018). Through this motion, a high percentage of the force applied by the operator is transferred to the hoe blade, helping sever weeds in a more efficient manner (Coleman 2018; Fourtier 2014). The hoe blade can also be switched out with small spades that can run below the soil surface and sever weed seedlings. Unfortunately, wheel hoes can be difficult to use in rocky soils and large rocks may damage the hoe blade, which may affect the tool's efficacy.

Hand Weeding

Hand weeding is often employed by small-scale organic farmers during the growing season to eliminate weeds growing directly around crops, which pose the greatest threat to crop yield. It can be useful in high-value crops where it is important to avoid crop damage from tools or when crops are too small to cultivate. However, hired labor can be difficult to access. Additionally, unlike tractor-mounted tools, the working rate of hand weeding is dependent on the density of weeds (Figure 1.4) which necessitates multiple hand weeding events over the growing season to prevent yield losses and weed seedrain, making the task both laborious and expensive. This challenge is experienced by smallholders around the world. On smallholder farms in China and Southern Africa, hand weeding is the primary form of weed management because tractor purchases are not feasible due to limited capital (Lee and Thierfelder 2017; Su and Ahrens 1997). Lack of time and labor to perform in-season hand weeding in lowland rice in sub-Saharan African has been found to result in an annual yield loss to weeds of 15-23% (Rodenburg et al. 2015). In a comparison of mulching versus hand weeding in maize in Pakistan, the season-long hand weeding treatment resulted in the lowest fresh weed biomass; however, this treatment also resulted in the lowest cost-benefit ratio due to high labor requirements (Hashim et al. 2013).

Case studies of small-scale organic vegetable farmers in northern New England, United States show the benefits and tradeoffs of adopting different weed management strategies on labor. On farms where weeds are only managed during the critical weed-free period, labor requirements across the whole season can be lowered, but this results in a very high (>35,000 seeds m^{-2}) germinable weed seedbank (Brown and Gallandt 2019). Conversely, farms adopting a "zero seed rain" approach have found that weeding labor can be high in the first few years of using this strategy, but it has the potential to drastically reduce the germinable weed seedbank and labor requirements over time (Brown and Gallandt 2019). Use of plastic and natural mulches can require a lot of labor to set up annually but can reduce the need for additional hand weeding through physical suppression of weeds. Mulching also comes with the added benefits of increased soil water retention and soil organic matter (Brown and Gallandt 2019). On farms where weed densities are high, hand weeding can be supplemented with other weed management practices such as hand tools or mulching to make weeding more economical over time by reducing the weed seedbank.

Seedbank Management

To improve weed management by reducing weed densities early in the season and over time, practices that deplete the germinable weed seedbank should be implemented. Strategies such as stale seedbeds, cover cropping, and tarping may encourage fatal germination and preempt seed rain, thereby reducing the germinable seedbank if performed each year. Shallow tillage to create a false seedbed and encourage weed seed germination, cover cropping as a disturbance mechanism, and tarping and solarization are discussed below.

Shallow Tillage to Create a False Seedbed

Most weed seeds can only germinate if they reside in the top 5 cm of the soil due to their small size and low energy reserves. Seeds residing in this soil layer and that are non-dormant will emerge rapidly following shallow soil disturbance (Merfield 2015). The false seedbed technique uses disks or harrows to encourage weed seed germination in this soil layer through soil aeration and seed exposure to light (Merfield 2015). Creating a false seedbed by performing multiple shallow tillage events leading up to, and just prior to crop planting, can be an effective way to deplete the germinable seedbank and create a “clean” seed bed to give the crop a head start over the next flush of weeds (Gallandt 2006). Following weed seed emergence, shallow tillage is repeated to kill the flush of weeds right before crop planting. Because tillage is performed only to a shallow depth, weed seeds residing deeper in the soil profile are not brought closer to the soil surface where they could more easily germinate. Care must be taken during subsequent tillage to not till too deeply, as this can encourage weed seeds deeper in the soil profile to germinate when the goal is to only kill the emerged weed seedlings (Merfield 2015). Therefore, creating a false seedbed requires correct tool adjustment and operation. However, the effectiveness of repeated shallow tillage can be affected by soil characteristics. Soils that are more prone to crusting may require more aggressive tool operation to break through the soil, which results in greater soil disturbance and can stimulate germination of weed seeds below the top 5 cm (Caldwell and Mohler 2001).

Timing Disturbance with Weed Emergence

Weeds emerge based on environmental conditions, and their germination periodicity, or the period of time over which a species germinates (Stoller and Wax 1973). The most effective time to kill weeds is right after emergence when they are in the white thread or cotyledon stages.

At these growth stages weeds do not have sufficient nutrient reserves or a well-established network of roots to recover from mechanical damage (Liebman et al. 2001). Disturbance can also be timed with a crop's critical weed-free period, or the time after crop emergence when it is important to manage weeds to prevent major yield losses (Knezevic et al. 2002). Shallow disturbance with harrows can be utilized after crop sowing to manage weeds before crop emergence, and after crop emergence during the critical weed-free period, to kill weeds across different germination periodicities (Rasmussen 1996). Field trials at organic farms in Sweden found that the most effective way to reduce weed densities was by performing shallow soil disturbance both pre- and post-crop emergence (Lundkvist 2009). Timing of disturbance should also take into consideration crop tolerance to disturbance. A crop's ability to recover from cultivation, and resist being covered by soil, can influence the success of post-emergence disturbance events (Rasmussen et al. 2009).

Flame Weeding

Flame weeding, a non-selective stale seedbed technique, controls small emerged weeds without disturbing the soil and stimulating another flush of weeds (Caldwell and Mohler 2001; Merfield 2015). Hand-held wands, backpack flame weeders, and hand-pushed rolling flame weeders are all available for use at a small-scale (Figure 1.5). By briefly exposing weed seedlings to natural gas or liquid propane flame, the internal temperature of the weed increases, causing the plant cells to rupture and the weed to desiccate (Mutch 2012). Flame weeding can be useful in small-seeded, slow emerging vegetables, such as carrots and beets. These crops often emerge with small weed seedlings whose germination was induced from soil disturbance at crop planting (Ascard 1995). Fourtier (2014) often mixes in some crop seeds that are known to germinate quicker than the main crop at planting – when this crop emerges, it is a good indicator to flame weed, as the main crop will be emerging soon. By flame weeding a day or two prior to anticipated crop emergence, the crop can emerge into a “clean” seed bed with less weed competition and have a head start over the next flush of weeds. The use of flame weeding in organic garlic production showed that just one application of flame weeding right before crop emergence reduced weed density by 64% compared to hand weeding only (Chehade et al. 2018).

Flame weeding is most effective when weeds are in the cotyledon to two-leaf growth stages, and broadleaf species tend to be better controlled than grasses. In a study by Cisneros and Zandstra (2008), flame weeding at various forward speeds resulted in 94-97% control of broadleaf species at the cotyledon to two-leaf growth stages, and 91% control when flame weeding was conducted at the two- to four-leaf stage. However, incomplete control of grass species was observed as grass weeds became larger, resulting in only 48-77% control and a reduction in control as forward speed increased (Cisneros and Zandstra 2008). These differences between broadleaf and grass species could be attributed to their respective growth habits, as the growing point of grasses is partially protected by the sheath of the plant, and they may require additional flame exposure for sufficient control. Although flame weeding alone does not provide season-long weed management, it is useful for reducing weed densities and weeding labor at the time of crop emergence, particularly in high-value, slow emerging crops.

Cover Cropping as a Disturbance Mechanism

Cover crops can interfere with weed growth through competition for nutrients, light, and water (Smith et al. 2015). Furthermore, cover crop planting and termination can act as disturbance mechanisms. Soil disturbance prior to cover crop planting can encourage weed seed germination, and cover crop termination with tillage or mowing can kill weeds growing with the cover crop and therefore reduce weed seedrain (Sarrantonio and Gallandt 2003). Planting cover crops after crop harvest can be useful for managing winter annual weeds in organic systems by reducing weed densities prior to crop planting the following season, thus reducing early-season competition (Price and Norsworthy 2013). Mirsky et al. (2010) examined the effect of combining cover crops with varying levels of soil disturbance. Weed seedbank losses were greatest when soil disturbance and cover cropping were associated with one another, i.e., tillage prior to cover crop sowing and for cover crop termination. Additionally, treatments receiving cover crops, but less soil disturbance saw greater weed "escapes" that were not killed and therefore reached maturity (Mirsky et al. 2010). Cover crops can also serve multiple purposes at once, such as attracting pollinators and beneficial insects, reducing soil erosion, or providing grazing opportunities for livestock – all of which contribute to a more resilient farming operation by providing multiple benefits.

Tarping and Solarization

Tarping with black plastic or soil solarizing with clear plastic can be effective weed management tactics for early season weed management and depletion of the weed seedbank. Black plastic absorbs solar energy and heats the soil below while blocking sunlight from reaching the soil. Seedbed preparation prior to tarping stimulates germination of weed seeds, but the lack of sunlight under the black plastic causes the seedlings to desiccate (Fortier 2014) (Figure 1.6). Clear plastic creates a greenhouse effect by allowing solar energy to penetrate through the plastic to the soil (Bond and Grundy 2001). The hot temperatures experienced under the clear plastic can cause weed mortality and can also reduce the viability of weed seeds residing in the top 5 cm of the soil profile (Peachey et al. 2001; Samtani et al. 2017). Numerous studies have shown the utility of soil solarization on reducing weed density and biomass in arid environments (Mudalagiriyappa et al. 1999; Singh 2006). Solarization with clear plastic for 30 days prior to crop planting reduced weed densities, weed biomass, and increased soybean yield in field studies in India (Singh 2006). However, the greenhouse effect of solarization may not heat the soil at deeper depths, which could result in insufficient control of weed species that grow by underground structures such as rhizomes or tubers (Kumar et al. 1993; Singh 2006).

Solarization may not be as effective as tarping in cooler regions where spring temperatures are not high enough to create a greenhouse effect (Walters and Pinkerton 2012); however, use of clear plastic to encourage weed seed germination followed by stale or false seedbed practices may also encourage seedbank losses (Birthisel and Gallandt 2019). In the Northeastern United States, Birthisel and Gallandt (2019) found that solarization with clear plastic for two weeks followed by bed flaming resulted in 78% lower weed density relative to flame weeding only. Additionally, both flame weeding alone and flame weeding after solarization reduced weed densities and raised soil temperatures enough for fatal weed seed germination or death due to thermal inactivation (Birthisel and Gallandt 2019). Jean-Martin Fourtier, a small-scale organic farmer in Canada, has used 6-mm black plastic tarps for weed seed management for over a decade. Fourtier (2014) has seen how tarping can be an effective strategy for small operations because it can reduce weed densities before crop planting, can be installed easily, and has no additional labor required until it is time to remove the tarps.

Future Needs

Presently, most agricultural tool research for weed management in the United States is focused on tractor-mounted cultivation tools and camera-guided equipment for use at larger scales, and these tools are typically not an economical option for small farms. Development of new hand tools, improvements to existing hand tools, and more information on the efficacy of hand tools in different environments could benefit small-scale organic farmers' weed management efforts. For example, research that examines the efficacy of hand tools with varying levels of weed densities or when used on different soil types, could help farmers make more informed tool purchases. Additionally, research that determines the best ergonomic designs for the user could help make weed management with hand tools less labor intensive and more effective. Tools such as torsion weeders, finger weeders, and tine harrows may be of use to small-scale farmers if they can be attached to hand tools. Tractor-mounted cultivation tools may not always be an economical option for a small-scale farm, but research about these tools may be applicable to hand tools that operate with the same mode of action. In a recent study by Brown and Gallandt (2018), the effects of tool "stacking," or using more than one tool at a time, on intra-row weed control efficacy were examined and compared to the efficacy of individual tools, whose efficacy tends to be low and often highly variable. The authors found that tool stacking increased weed control efficacy compared to a single tool. Certain tool combinations resulted in synergy, where the resulting efficacy from the combined tool use was greater than the additive effect of each tool used individually (Brown and Gallandt 2018).

The Terrateck Double Wheel Hoe (Terrateck, Lestrem, France) is a recently developed wheel hoe available for small-scale operations. It is designed with two wheels to straddle the crop row and comes with the option to purchase several tool attachments, including torsion weeders, finger weeders, and tine harrows, which are typically only available to mount on tractors or walk-behind tool carriers. The wheel hoe also has two points of attachment for toolbars, giving a farmer the option to utilize tool stacking, which could increase efficacy as shown with tractor mounted tools. While the authors are unaware of any published research directly comparing the efficacy of tractor-mounted tools to hand tools, the option to use multiple tools at a time on the Terrateck double wheel hoe could be beneficial for weed management at a small-scale based on previous tool stacking findings.

Autonomous machine technologies to reduce weeding labor and costs could benefit small-scale organic producers, and there is increasing potential for the use of autonomous weeders on small farms (Fennimore and Cutulle 2019). Autonomous robots designed to perform physical weed control have the added benefit of being organic-compliant in the United States. Machine vision and data processors can be used to identify crop row patterns and spacing and perform tasks such as removal of weeds and crop stand thinning (Fennimore et al. 2016). Small robotic weeders could be utilized for weed management while the farmer is performing other tasks, thus saving time and money. However, it is important to note that autonomous technologies can only perform these tasks if the crop has a size advantage over the weeds, and if the density of weeds is low (Sanchez and Gallandt 2020). Otherwise, the machine vision cannot differentiate between crops and weeds, resulting in poor selectivity (Fennimore et al. 2016). Small autonomous weeders could be beneficial for small-scale farms but only if the above criteria are met.

Intelligent tractor-mounted machines are already being developed and tested at larger scales with promising results. Intra-row cultivation machines such as the Robovator (F. Poulsen Engineering ApS, Hvalsø, Denmark) have been tested in specialty crops like broccoli and lettuce in California, United States. The Robovator, when equipped with reciprocating knives to sever weeds, reduced intra-row weed density by 41% and decreased subsequent hand weeding time 38-45% (Lati et al. 2015). However, intelligent tractor-mounted machines are currently expensive to manufacture and likely cost prohibitive for small-scale operations, and they currently lack standardization and comprehensive safety information (Fennimore and Tourte 2019; Peruzzi et al. 2017).

Conclusions

Organic farmers face many production risks, with weed management being one of the most challenging and costly. Weed management in vegetables can be particularly difficult due to the slow growth and low competitive ability of some crops. Small-scale organic farmers must deal with challenges such as labor for weed management, access to new weeding tools, and access to capital to improve their operations. In order for small farms to improve their weed management, farmers’ efforts should focus on giving the crop a head start over the weeds in order to minimize competition, tackling weeds with both cultivation and seedbank management to minimize seedbank additions, and reducing the labor and costs associated with weed management. Practices such as tarping, repeated shallow tillage to create a false seedbed, and the use of cover crop planting and termination as disturbance mechanisms are all ways to encourage fatal weed seed germination. Weed management can also be achieved by flame weeding, hand weeding, and through the use of a variety of hand tools such as short- and long-handle tools, wheel hoes, and walk-behind tool carriers. By utilizing multiple stressors each season, the germinable weed seedbank can be depleted, resulting in a decline in the amount of labor and costs for weed management over time. New tools are starting to come onto the market, including the potential for small autonomous weeders. However, hand tool research and research on scale-appropriate technologies are needed to help farmers make more informed tool purchases for their operation.

Figure 1. 1. The Tilmor Power Ox, a walk-behind tractor option for small-scale farmers. It can be equipped with implements such as sweeps and finger weeders (pictured above), which can be adjusted to kill weeds in the crop row. Source: Tilmor.

Figure 1. 2. A common long-handled tool, the stirrup hoe can be used to kill weeds between crop rows and in the crop row. Source: Johnny’s Selected Seeds.

Figure 1. 3. A wheel hoe can be used to easily kill weeds in the footpaths between crop rows and can be adjusted to the user's height. Source: Johnny's Selected Seeds.

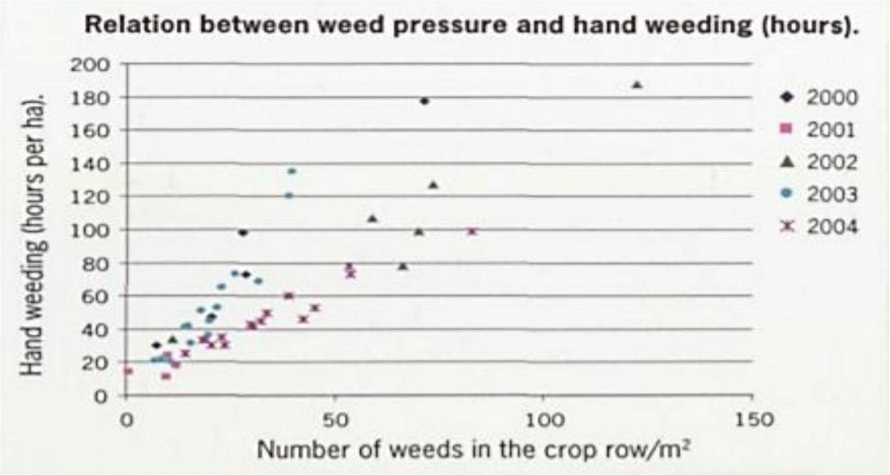


Figure 1. 4. Time spent hand weeding is density-dependent, as indicated by the linear increase in hours spent hand weeding as weed density increases. Source: van der Schans and Bleeker, 2006.

Figure 1. 5. Flame weeding using a hand-held wand. Source: Johnny’s Selected Seeds.

Figure 1. 6. Non-tarped research plots (left), and research plots where tarps were recently removed (right); Maine, United States.

CHAPTER 2

CULTIVATION TOOL STACKING COUPLED WITH WEED SEEDBANK MANAGEMENT REDUCES WEED DENSITIES IN ORGANIC VEGETABLE SYSTEMS

Abstract

The combined effects of reducing the germinable weed seedbank and improving weed control efficacy could improve weed management on organic farms. Cultivation, or ‘physical weed control’ (PWC) remains a foundational practice for organic farmers, but efficacy is often low and variable. In an organic vegetable weed management systems trial, we assessed two levels of seedbank management, where seedbank management was either not performed or performed using silage tarps followed by flame weeding. Cultivation treatments consisted of finger weeders as a single tool, or “stacking” in which finger weeders were followed by torsion weeders or hoe ridgers. Field experiments over three years showed that tarping for six weeks prior to crop planting, with pre-emergence flame weeding, reduced early-season intra-row weed densities from 90 weeds m^{-2} to fewer than 20 weeds m^{-2}. Stacking additional tools with finger weeders provided 91% (±5%) weed control efficacy compared to 65% (±14%) using finger weeders alone, without an increase in crop mortality. Tool stacking using hoe ridgers also reduced intra-row weed recruitment 14 days after last cultivation, resulting in 10 weeds m^{-2} compared to 45 weeds m^{-2} when hoe ridgers were not used. In treatments without seedbank management, where only cultivation was performed, the germinable weed seedbank increased from a starting density of 4,000 seeds m^{-2} to 8,500 seeds m^{-2} by year three. In contrast, seedbank management decreased the germinable weed seedbank from 4,500 seeds m^{-2} to 2,100 seeds m^{-2}.

Partial budget analysis showed that although the addition of seedbank management can result in higher variable costs, this was offset by greater crop yields, leading to higher net returns. Tool stacking and seedbank management did not provide expected synergy of effects; rather, treatment main effects contributed to the goals of increasing efficacy and reducing the germinable seedbank, respectively. Tool stacking to increase weed control efficacy, coupled with targeted weed seedbank management prior to crop planting to encourage fatal weed seed germination, have the potential to reduce weed densities and increase profitability in organic vegetable systems.

Introduction

Organic farmers and those transitioning to organic production often struggle with weed management which results in abundant weed seed rain and large weed seedbanks. Many organic farmers rely on cultivation, which is often used to describe ‘physical weed control’ (PWC), or the use of various tools to uproot, slice, or bury weeds, as well as hand-weeding in high-value crops to reduce yield loss, often resulting in high costs of production (DeDecker et al. 2014; Jabbour et al. 2014). In vegetable systems, weeds notably also contribute to the loss of crop quality, which is imperative for high-value, fresh market sales. These farmers must consider the balance between costs of weed management and loss of crop yield and quality to weeds.

Cultivation can be highly effective at managing weeds between crop rows, or the inter-row, but managing weeds within the crop row, or intra-row where competition with the crop is highest, can be especially challenging (Ascard and Fogelberg 2008; Vanhala et al. 2004). Cultivation tools designed to target the intra-row zone are not particularly sophisticated regarding their selectivity, i.e., killing weeds but not the crop. Selectivity generally relies on a size differential between the crop and weeds, and often the tools need to be adjusted away from the crop row to avoid crop stand loss or damage (Rasmussen et al. 2010), usually sacrificing weed control. Consequently, intra-row tools such as finger weeders, torsion weeders, and hillers tend to provide low, and highly variable, efficacy (Gallandt 2014, Gallandt et al. 2018a).

Tool "stacking" refers to the use of more than one tool in a single pass or in subsequent tractor passes and is a strategy to increase weed control efficacy (Brown and Gallandt 2018a). Cultivation tools kill weeds by burial, uprooting, or severing roots from shoots (Kurstjens and Perdok 2000; Mohler 2001); tool stacking may provide increased weed control efficacy due to the combined effects of these mechanisms. Brown and Gallandt (2018a) found that stacking two or three intra-row cultivation tools increased weed control efficacy in corn compared to individual tool use, but with an increase in crop mortality. The combination of torsion weeders, finger weeders, and tine harrows proved to be synergistic, with total efficacy greater than the summed efficacy of individual tools (Brown and Gallandt 2018a).

Weed seedbank management is a proven strategy to reduce weed seedling densities prior to crop planting (Gallandt 2006; Liebman and Gallandt 1997; Mirsky et al. 2010). Seedbank management may also become increasingly important for weed control as farmers experience more variable environmental conditions that hinder cultivation efforts (Birthisel et al. 2021). Because efficacy is largely density independent, a reduction in the weed seedbank will improve the outcome of subsequent cultivation events (Gallandt et al. 2018b).

A practice farmers refer to as 'tarping,' whereby black plastic silage tarps are placed over tilled soil for four to six weeks, is a very effective seedbank management practice for small-scale farms (Birthisel and Gallandt 2019). Black plastic absorbs shortwave radiation, heating the soil underneath via conduction, but blocks out the photosynthetically active light required for weeds to grow (Ham et al. 1993; Teasdale and Mohler 2000). Black plastic reduced weed seedling densities compared to clear plastic in laboratory studies and provided 100% weed control in field experiments in California (Johnson and Fennimore 2005). Tarping for as little as three weeks in Maine and New York reduced weed cover before planting by 95-100%, and white thread-stage weed seedlings present at tarp removal desiccated shortly after (Rylander et al. 2020).

Weed seedbank management can further be supported by flame weeding which controls weed seedlings without stimulating additional seedling recruitment. Flame weeding prior to planting, just before crop emergence, or after emergence in heat-tolerant crops, controls small dicot weeds without soil disturbance. Weed seedlings are subjected briefly to high temperatures that denature cell membrane proteins and causes destruction of the cell wall (Cisneros and Zandstra 2008; Diver 2002). Flame weeding once just after garlic emergence controlled weeds for the entire growing season, and flame weeding twice in corn resulted in 70% weed control over the growing season compared to no flame weeding (Chehade et al. 2018; Stepanovic et al. 2015). In a simulated seeding study, stale seedbed preparation with flame weeding resulted in fewer broadleaf weeds compared to a tine weeder or rotary tiller (Caldwell and Mohler 2001). In processing tomato, stale seedbed preparation with a rolling harrow followed by flame weeding resulted in higher crop yield compared to conventional herbicide application (Raffaelli et al. 2011).

Reducing weed seedling densities early in the season by tarping and flame weeding, coupled with greater cultivation efficacy provided by tool stacking, may be an effective strategy to both maximize short-term crop yield and quality, and reduce the germinable weed seedbank over the longer term. The objectives of our study described here were to: 1) compare intra-row weed control efficacy between cultivation treatments with a single tool versus stacked tools; 2) examine the effect of cultivation and seedbank management treatments on vegetable crop yield and overall economic performance; and 3) evaluate the combined effects of tool stacking and seedbank management on the germinable weed seedbank. We hypothesized that: 1) stacking tools would increase weed control efficacy compared to a single tool; 2) combining tool stacking and seedbank management would result in higher crop yields due to greater weed control, and therefore greater net returns; and 3) combining tool stacking and seedbank management would decrease the germinable weed seedbank, perhaps with additional short-term costs, but longer-term benefits.

Materials and Methods

Site Description and Field Preparation

An organic vegetable cropping systems experiment was conducted at the University of Maine Rogers Farm in Old Town, Maine (44°55′N, 68°41′W) over three field seasons from 2019 through 2021. The soil at the USDA Certified Organic site is comprised of Pushaw-Boothbay silt loam. The site is in USDA Plant Hardiness Zone 4b, with an average annual high/low temperature of 20/-7 °C and an average annual precipitation of 1,023 mm.

Soils were amended each year based on soil test results by applying OMRI-approved fertilizer materials. The field was tandem-offset disked to control winter annual weeds and incorporate residue. Pre-plant fertility was then applied as Nutri-wave™ 4-3-2 (Northeast Agricultural Sales Inc., Detroit, ME, USA) at 60-100 kg ha^{-1} plant-available nitrogen each year. In 2020, feathermeal 13-0-0 (FedCo Seeds, Clinton, ME, USA) was used to sidedress nitrogen three and five weeks after planting at 67 kg ha^{-1} plant-available nitrogen. In 2021, blood meal 13-0-0 (FedCo Seeds) was sidedressed three weeks after planting at 56 kg ha^{-1} plant-available nitrogen. Bone char 0-16-0 (FedCo Seeds) was applied pre-plant at 67 kg ha^{-1} plant-available phosphorus. In 2020, soluble borate (20.5% B; FedCo Seeds) was applied at 5.6 kg ha^{-1} prior to crop planting. Fertilizers were incorporated with a Perfecta® Field Cultivator (Unverferth Manufacturing Company Inc., Kalida, OH, USA). In plots receiving seedbank management, seedbeds were prepared using the same Perfecta® field cultivator just before silage tarps were installed to create a false seedbed, and again before crop planting.

Experimental Design and Treatments

Experimental factors included cultivation with select tools and weed seedbank management. Tools consisted of either finger weeders as a single reference tool, hereafter referred to as "Single," or stacked tools using the finger weeders followed by hoe ridgers or torsion weeders, hereafter referred to as "Stacked" (Figure 2.1). Tools were selected to represent those typically used by farmers growing each crop and were adjusted to optimal settings in practice areas sown for each crop (Appendix B Supplemental Table 2.1). All treatments were cultivated twice in each year after crop emergence, with the second tool in "stacked" treatments being chosen (torsion weeder or hoe ridgers) based on the crop and its size. In 2019, tools were attached to a HAK (Schoffeltechniek, Bleiswijk, Holland) steerable 3-point hitch-mounted cultivator operated at 4 km h^{-1}. In 2020 and 2021, crops were cultivated using a HAK cultivating tractor with a center-mounted toolbar, also at 4 km h^{-1}. Seedbank management included tarping with 6-mm black plastic silage tarps, applied black-side up for six weeks before planting, pre-emergence flame weeding, post-cultivation hand-weeding, and post-harvest cover cropping. After tarp removal, plots were harrowed to a depth of 2.5 cm to create a seedbed for crop planting, and weeds that emerged following this soil disturbance were subjected to flame weeding. Flame weeding was done using a Pyroweeder® (Farmers Friend, Williamsport, TN, USA) at 25 psi operated at 1.6 km h^{-1} with burners adjusted to 45˚. In 2019, an organic oat (*Avena sativa*) cover crop was planted in early September at 67 kg ha^{-1} using a Great Plains® drill. In 2020. organic winter rye (*Secale cereale*) was planted in mid-October at 112 kg ha^{-1} using the same drill. In 2021, an organic winter rye and hairy vetch (*Vicia villosa*) mix was planted in late-August at 90 and 22 kg ha^{-1}, respectively. Cover crop residue was incorporated using a tandem-offset disk each spring. The addition of these practices (tarping, flaming, post-cultivation hand-weeding, post-harvest cover cropping) is denoted by (+SB), while the absence of seedbank management (relying on cultivation only) is denoted by (-SB).

Treatments were imposed in a full factorial, randomized complete block design with four replications. Each block consisted of four plots (12 x 3 m) representing each of the four treatments. A different vegetable crop was planted in each of three years. In year one (2019), bush bean (*Phaseolus vulgaris* L.) 'Provider' was planted using a John Deere® four-row planter (John Deere®, Moline, IL, USA) on 76-cm rows with four rows per plot. In year two (2020), table beet (*Beta vulgaris* subsp. vulgaris L.) 'Boro' was planted using a Wizard® vacuum seeder (Sutton Agricultural Enterprises, Inc., Salinas, CA, USA) on 51-cm rows with four rows per plot. In year three (2021), sweet corn (*Zea mays* L.) 'Sweetness F1' was planted using a John Deere® four-row planter on 76-cm rows with four rows per plot.

Weed Control Efficacy and Crop Density

Crop mortality and selectivity were measured in four $0.25m^2$ permanent subsampling areas established in random locations in the center two rows of each plot. The number of crop plants in each subsampling area was recorded just prior to each cultivation event and counted again approximately 24 h later to determine crop mortality. Subsamples were averaged at the plot level prior to analysis.

Weed control efficacy was measured in quadrats partitioned into a 10-cm wide intra-row zone centered over the crop row, with the adjacent areas on either side of this zone identified as inter-row zones. Weed density was recorded in both the intra- and inter-row zones, both before and after each cultivation event.

Additional intra-row weed density data were recorded 14 days after planting (DAP) in 2020. Cultivation was delayed until approximately 28 DAP when beets had reached the three- to four-true leaf stage, which is the recommended growth stage to cultivate beets, but this necessitated hand-weeding prior to cultivation. The data were used to provide information on weed control following tarping and flame weeding to see if lower initial weed densities could result in a better cultivation outcome. Weed density was not recorded 14 DAP in 2021; rather, it was recorded 14 days after last cultivation to provide an estimate on hand-weeding requirements, because the first cultivation event in corn occurred within the 14-DAP window.

Hand Weeding

To determine whether treatments had an effect on hand weeding labor requirements after the crop was too large to cultivate, hand weeding time was assessed 14 DAP in 2020 while the crop was too small to cultivate, and was also recorded 14 days after last cultivation in 2020 and 2021. A wheel hoe was used to cultivate between crop rows, followed by a stirrup hoe targeting weeds on the edge of the row; large weeds within crop rows were pulled by hand. One person performed these tasks in all plots in a block, and the time to complete the entire hand weeding process was recorded for each plot.

Crop Yield and Quality

Crops were graded using current USDA fresh market grading requirements, counted, and weighed for each species. Bush bean yield was determined by harvesting a 3-m section from each of the two center rows in each plot. Plants were pulled by hand, counted, and weighed, and marketable pods removed and weighed. Table beet yield was measured by harvesting all beets from the four 0.25m^2 subsampling areas described previously. Table beets were pulled by hand, washed briefly to remove soil, and separated into “marketable,” “marketable size with defects,” and “unmarketable.” Within each grading category, table beets were counted, and total fresh weights were recorded. Subsamples were averaged prior to analysis. Sweet corn yield was determined by hand harvesting all ears from a 6-m section in each of the two center rows in each plot. Ears were separated into “marketable” and “unmarketable,” and each category was counted, and total fresh weight recorded.

Weed Seedbank

To determine the density of germinable weed seeds, soil samples were collected each spring (Dessaint et al. 1996). Ten 8-cm diameter soil cores taken to a 10-cm depth were randomly collected in each plot, mixed, and passed through a 6.5-mm sieve to remove coarse fragments and residues. Samples were placed in plastic growing trays over a 2.5-cm layer of vermiculite in the greenhouse and watered daily as needed. After 30 days, weed seedlings were identified, counted by species, and removed. Soil was allowed to dry, sieved, and the process began again for a total of three germination rounds (Gallandt et al. 1998).

Economic Analysis

Variable costs and net returns for each weed management system were analyzed using a partial budget analysis. Field practices such as discing, harrowing, flail-mowing, and planting were included as use-related machinery costs (Lazarus 2021). Production costs also included crop and cover crop seed, fertilizer, and labor for hand-weeding and hand-harvesting. Costs for field practices were taken from the University of Minnesota use-related machinery cost estimates (Lazarus 2021). Crop income was determined using average yields and current market prices (USDA ERS 2022). Net returns (US \$ ha^{-1}) were calculated by subtracting all field operations, seed, fertilizer, and labor costs from crop gross revenue, and compared across treatments using the single cultivation tool and no seedbank management treatment as the baseline for comparisons.

Statistical Analysis

All data were analyzed for normality using Shapiro-Wilk goodness-of-fit tests, and data transformations were performed where necessary. Weed control efficacy, crop mortality, hand-weeding time, and crop yield parameters were analyzed with ANOVA in JMP v16.0 (SAS Institute Inc., Cary, NC). Crop yields were analyzed separately by year, as a different vegetable species was grown each year. For other dependent variables, block and year were included in the model as random effects. Tukey-Kramer mean separations were performed at $\alpha = 0.05$.

Results and Discussion

Weed Control Efficacy

Intra-row weed control efficacy, assessed 24 to 48 h post-cultivation, did not differ among treatments for either the first or second cultivation event (Table 2.1). However, when each year was analyzed separately, efficacy was affected by tool stacking in two of three years (Table 2.2). In 2020 and 2021, tool stacking increased weed control efficacy and reduced variability relative to the use of a single cultivation tool (2020 $p<0.001$; 2021 $p=0.045$; Table 2.2). Brown and Gallandt (2018a) found that stacking two or three tools provided greater efficacy than a single tool in corn. In organic carrot, Hitchcock-Tilton (2018) found that finger weeders plus hilling discs increased weed control efficacy relative to the efficacy of each tool used individually. Although research on cultivation tool stacking is limited, these two published data sets show that it can provide high rates of efficacy and may help reduce the number of cultivation events that must be performed. The concept may prove useful in years where field operations are delayed due to environmental conditions, such as when precipitation delays cultivation and results in large weeds that are not sufficiently controlled by a single tool (Melander and McCollough 2021).

Crop Mortality and Yield

Crop mortality at the first cultivation event was affected by tool treatment but did not differ across years (Table 2.1). Crop mortality in tool stacking treatments averaged 6%, approximately 4% higher than when a single tool was used. Crop mortality at the second cultivation event was similar between tool treatments and across years (Table 2.1), ranging from zero to 6%. Brown and Gallandt (2018a) reported much greater crop mortality from tool stacking, with an average of 16%, which is higher than most farmers would accept. If tool stacking can be used without high levels of crop mortality, tool aggressiveness may be able to be exploited to increase weed control efficacy further, thereby reducing the number of surviving weed seedlings.

Total plant fresh weight of bush bean averaged 9.8 Mg ha^{-1} (±1.2) and was similar across treatments (Table 2.3). Bush beans can exhibit compensatory growth and may have compensated for any crop injury that reduced stands in the first cultivation event, leading to no differences in whole plant weight. Seedbank management increased bush bean pod yield to 11.3 Mg ha^{-1} (±0.50) compared to 8.3 Mg ha^{-1} (±0.72) where seedbank management was not used (Table 2.3, Figure 2.2). In other work, number and weight of bean pods decreased as duration of weed competition increased (Malik et al. 1993). Bean pod weight in plots without seedbank management may have been influenced by competition from high weed densities over the growing season, resulting in plant stress as the bean plants went into their reproductive stage. A longer weed-free period that extends to early pod set may be needed to reduce yield loss (Odero and Wright 2018). Seedbank management may increase crop yield by reducing competition during the season, post-cultivation hand weeding, and weed seedrain and thus the germinable weed seedbank.

Table beet yield, as well as unmarketable density, were affected by seedbank management (Table 2.3). Marketable table beet density at harvest was similar across treatments, averaging 21 plants m^{-2} (±2). However, the density of unmarketable beets was twice as high without seedbank management (Table 2.4). Unmarketable beet density averaged 4 plants m^{-2} (±1) without seedbank management compared to 2 plants m^{-2} (±1) with seedbank management. Early-season competition from higher weed densities may have contributed to slow growth that delayed canopy closure, and smaller beets at harvest, showing that seedbank management with tarping and flame weeding may be important for crop yield and quality (Melander et al. 2005). Additionally, marketable fresh weight was affected by seedbank management but not by tool treatment (Table 2.3, Table 2.4). Marketable fresh weight was approximately 10 Mg ha^{-1} higher with seedbank management compared to no seedbank management (Table 2.4). In a field experiment of table beet cultivars, Priddy (2021) found that the cultivar Boro tended to be more competitive against surrogate weeds due to greater shoot biomass and height. Boro was used in this study, and although we did not measure shoot biomass and height at cultivation, beets in plots where seedbank management was absent may have exhibited slower growth from weed competition compared to the other plots where high levels of weed control were achieved. Unmarketable total fresh weight did not differ across treatments (p=0.581; data not shown).

Sweet corn yield was not affected by treatments (Table 2.3). Marketable ears and unmarketable ears averaged 16,590 (±413) ears ha^{-1} and 13,929 (±881) ears ha^{-1}, respectively. Across treatments, marketable ear weight averaged 19 (±0.61) Mg ha^{-1} and unmarketable ear weight averaged 6.1 (±0.40) Mg ha^{-1}. The absence of treatment effects is perhaps not surprising given the robust nature of the crop and its ability to withstand mechanical damage, which was expected to result in greater yield where tool stacking occurred. Our variety choice, Sweetness F1, is an early variety that has growth characteristics such as rapid canopy development and large leaf area. These traits may facilitate greater tolerance to cultivation and also aid in weed suppression (Boydston and Williams 2015). Despite the lack of treatment effects, tool stacking did not result in yield or quality loss compared to a single tool, emphasizing that tool stacking can still be utilized to increase weed control efficacy.

Weed Seedbank

At the start of the experiment in 2019, the germinable seedbank averaged 4,000 seeds m^{-2} (±800) and was not different across treatments (Figure 2.3). In 2020, the germinable seedbank of plots that did not receive any seedbank management (-SB) increased to 12,385 seeds m^{-2} (±3,166), whereas plots receiving seedbank management (+SB) decreased to 3,597 seeds m^{-2}

(±514) (Figure 2.3). In 2021, the germinable seedbank of plots that did not receive any seedbank management (-SB) averaged 8,500 seeds m^{-2} (±2,200). This decrease from 2020 may be attributed to hand weeding that was performed after last cultivation, which was not performed in 2019, that prevented additional seed rain from occurring. In contrast, plots receiving seedbank management (+SB) further decreased to 2,100 seeds m^{-2} (±400) (Figure 2.3).

Seedbank composition consisted mostly of annual broadleaf species such as redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), common chickweed (*Stellaria media* L. Vill.), and common purslane (*Portulaca oleracea* L.), as well as some large crabgrass (*Digitaria sanguinalis* L. Scop.). In a comparison of several weed management strategies, Brown and Gallandt (2018b) found that preventing weed seedrain resulted in lower weed biomass and seed rain compared to only cultivation after planting during the critical weed-free period. The “zero seed rain approach” resulted in lower weed densities in the following crop year and produced similar yields compared to cultivation only (Brown and Gallandt 2018b). Our results reinforce that seedbank management is an important strategy to reduce weed seedling densities through multiple stressors, and these practices can reduce the germinable weed seedbank, resulting in lower weed densities over time (Forcella 2003; Gallandt 2014).

Economic Performance

Partial budgeting results reflect the larger seedbank management treatment effects on yield, and production costs, particularly differences in hand weeding. Seedbank management (+SB) in table beet reduced hand-weeding time to 114 h ha^{-1} compared to 215 h ha^{-1} where no seedbank management was applied (p=0.001). At \$12 h^{-1} costs were \$1,368 ha^{-1} and \$2,580 ha^{-1} where seedbank management was used and where no seedbank management was used, respectively (Table 2.5). In sweet corn, tool stacking with finger weeders and hoe ridgers reduced hand weeding time to 52 h ha^{-1} (±4) compared to 128 h h^{-1} (±17) when finger weeders were used alone (*p*= <0.001). At \$12 h^{-1} costs were \$624 ha^{-1} and \$1,356 ha^{-1} for finger weeders plus hoe ridgers and finger weeders alone, respectively (Table 2.5). Hitchcock-Tilton (2018) found similar results by stacking finger weeders with hilling discs. Hilling discs and hoe ridgers act similarly in the intra-row, both reducing survival and emergence through burial. Hand-weeding labor can be expensive, but the addition of seedbank management early in the season (tarping, flame weeding), plus tool stacking, could provide labor reductions over the course of the season, which may be reduced further over time as these practices reduce the germinable weed seedbank.

In two of three years, seedbank management (+SB) resulted in higher net returns due to greater crop yield (Table 2.5). Although seedbank management resulted in higher total variable costs due to the addition of cover crop seed and labor for tarping, flame weeding, and more hand-weeding, this was offset by the increase in crop yield. The Single tool plus seedbank management (+SB) treatment resulted in higher net returns than the Stacked tool plus seedbank management (+SB) treatment due to greater tractor use-related costs in the tool stacking treatment; however, these costs could be lowered in future years due to a reduction in the germinable weed seedbank resulting in the need for fewer cultivation events (Figure 2.3). Net returns were negative across all treatments in 2021 due to high variable costs and low crop yield (Table 2.5). Total variable costs varied by year due to differences in the number and type of field operations, as well as the amount and type of fertilizer needed each year. For example, soil tests indicated that no phosphate fertilizer was required in 2021, but fertilizer costs increased compared to other years due to the high N requirements of the corn crop. Across three years, variable costs in the seedbank management treatment (+SB) totaled \$51,832 ha^{-1}, and net returns totaled \$2,360 ha^{-1}. Where seedbank management was not used (-SB), variable costs totaled \$44,262 ha^{-1}; however, total net returns were negative at -\$1,327 ha^{-1} due to the high costs and lack of yield differences across treatments in 2021. Although the addition of seedbank management can result in higher variable costs, it can be offset by higher crop yields in some years and therefore greater net returns in certain crops.

Treatment Effects on Subsequent Weed Recruitment

Additional data on weed recruitment following seedbank management prior to crop planting, and following tool stacking after last cultivation, were explored to determine if treatments influenced subsequent weed germination. Seedbank management (+SB) affected intra-row weed density 14 DAP in table beets in 2020. Tarping and flame weeding resulted in 12 (±2) weeds m^{-2} compared to 70 (±33) weeds m^{-2} where tarping and flame weeding were not used (p=0.026), likely due to the combined effects of stale and false seedbeds (Merfield 2015; Teasdale and Mohler 2000). Tool stacking resulted in 75% fewer intra-row weeds 14 days after last cultivation in 2020 with an average density of 11 weeds m^{-2} (p=0.001). Hoe ridgers were used in the second cultivation event following finger weeders, and the hilling mechanism of the tool creates a loose ridge of soil around the crop while also uprooting weeds next to the crop row. A burial depth of 1.5 to 2 cm can be sufficient to kill small, emerged weeds (Terpstra and Kouwenhoven 1981). Recruitment of new weed flushes was likely reduced due to the loose soil and thus reduced seed-soil contact. This concept is worth exploring with different tool mechanisms and stacking combinations to see if certain tools and tool combinations can further reduce weed densities later in the season.

Conclusions

Tool stacking and seedbank management together did not result in combined effects on efficacy and seedbank density. However, the main effect of tool stacking resulted in increased weed control efficacy in two of three years, and the addition of seedbank management decreased the germinable weed seedbank over three years, contributing to the overall goals to improve weed management through multiple stressors. While tool treatments did not affect crop yield in any of the three years, seedbank management was found to be important for increasing crop yield in bush bean and table beet. Although seedbank management contributed to higher variable costs due to greater labor requirements and the addition of cover crop seed, this was offset in 2019 and 2020 by greater crop yield, therefore resulting in higher net returns compared to no seedbank management. However, precaution should be taken in years where crop yield is low, as shown by negative net returns in 2021. Seedbank management was important in reducing the germinable weed seedbank, which declined over three years compared to the absence of seedbank management. Overall, tool stacking is important for improving efficacy and reducing weed densities during the growing season. Seedbank management can contribute to reduced weed seedling densities ahead of cultivation events, as well as greater crop yields, leading to greater profitability and a reduction of the germinable weed seedbank over time. When used together, these can reduce weed densities in organic vegetable systems and improve weed management outcomes.

Table 2. 1. Effects of year, cultivation, and seedbank management treatments on crop mortality and intra-row ambient weed control efficacy for two cultivation events. Year and block were included as random model effects.

	Crop Mortality [a]		Intra-row Ambient Weed Control Efficacy	
	Cultivation Event			
Source	1	2	1	2
	---------------------- *p-value* ----------------------			
Year (Y)	0.965	0.445	0.349	0.328
Cultivation (C)	0.021	0.458	0.082	0.054
Seedbank (S)	0.162	0.811	0.755	0.150
C x S	0.966	0.208	0.833	0.166
Y x C	0.335	0.773	0.186	0.166
Y x S	0.530	0.930	0.932	0.154
Y x C x S	0.708	0.433	0.742	0.403

[a] Crop mortality data were square root transformed to meet assumptions of normality due to zeroes causing skew.

Table 2.2. Mean (±SE) intra-row weed control efficacy for each cultivation event, and main effects of year, cultivation treatment, and seedbank management treatment. [a]

		Intra-row Weed Control Efficacy					
		Cultivation Event					
Treatment		1			2		
		2019	2020	2021	2019	2020	2021
Cultivation	Seedbank Management	------ % ------					
Single tool	-SB	52±11	85±2 b	77±8 b	5±4	77±6	69±12 b
	+SB	60±21	83±3 b	70±16 b	24±7	83±4	45±17 b
Stacked tools	-SB	56±8	95±2 a	96±2 a	0±0	83±3	78±8 a
	+SB	50±12	94±2 a	95±3 a	32±9	89±4	95±5 a
Main Effects:							
Year	2019		55±6 B			15±7 B	
	2020		89±2 A			83±2 A	
	2021		85±5 A			72±7 A	
Cultivation	Single tool		71±5 B			51±7	
	Stacked tools		81±5 A			63±8	
Seedbank	-SB		77±4			52±8	
	+SB		75±6			61±8	

[a] Within column sections, means not followed by the same letter are significantly different ($p<0.05$).

Table 2. 3. Effects of cultivation and seedbank management treatments on bush bean, table beet, and sweet corn marketable yield.

	2019 - Bush bean		2020 - Table beet		2021 - Sweet corn	
Source	Total plant fresh wt.	Bean pod fresh wt.	Beet density	Total plant fresh wt.	Ear density	Ear fresh wt.
	-- *p-value* --					
Cultivation (C)	0.701	0.964	0.221	0.551	0.288	0.103
Seedbank (S)	0.412	0.006	0.149	0.002	0.215	0.350
C x S	0.675	0.183	0.182	0.263	0.649	0.351

Table 2. 4. Mean (±SE) marketable and unmarketable beet density and fresh weights by treatment in 2020. Different letters indicate significant differences in the main effect of seedbank management at α=0.05. [a]

		Density (no. m^{-2})			Total Fresh Wt. [b] (Mg ha^{-1})		
Treatment		Marketable	Marketable with defects	Unmarketable	Marketable	Marketable with defects	Unmarketable
Cultivation	Seedbank Management						
Single tool	-SB	19±3	1±1	5±1	27±6	1.4±0.5	1.5±0.3
	+SB	25±2	2±1	2±1	31±3	2.0±0.7	1.0±0.4
Stacked tools	-SB	20±1	1±1	3±1	43±3	2.0±0.9	0.74±0.3
	+SB	20±2	2±1	2±1	36±4	3.8±1.8	0.62±0.4
Main Effects:							
Cultivation	Single tool	22±2	2±1	4±1	35±4	1.7±0.5	1.2±0.2
	Stacked tools	20±1	2±1	2±1	33±3	2.8±1.0	0.83±0.3
Seedbank	-SB	19±2	2±1	4±1 A	29±3 B	1.7±0.4	1.3±0.2
	+SB	22±1	2±1	2±1 B	39±3 A	2.9±1.0	0.68±0.2

[a] Within column sections, means not followed by the same letter are significantly different ($p<0.05$).

[b] Total weight of roots plus shoots.

Table 2. 5. Partial budget analysis for each treatment for each growing season. Variable costs include crop and cover crop seed, hand-weeding and hand-harvesting labor, and estimated labor and fuel costs of field operations for establishing seedbeds, crop planting, and mechanical cultivation. Net returns ($ ha^{-1}) were calculated by subtracting variable costs from income obtained from crop yields based on an average organic market prices.

	2019 – Bush bean*				2020 – Table beet**				2021 – Sweet corn***			
	Single tool		Stacked tools		Single tool		Stacked tools		Single tool		Stacked tools	
Partial budget	(-SB)	(+SB)	(-SB)	(+SB)	(-SB)	(+SB)	(-SB)	(+SB)	(-SB)	(+SB)	(-SB)	(+SB)
Gross returns												
Marketable Crop yield (kg ha^{-1})	7,891	11,688	8,808	10,827	27,237	42,763	31,015	36,034	21,029	18,837	17,913	17,911
Receipts ($ ha^{-1})[a]	6,865	10,168	7,662	9,419	8,913	13,995	10,150	11,792	5,046	4,520	4,299	4,298
Variable Costs ($ ha^{-1})												
Crop seed	1,002	1,002	1,002	1,002	1,956	1,956	1,956	1,956	1,437	1,437	1,437	1,437
Cover crop seed	0	212	0	212	0	359	0	359	0	852	0	852
Fertilizer[b]	1,348	1,348	1,348	1,348	2,386	2,386	2,386	2,386	4,594	4,594	4,594	4,594
Tarping labor[c]	0	1,141	0	1,141	0	1,155	0	1,155	0	1,050	0	1,050
Flame weeding labor[c]	0	0	0	0	0	45	0	45	0	45	0	45
Hand weeding labor[c]	266	325	266	325	2,580	1,368	2,580	1,368	1,536	1,536	624	624
Harvest labor[c]	2,489	2,489	2,489	2,489	1,067	1,067	1,067	1,067	1,440	1,440	1,440	1,440
Tractor use-related costs[d]	222	235	236	249	147	187	161	201	96	122	110	136
Total variable costs	5,327	6,752	5,341	6,766	8,136	8,523	8,150	8,537	9,103	11,076	8,205	10,178
Net Returns ($ ha^{-1})	1,538	3,416	2,321	2,653	777	5,472	2,000	3,255	-4,057	-6,556	-3,906	-5,880

[a] Market price of $0.87 kg^{-1} for bush bean (2019), $3.60 11 kg^{-1} for table beet (2020), and $0.24 kg^{-1} for sweet corn (2021).

[b] Includes total cost of pre-plant and sidedress fertilizer applications.

[c] Labor costs based on local wage of $12 hour^{-1}.

[d] 2021 Minnesota use-related machinery costs ha^{-1}; represents total cost of all tractor operations. Use-related costs include estimates for fuel, lubricants, labor, and repairs and maintenance.

[*] crop marketable yield C x S p=0.675

[**] crop marketable yield C x S p=0.263

Table 2.4, continued

*** crop marketable yield C x S *p*=0.351

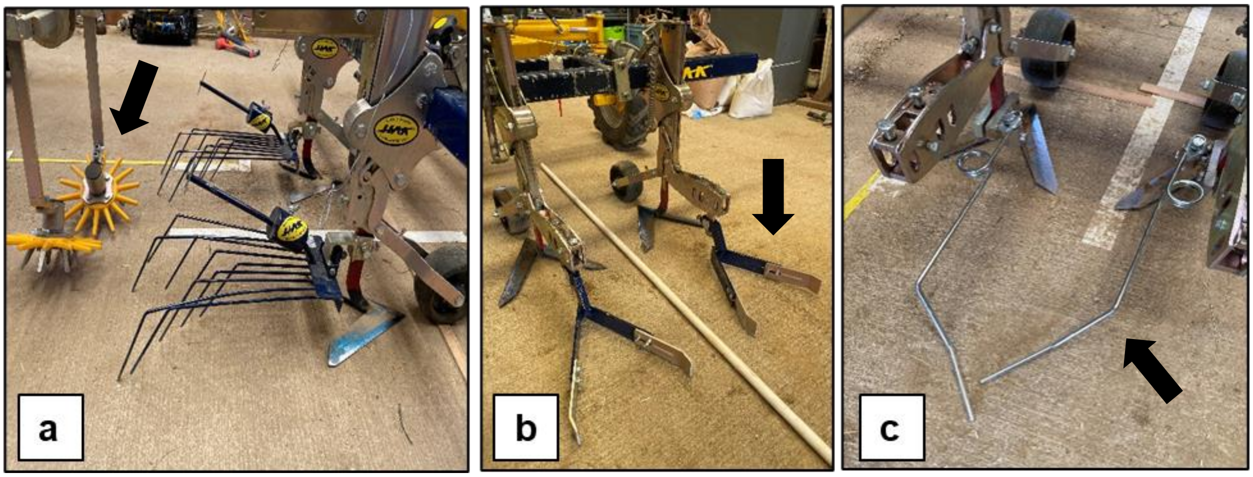


Figure 2. 1. Cultivation tools used in experiments, including a) finger weeders; b) hoe ridgers; and c) torsion weeders. Finger weeders were preceded by tine harrows for inter-row weed control in all treatments, and sweeps were placed in front of all cultivation tools to help break soil crust. All cultivation tools were from HAK (Schoffeltechniek, Bleiswijk, Holland).

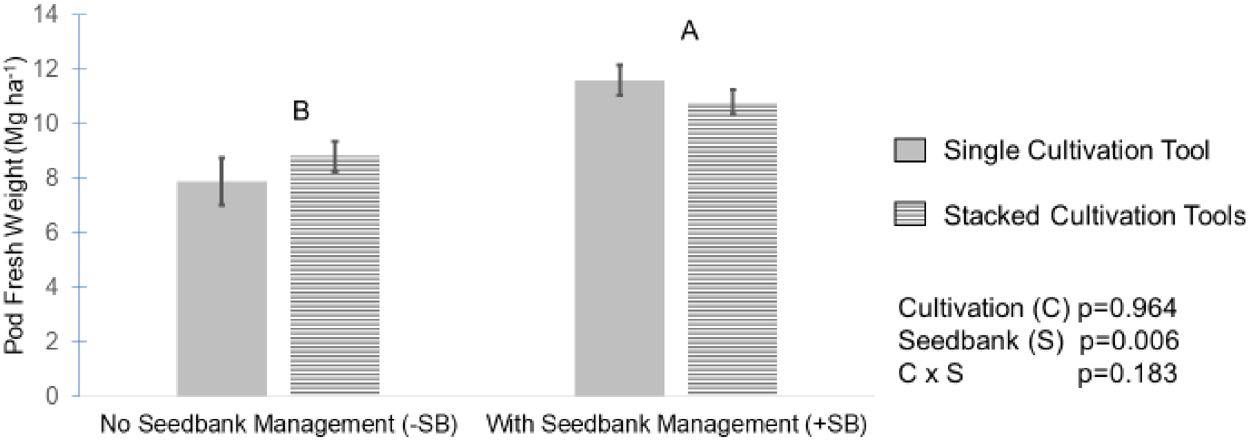


Figure 2. 2. Marketable bush bean pod weight. Data are summed pod weight from two harvest events. Error bars represent standard error of the mean. Different letters indicate significant differences in the main effect of seedbank management at α=0.05.

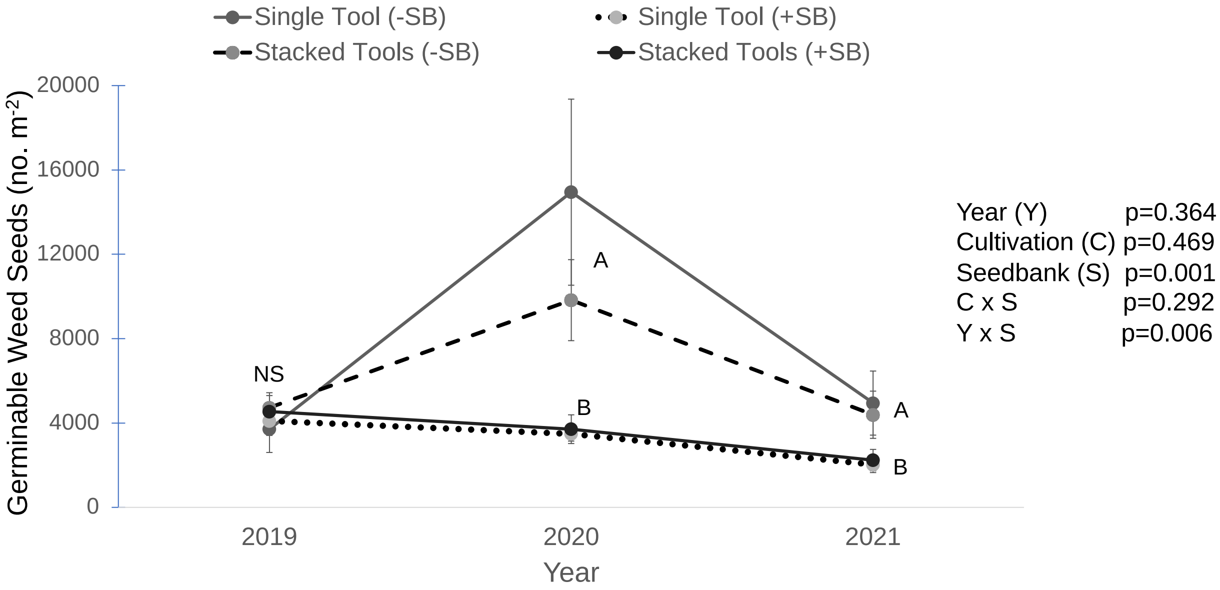


Figure 2. 3. Germinable weed seeds by treatment and year. Samples were taken to a depth of 10 cm. “Single” refers to single cultivation tool; “stacked” refers to cultivation tool stacking. Absence of seedbank management is denoted by (-SB), and addition of seedbank management (including silage tarps, flame weeding, and cover cropping) is denoted by (+SB). Error bars represent standard error of the mean. Different letters indicate significant differences in the main effect of seedbank treatment at α=0.05.

CHAPTER 3

STACKING HAND TOOLS TO INCREASE WEED CONTROL EFFICACY FOR SMALL-SCALE ORGANIC FARMERS

Abstract

Small-scale, highly diverse organic farms typically rely on various hand tools for their weed management. Common tools include wheel hoes, stirrup hoes, and tine rakes, with hand pulling used as a last resort to remove weeds often in the crop row. Weeding labor is expensive, and many hand tools operate with a density-dependent working rate, increasing costs proportional to the weed pressure. We evaluated the effects of single tools and tool combinations or “stacking” with the Terrateck Double Wheel Hoe, measuring weed control efficacy, crop mortality, crop fresh biomass, and time required for hand weeding to control weeds surviving cultivation. In two consecutive years, six single tools and all possible two- and three-tool combinations were examined, including: biodiscs, finger weeders, tine harrows, L-sweeps, preci-discs, and torsion weeders. Bush bean (*Phaseolus vulgaris*) and table beet (*Beta vulgaris* L.) were chosen as our test crops, thereby including a large- and a small-seeded crop. Based on two site-years, tool stacking across both crops provided 55% (±3) weed control efficacy compared to 41% (±2) efficacy when single tools were used. Notably, tool stacking combinations using tine harrows and torsion weeders provided the greatest weed control efficacy. Tool stacking did not increase crop mortality compared to a single tool in bush bean, averaging 5% (±1) across all tools. However, table beet mortality was increased by tool combinations with torsion weeders. Table beet mortality averaged 32% (±3) but was as high as 66% (±6) when torsion weeders were used. Tool stacking provided greater intra-row weed control efficacy compared to a single tool in bush bean and table beet. Despite improved efficacy, crop fresh biomass and subsequent hand-weeding times were not affected by choice of individual tool nor by tool stacking. The Terrateck Double Wheel Hoe provides farmers with the ability to stack tools and increase weed control efficacy in a single pass, and future work should examine the use of the Terrateck in different crops, crop growth stages, and soil environments so that farmers can make more informed tool purchases.

Introduction

Weed control is a continual challenge for organic farmers. Cultivation, often referred to as ‘physical weed control’ (PWC), remains a primary strategy, but tool efficacy can be low and highly variable, often with poor selectivity and high levels of crop injury and yield loss (Gallandt 2014). Small-scale organic vegetable farmers, i.e., those farming 0 to 2 hectares, rely heavily on labor for weeding. These farmers rely on various hand tools and hand weeding, especially during the early stages of crop growth when it is crucial to control weeds and give the crop a competitive advantage. Hand tools and hand-weeding are frequently used after tractor-based cultivation to remove weeds that escaped control, usually weeds remaining close to or within the crop row (Bond and Grundy 2001). In New England, USA, common hand tools on an organic vegetable farm include wheel hoes manufactured by Planet Jr., Glaser and Hoss, Glaser stirrup hoes, and the colinear hoe, designed by Eliot Coleman and sold by Johnny’s Selected Seeds. There are, however, dozens of other long- and short-handled tool options farmers can choose from. While hand tools are relatively inexpensive, hand-weeding labor can make up a large percentage of an enterprise’s operational costs often because of density-dependent working rates of hand-weeding and hand tools. Hand-weeding labor costs can reach on average $6,000 USD ha^{-1} annually for common row crops, with at least 600 hours ha^{-1} spent weeding (Deese 2010; Sørensen et al. 2005). Reducing these labor costs is important for improving the profitability of organic farming systems.

Weeding labor costs could be reduced if cultivation tool efficacy were improved. Brown and Gallandt (2018) examined cultivation tool “stacking,” or using more than one cultivation tool at a time, with promising results. A tractor-mounted cultivator equipped with one, two, or three types of intra-row tools was examined, and increased efficacy was observed when tools were stacked relative to the efficacy of a single tool. Moreover, tool stacking resulted in synergistic effects of efficacy, i.e., a total efficacy higher than the additive efficacy of each tool used individually (Brown and Gallandt 2018).

The Terrateck Double Wheel Hoe (Terrateck, Cesson-Sévigné, France) is a uniquely designed hand-tool that can accommodate tool stacking, making this strategy available to small-scale farms. The tool has a pair of wheels that straddle the crop row with 17 cm of clearance above the soil surface. Terrateck offers several tools that are usually seen only on tractor-mounted cultivating units, such as finger weeders, hilling discs, torsions, tine harrows, and sweeps. Additionally, a notched tool bar means that tool spacing can be easily adjusted relative to the crop row, so the operator can optimize selectivity. The individual weeding tools likely include the full compliment of tool mechanisms, such as burial, uprooting, and severing roots from shoots, which in combination may offer increased weed control efficacy compared to tools used individually (Brown and Gallandt 2018; Mohler 2001).

Research on cultivation tools is somewhat limited, with very few studies of hand tools. In this study, we evaluated the effects of single tools and tool stacking with the Terrateck Double

Wheel Hoe on weed control efficacy, crop mortality, and crop biomass in field experiments conducted over two years. Bush bean (*Phaseolus vulgaris*) and table beet (*Beta vulgaris* L.) were chosen as the test crops to represent large- and small-seeded crops, respectively. Based on the results of Brown and Gallandt (2018), we hypothesized that: (1) stacking two or three tools on the Terrateck would result in increased weed control efficacy compared to single tools; (2) tool stacking would result in greater crop mortality due to increased aggressiveness of the weeding operation; (3) tool stacking would lower hand weeding time due to greater weed control efficacy; and (4) tool stacking would increase crop biomass 40 days after planting due to greater weed control efficacy and increased crop competitive ability.

Materials and Methods

Site Description and Field Preparation

Experiments were conducted at the University of Maine Rogers Farm in Old Town, Maine (44°55′N, 68°41′W) in 2019 and 2020. The soil at the site is comprised of Pushaw-Boothbay silt loam. The site is in USDA Plant Hardiness Zone 4b, with an average annual high/low temperature of 20/-7°C, and average annual precipitation of 1,023 mm.

Fields were disked to incorporate cover crop and winter annual weed residue. Pre-plant nitrogen was applied as Nutri-wave™ 4-3-2 (Northeast Agricultural Sales Inc., Detroit, ME, USA) at 60 kg ha^{-1} plant-available nitrogen and incorporated with a Perfecta® Field Cultivator (Unverferth Manufacturing Company Inc., Kalida, OH, USA). Plots were firmed using a cultipacker; bush bean ‘Provider’ and table beet ‘Chioggia Guardsmark’ were planted using a Wizard® vacuum seeder (Sutton Agricultural Enterprises, Inc., Salinas, CA, USA) on 51-cm rows with two rows per bed. Bush bean was planted in two experiments in both 2019 and 2020 in adjacent fields, whereas table beet was also planted twice, but only in 2020 in the same field as bush bean. In both years, crops were planted in early June for the first experiment, and mid-July for the second experiment. In 2020, bush bean and table beet were planted at the same time for both experiments. Condiment mustard ‘Pacific Gold’ was used as a surrogate weed species. Mustard was broadcast with a Brillion® drop seeder (Landoll, Marysville, KS, US) at eight kg ha^{-1} 10 days prior to cultivation in each crop. Surrogate weeds were chosen due to inconsistent ambient weed densities across the experimental area.

Experimental Design and Treatments

Terrateck tool combinations were chosen by setting up each combination of tools on the toolbar and eliminating any combinations that were not possible due to tool interference. Six tools (Figure 3.1), alone and in combination, were chosen for field testing. The experiment was established as a completely random design with 20 treatments and three replications. Treatments included six single tools, 11 two-tool combinations, and three three-tool combinations. Plots consisted of a single crop row measuring 9.1 m long by 0.5 m wide. Tool treatments were randomly assigned to plots across the field site.

Bush bean was cultivated when the crop reached the first true-leaf stage, and table beet at one- to two-true leaves. At the time of cultivation, surrogate mustard was at the cotyledon to one true leaf stage. Cultivation events were timed to coincide with warm, dry days where soil moisture was less than 15% to ensure that weeds would desiccate. Tools were adjusted to recommended settings and tested on at least 100 row feet prior to use in experimental plots. One tool operator was selected for all experimental runs to minimize operator error.

Data Collection

Three permanent 0.25 m^2 subplots were randomly established in each plot and marked on each end by a wooden stake that was centered in the crop row. Quadrats, constructed 51cm wide to match crop row spacing, were centered at the wooden stake over the crop row and pre-cultivation crop density was recorded just prior to cultivation. Surrogate weed densities were also recorded across the entire quadrat in each subplot. Post-cultivation crop and surrogate weed densities were recorded approximately 24 h after cultivation to allow adequate time for desiccation. Data were averaged across subsamples prior to statistical analyses.

Fourteen days after cultivation in 2020, the time to hand weed each plot was recorded to provide additional information on how each tool treatment affected the labor requirements needed after cultivation. One person was assigned to each replication of all treatments and the total time to weed an entire plot using a stirrup hoe and pulling large intra-row weeds was recorded. Above-ground crop fresh biomass was harvested from each 0.25m^2 subplot 40 days after planting (DAP) to provide an estimate of yield. Crop plants were clipped at the ground level and immediately weighed. Data were averaged across subsamples prior to analysis.

Statistical Analysis

All data were analyzed for normality using goodness-of-fit Shapiro-Wilk tests and means analyzed with analysis of variance in JMP 14.0 (SAS Institute Inc., Cary, NC). Efficacy was analyzed both separately for the intra- and inter-row zones and combined to represent “total efficacy” across the sampling area. Site-year was included as a random effect, and data were pooled across site-years prior to mean separations if site-year was non-significant. Tukey-Kramer mean separations were performed at $\alpha = 0.05$. A separate model was constructed using tool number as a fixed effect, with mean separations occurring as described above. Orthogonal contrasts were conducted to further explore differences between tool numbers.

To test for possible additive, synergistic, or antagonistic effects from tool stacking, observed total weed control efficacy for each tool combination was compared to the expected efficacy using the method of Colby (1967):

Two tools:

$$\text{Expected Efficacy (\%)} = 100 - ((X*Y)/100)$$

Three tools:

$$\text{Expected Efficacy (\%)} = 100 - ((X*Y*Z)/10{,}000)$$

where X is the percent mean weed survival of the first tool when used by itself, Y the percent mean weed survival for the second tool, and Z the percent mean weed survival for the third tool. Combined effects were determined using a two-tailed, one-sample t-test based on Walsh et al. (2012), with a significant t-test indicating synergy or antagonism from tool stacking. If a p-value at $\alpha=0.05$ was significant, and observed efficacy greater than the expected, this indicated synergy, whereas observed efficacy less than the expected indicated antagonism. A non-significant p-value indicated simple additive effects.

To determine which tools and tool combinations were the best performing with regards to total weed control efficacy, a regression tree was constructed using JMP with efficacy as the response variable. Splits were made in the tree by lowest tool variance and then by tool number (1, 2, or 3 tools) within the tools that were determined to have the highest mean weed efficacy and lowest variability.

Results and Discussion

Weed Control Efficacy

In both bush bean and table beet, tool stacking provided greater surrogate weed control efficacy compared to a single tool, while two- and three-tool combinations had similar efficacy to each other (Table 3.1, Table 3.2). These results are supported by those of Brown and Gallandt (2018), who found that tool stacking with tractor-mounted cultivation tools such as torsions, tine harrows, and finger weeders provided greater weed control efficacy than the individual, single tools. While the Terrateck tools and tractor-mounted cultivation tools may be of different scale, they operate through similar mechanisms to kill weeds by uprooting and burial (Kurstjens and Perdok 2000; Mohler 2001), supporting the concept of tool stacking for hand tools.

Efficacy of surrogate mustard weed control in bush bean was not different across site-years (Table 3.1); therefore, bush bean efficacy data were pooled and presented across the site years (Table 3.3). Efficacy was affected by tool treatment in bush bean (Table 3.1, Table 3.3), but not in table beet (Table 3.1). However, efficacy differed between the two experiments conducted in table beet (Table 3.1, Table 3.3). In table beet experiment one, total efficacy averaged 41% (±3) across all tool treatments and in table beet experiment two averaged 54% (±4) across all tool treatments (Table 3.3). This may be attributed, in part, to hot and dry conditions during the first experiment that would have led to quicker desiccation and greater weed mortality. In previous experiments, soil moisture was negatively correlated with efficacy (Brown and Gallandt 2018; Mohler et al. 2016), as higher soil moisture can decrease soil movement leading to lower efficacy.

In bush bean, tool combinations including the L-sweeps (L), tine harrows (H), and torsion weeders (T) performed best with regard to weed control efficacy (Figure 3.2). Regression tree analysis showed that these tool combinations, which includes L-sweep+Torsion (LT), Torsion+L-sweep (TL), and L-sweep+Harrow+Torsion (LHT), had greater efficacy and lower variation compared to other tools (Figure 3.2). These tool combinations likely include different modes of action, and perhaps more importantly, they also cover a greater area, lending to better efficacy compared to a single tool. Tool working width was measured and these tool combinations covered a wider area compared to single tools (Table 3.3). The tool on the front toolbar may have helped loosen soil and increased the effectiveness of the tool on the second toolbar. Torsion weeders and harrows have been found to contribute to increased weed control efficacy. Kunz et al. (2018) observed 69% efficacy with fingers, torsions, and a rotary harrow, and Ascard and Fogelberg (2008) found that harrowing followed by use of torsion weeders resulted in lower weed densities and hand-weeding time compared to only harrowing or inter-row cultivation in transplanted onions. Torsions are designed to be flexible and be angled down at the soil, running 2-3 cm below the soil surface (Melander et al. 2015). This could help break soil crust, allowing for greater efficacy of a subsequent tool.

Testing for Combined Tool Effects

All tool combinations were tested for additive, synergistic, or antagonistic effects based on their respective observed and expected surrogate weed control total efficacies (Colby 1967; Walsh et al. 2012). Tool order, that is, being placed on the front or back toolbar, may contribute to weed control success. Based on efficacy of the intra- and inter-row census areas combined, most tool stacking combinations resulted in an antagonistic effect across the total sampling area (Table 3.4). Tools starting with L-sweeps, torsion weeders, and preci-discs showed evidence of additive effects (Table 3.4), suggesting that if tools that sever roots from shoots are placed on the front toolbar, weed control efficacy may be improved compared to these tools being used alone by breaking soil crust ahead of the second tool. However, no synergistic effects were observed, which is a departure from the results of Brown and Gallandt (2018), who found tool synergy from stacking. This may be attributed to the size and aggressiveness of tractor-mounted tools compared to those of the Terrateck, which are much smaller and limited by the force applied by the operator.

Crop Mortality and Biomass

Bush bean mortality at one true leaf was not affected by tool treatment or tool number in any of the site years (Table 3.1), averaging 5% (±1) (Table 3.3). Although we expected higher mortality from tool stacking, the tools were not set to their most aggressive and bush bean seedlings were relatively large and well-anchored at the time of cultivation. While table beet mortality was not affected by tool number (Table 3.1), averaging 22% (±3), it was roughly four-fold greater than bush bean mortality (Table 3.3). Table beet mortality was affected by the interaction of Tool Treatment x Site-Year and was different between the two experiments conducted in 2020 (Table 3.1). The combination of torsion weeders plus harrows, and torsion weeders plus L-sweeps resulted in the greatest crop mortality in table beet experiment one in 2020, averaging 66% (±6) compared to an average mortality of 32% (±3) for all other tools (Table 3.3). In table beet experiment two in 2020, mortality across all tools averaged 11% (±2) (Table 3.3). Cultivation was performed at one-true leaf due to high weed densities. While the timing was appropriate based on the weeds present, the crop was too small, resulting in high mortality. Table beets are a sensitive crop, and it is recommended that cultivating with tractor-mounted implements occur at the three- to four-true leaf stage or greater to prevent high rates of injury (Van der Weide et al. 2008). Waiting to cultivate with the Terrateck until table beets have reached two- to three-true leaves could result in a more acceptable level of crop mortality, but this comes with the tradeoff of larger weeds at cultivation and reduced efficacy.

Bush bean fresh biomass at 40 DAP in 2020 was unexpectedly not affected by tool treatment or tool number (Table 3.1), suggesting that tool choice would not affect final biomass at harvest. Colquhoun et al. (1999) reported reduced yields in snap bean when flex-tine and rolling cultivators were used in combination; however, these are tractor-mounted cultivation tools that likely operate more aggressively than a hand tool. Additionally, the crop may have compensated for injury due to its indeterminate growth, so any damage from cultivation may not have translated to yield. Fresh biomass averaged 6,835 kg ha^{-1} (±266) and 8,678 kg ha^{-1} (±226) in experiments one and two in 2020, respectively. This can likely be attributed to drought conditions experienced during the first experiment, which may have resulted in plant stress and decreased biomass. Barrios et al. (2005) observed that dry bean in a water-stressed treatment had 50% fewer branches and 60% less leaf area compared to an irrigated system, therefore affecting the final yield.

Table beet biomass (roots plus shoots) 40 DAP was also unexpectedly not affected by tool treatment or tool number (Table 3.1) and was different between the two experiments conducted in 2020. Fresh biomass averaged 2,727 kg ha^{-1} (±245) and 3,397 kg ha^{-1} (±214) in experiments one and two, respectively, again reflecting drought conditions at the one- true leaf growth stage. Mohammadian et al. (2005) found that sugar beets in drought conditions had lower leaf area, shoot weight, and root weight compared to non-stressed conditions. Damage to beets can occur if cultivated too soon after emergence, regardless of tool choice (Melander 2000). It is likely that biomass was reduced early in the season from injury at cultivation due to the small size of the table beets.

Hand-Weeding Labor

Time to hand weed an entire plot 14 days after cultivation, which was measured in 2020 to provide information on hand-weeding labor requirements after cultivation, was not affected by tool treatment or tool number in bush bean or table beet (Table 3.1). This was unexpected due to the differences in weed control efficacy between tools in bush bean, which would have resulted in different weed densities post-cultivation. However, efficacy results pertain to surrogate mustard, and hand-weeding time may have been affected by differences in ambient weed densities across plots. In bush bean, hand weeding time across all tool treatments averaged 40 (±2) h ha^{-1} and 59 (±2) h ha^{-1} in experiments one and two, respectively. In table beet, hand weeding time across all tool treatments averaged 59 (±3) h ha^{-1} and 69 (±2) h ha^{-1} in experiments one and two, respectively. Prior to hand weeding, surrogate mustard density was recorded to determine if tool treatment affected the "recruitment" of new weeds after cultivation, but this did not differ across tool treatments or crops (data not shown). The absence of tool effects on hand weeding time in bush bean may have resulted from crop competition with weeds that remained after cultivation, especially since no differences in crop mortality were detected, leading to similar surrogate weed densities at hand weeding time but perhaps different ambient weed densities.

Hand-weeding time was lower in experiment one in site-year two for both crops (Table 3.1), which may be attributed to the drought conditions previously mentioned, as the same individuals were assigned to hand weed the same replicate in both experiments. The drought conditions may have caused plant stress and led to differences in weed emergence or size at hand-weeding time between the two experiments. Drought conditions have been shown to decrease weed height and number of leaves of several common annual weed species compared to non-drought conditions (Cordeau et al. 2018). This may have resulted in smaller weeds and a decrease in the time required to remove these weeds with the stirrup hoe.

Conclusions

Weed control efficacy increased with tool stacking in both bush bean and table beet, which supports our hypothesis and is also supported by Brown and Gallandt (2018) tool stacking results. Notably, tool combinations including L-sweeps, torsion weeders, and tine harrows resulted in greater efficacy, but surprisingly, there were no instances of synergy, despite the high number of tool combinations tested. We observed no difference in crop mortality in one-leaf bush bean between single and stacked tool treatments, which was a departure from our hypothesized results. However, table beet mortality increased with tool stacking, which was expected due to more aggressive cultivation and the size of the crop at cultivation. We suggest that table beets be at two- to three-leaf when stacking tools on the Terrateck to avoid high crop mortality, but this would require hand weeding at earlier table beet stages to avoid large weeds at cultivation. Contrary to our hypotheses, hand-weeding time did not decrease with tool stacking, and crop aboveground fresh biomass 40 DAP did not increase. Similar hand-weeding times and crop fresh biomass between single tools and tool stacking were observed in both bush bean and table beet. Other factors besides cultivation tools can contribute to post-cultivation crop and weed success. Tool stacking can be applicable to hand tools like the Terrateck and may help increase weed control efficacy, thereby reducing seedling survival and seedrain, but crop growth stage and tool choice must be considered to prevent high crop mortality in small-seeded crops.

Table 3. 1. Effect of tool treatment and tool stacking on crop mortality, surrogate weed control total efficacy, hand-weeding time, and crop aboveground fresh biomass in bush bean and table beet. Crop mortality and weed control efficacy represents data from two-site years in bush bean; all other data are from one-site year.

Source	Crop Mortality		Surrogate Weed Control Total Efficacy		Hand-Weeding Time		Crop Aboveground Fresh Biomass 40 DAP	
	Bush bean	Table beet	Bush bean	Table beet	Bush bean	Table beet	Bush bean	Table beet
	---------- *p-value* ----------							
Tool Treatment (T)	0.084	<0.001	<0.001	0.074	0.239	0.380	0.131	0.362
Site-Year (Y) [a]	0.551	<0.001	0.209	0.004	<0.001	0.003	<0.001	0.049
T x Y	0.113	<0.001	0.104	0.163	0.999	0.514	0.077	0.520
Contrasts – Tool Number								
1 vs. 2 + 3 tools	0.184	0.297	<0.001	0.004	0.286	0.314	0.308	0.454

[a] Site-Year was used as a random effect.

Table 3. 2. Mean (± SE) total weed control efficacy by tool number (one, two, or three tools stacked on the Terrateck). Data are averaged across site-years. Different letters indicate significant differences between means at α = 0.05.

No. of Tools	*Surrogate Weed Control Total Efficacy (%)*	
	Bush bean	*Table beet*
1	38±2 *b*	45±3 *b*
2	51±2 *a*	53±2 *a*
3	55±3 *a*	60±5 *a*

Table 3. 3. Surrogate weed control efficacy (intra- and inter-row) and crop mortality from cultivation with Terrateck tool treatments in bush bean and table beet.

		Surrogate Weed Control Efficacy			Crop Mortality		
		Bush bean	Table beet		Bush bean	Table beet	
Tool Treatment	Working Width	Site-Years 1-2	Site-Year 2 Experiment 1	Site-Year 2 Experiment 2	Site-Years 1-2	Site-Year 2 Experiment 1	Site-Year 2 Experiment 2
	----- *cm* -----	--- *%* ---					
Biodiscs	20	29±3	41±6	59±6	4±1	22±5	10±5
Finger weeders	18	38±4	25±2	46±5	5±2	16±4	3±3
Harrows	38	36±4	39±2	52±7	7±2	37±7	0±0
L-sweeps	30	48±5	47±3	55±8	2±1	19±10	10±5
Preci-discs	33	41±5	44±4	40±4	3±1	26±8	7±4
Torsion weeders	15	37±5	46±5	42±5	7±2	37±9	15±5
Single tool average	26	38±2	40±2	49±3	5±1	26±3	9±2
Biodiscs + Finger weeders	25	35±3	37±1	34±8	4±2	26±8	3±3
Biodiscs + Harrows	38	42±4	43±9	48±9	4±2	20±5	8±4
Harrows + Torsion weeders	51	48±3	42±2	43±4	5±3	35±6	4±4
L-sweeps + Biodiscs	30	53±4	55±2	52±6	4±1	17±8	15±5
L-sweeps + Finger weeders	30	58±5	50±6	57±6	2±1	22±4	8±8
L-sweeps + Harrows	38	52±5	61±1	60±6	4±2	21±3	13±8
L-sweeps + Torsion weeders	30	64±4	75±6	55±10	6±3	67±4	22±12
Preci-discs + Finger weeders	18	50±4	46±5	57±7	2±1	10±7	5±5
Preci-discs + Harrows	38	44±4	59±3	56±5	4±1	31±14	3±3
Torsion weeders + Harrows	46	53±3	68±5	48±4	7±2	76±5	18±8
Torsion weeders + L-sweeps	51	62±3	67±6	45±11	7±3	55±7	10±4

Table 3.3, continued

Two-tool Average	36	51±2	55±2	50±2	5±1	35±4	10±2
L-sweeps + Harrows + Torsion weeders	51	70±4	70±4	67±12	10±3	60±8	20±6
Preci-discs + Finger weeders + Harrows	51	42±5	45±6	61±16	5±2	17±5	6±3
Preci-discs + Harrows + Torsion weeders	46	56±4	56±2	57±6	5±2	24±8	21±12
Three-tool Average	49	55±3	57±4	62±6	7±2	30±8	19±4

Table 3. 4. Tool treatment screening for additive, synergistic, or antagonistic effects in bush bean and table beet. Data represent total efficacy (intra- plus inter-row) and are combined across site-years. Expected efficacy calculated based on Colby (1967). Combined effects were determined using a two-tailed, one-sample t-test in JMP based on Walsh et al. (2012).

Tool Treatment	Bush bean				Table beet			
	Expected	*Observed*	*Prob >* $\lvert t\rvert$	*Combined effect*	*Expected*	*Observed*	*Prob >* $\lvert t\rvert$	*Combined effect*
	----- % -----				----- % -----			
Biodiscs	-	29	-	-	-	50	-	-
Finger weeders	-	38	-	-	-	36	-	-
Harrows	-	36	-	-	-	46	-	-
L-sweeps	-	48	-	-	-	51	-	-
Preci-discs	-	41	-	-	-	42	-	-
Torsion weeders	-	37	-	-	-	44	-	-
Biodiscs + Finger weeders	55	35	<0.001	Antagonism	45	35	0.056	Antagonism
Biodiscs + Harrows	54	42	0.014	Antagonism	64	45	0.026	Antagonism
Harrows + Torsion weeders	59	48	0.011	Antagonism	67	42	<0.001	Antagonism
L-sweeps + Biodiscs	63	53	0.035	Antagonism	67	53	0.008	Antagonism
L-sweeps + Finger weeders	69	58	0.031	Antagonism	62	53	0.091	Additive
L-sweeps + Harrows	68	52	0.007	Antagonism	75	61	0.003	Antagonism
L-sweeps + Torsion weeders	69	64	0.178	Additive	71	65	0.419	Additive
Preci-discs + Finger weeders	64	50	0.066	Additive	48	51	0.480	Additive
Preci-discs + Harrows	62	44	0.009	Antagonism	64	57	0.053	Antagonism
Torsion weeders + Harrows	59	53	0.060	Additive	67	58	0.161	Additive
Torsion weeders + L-sweeps	69	62	0.087	Additive	71	56	0.101	Additive
L-sweeps + Harrows + Torsion weeders	80	68	0.007	Antagonism	87	69	0.026	Antagonism
Preci-discs + Finger weeders + Harrows	76	42	<0.001	Antagonism	73	53	0.065	Additive
Preci-discs + Harrows + Torsion weeders	75	56	0.004	Antagonism	81	57	0.003	Antagonism

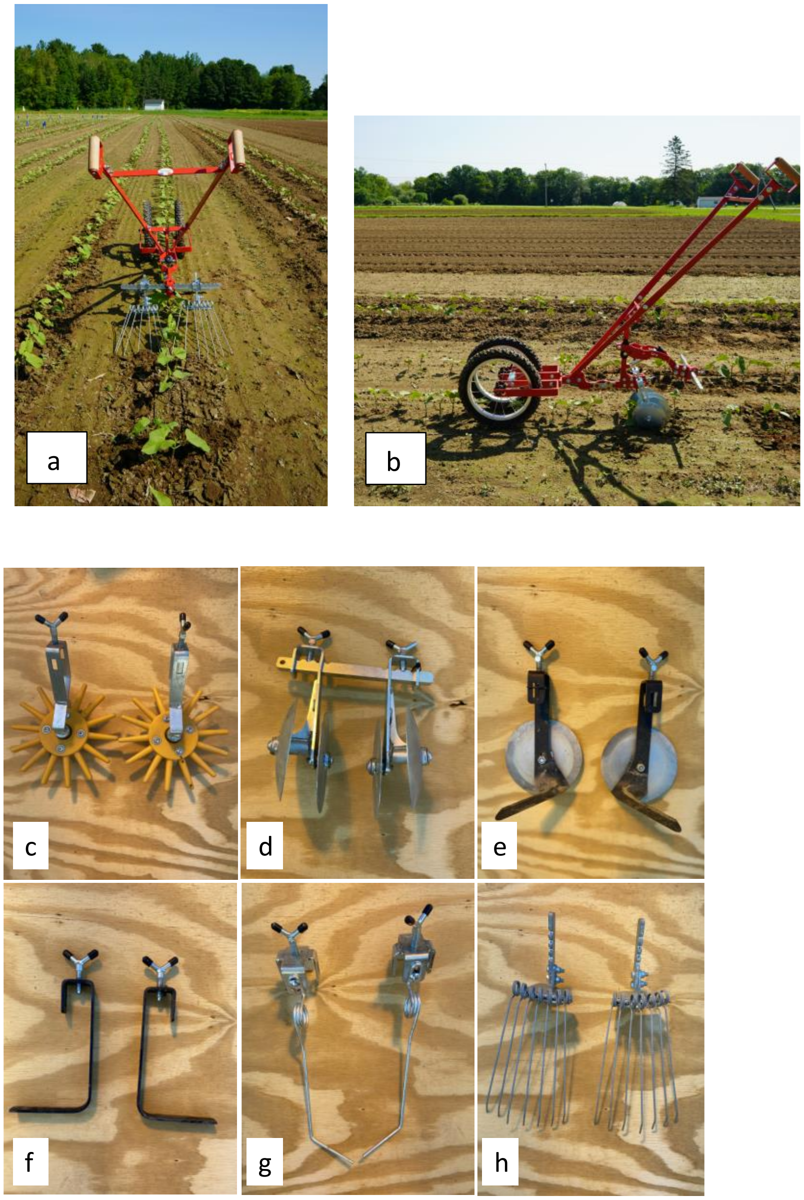
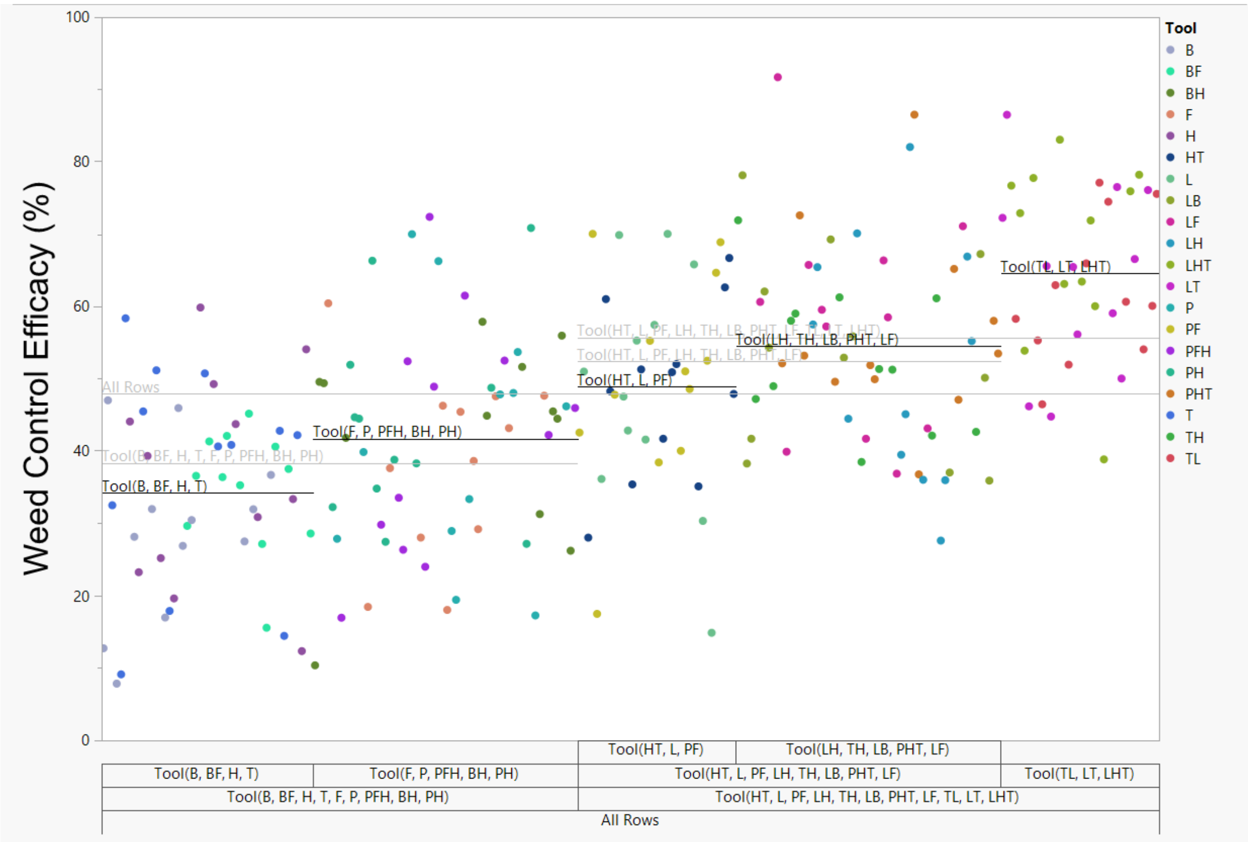


Figure 3. 1. The Terrateck Double Wheel Hoe and individual tools tested in field experiments in bush bean and table beet. a) Top view, with tine harrows; b) Side view, with biodiscs; c) Finger weeders, d) Biodiscs, e) Preci-discs, f) L-sweeps, g) Torsion weeders, and h) Tine harrows.



Tool	Abbreviation
Biodiscs	B
Finger weeders	F
Harrows	H
L-sweeps	L
Preci-discs	P
Torsion weeders	T

Figure 3. 2. Regression tree of weed control total efficacy (%) across crops and years, split by highest mean and lowest standard deviation.

CHAPTER 4

CARROT CULTIVARS ARE SIMILAR IN THEIR EARLY GROWTH TRAITS AND CULTIVATION TOLERANCE DESPITE DIFFERENCES IN MID- TO LATE-SEASON SIZE CATEGORIES

Abstract

Managing weeds in small-seeded organic vegetable crops can be challenging and costly. In organic carrot (*Daucus* carota L.), slow crop emergence and small seedling size leads to poor competitive ability against weeds and high mortality from cultivation, resulting in loss of crop yield and quality. Carrot breeding efforts for organic systems have worked to increase shoot growth to improve competition with weeds, but traits that confer tolerance to cultivation would also benefit organic carrot growers, allowing them to use more aggressive and effective cultivation. We selected nine carrot cultivars representing genotypes known to be large, average, and relatively small plants when mature. Over two years of greenhouse and field experiments we measured cultivar early growth characteristics and their responses to cultivation. Growth characteristics included shoot height, leaf area and mass, as well as root area and mass, root tips and forks, and anchorage force. In the field, cultivars were subject to either hand-weeding or cultivation with finger weeders or tine harrows, chosen to test effects of tools that differ in their uprooting and burial weed control mechanisms. Crop mortality, weed control efficacy, and marketable yield were measured. Cultivars had similar root and shoot mass at two-true leaves, but differed in their root and shoot morphology, including number of root tips and forks, and shoot height and area. Maximum anchorage force was unexpectedly not different between cultivars. Average anchorage force was different at two-true leaves but did not show a clear relationship to cultivar growth category and also had poor correlation with root mass. In the field, crop mortality was not different between cultivars for either the finger weeder or tine harrow, but mortality from tine harrows was greater than that from finger weeders suggesting that carrots may tolerate tools that act primarily by uprooting better than burial. Yields were inconsistent over the two-year study. Cultivars considered to be in our "small" category had lower marketable yield in year one but not year two. Despite some differences between cultivar early growth characteristics at two-true leaves, cultivar mortality differences were not detected in the field at the same growth stage. Current carrot cultivars are similar in their cultivation tolerance at the second true-leaf stage; therefore, management should focus on cultivation tool optimization and ecologically based weed seedbank management to permit more aggressive cultivation thereby increasing weed control efficacy.

Introduction

In organic vegetable systems, weed management continues to be a significant production challenge (Jerkins and Ory 2016). This is particularly true in organic carrot (*Daucus carota* L.) which is slow to emerge and grow, leading to a size disadvantage relative to fast-growing annual weeds (Colquhoun et al. 2017), poor competitive ability against weeds, and loss of both crop yield and quality. Goals to improve weed control in organic carrot systems include decreasing crop damage from cultivation and identifying crop traits that confer cultivation tolerance (Liebman and Davis 2009).

Cultivation, or physical weed control (PWC), remains a widely-used practice in organic vegetable production to prevent crop yield loss to weeds, but its effectiveness can be low and variable (Gallandt 2014). Cultivating close to the crop row can help reduce hand-weeding labor requirements; however, tools targeting the intra-row zone often have poor selectivity, i.e., the ability to kill weeds, but not the crop (Ascard and Mattsson 1994; Melander et al. 2005). In carrot, cultivation tool choice and tool “stacking” can lead to differences in crop mortality and weed control efficacy. Stacking refers to using more than one cultivation tool at the same time or in a subsequent tractor pass (Brown and Gallandt 2018). In slow to emerge crops like carrots, there is often a tradeoff between crop survival and weed control. Finger weeders resulted in the best carrot survival at one-true leaf, but lower weed control (Hitchcock-Tilton 2017). When stacking finger weeders and hilling discs, carrot stands were reduced from the combination of uprooting and hilling mechanisms, resulting in 32% crop mortality. However, the finger weeder and hilling discs provided significantly greater weed control efficacy than finger weeders alone, with an average efficacy of 72% (Hitchcock-Tilton 2017).

Cultivation selectivity could be improved by choosing cultivars which exhibit greater tolerance to cultivation and therefore lower crop mortality. For example, increased carrot root length and area are traits could help increase selectivity due to greater root anchorage in the soil (Fogelberg and Gustavsson 1998). In other crops, improved crop competitiveness was positively correlated with large seed size, taller plants, and greater leaf area (Mohler 2001). Selection of carrot cultivars with these traits could help achieve greater selectivity by decreasing mortality from cultivation, with more aggressive tool settings providing increased efficacy. Improving selectivity would reduce the time needed to hand weed after cultivation and increase crop yield and quality.

In this study we evaluated nine carrot cultivars, selected to represent large, average, and small carrot root and shoot growth morphology, in both field and greenhouse experiments over two years. Objectives included: (1) analyze carrot root and shoot mass, architecture, and root anchorage force in the greenhouse and lab; (2) examine carrot mortality, weed control efficacy, and carrot yield resulting from cultivation with select tools in the field; and (3) determine whether early growth traits correlate with crop mortality from cultivation to serve as a proxy for cultivar “cultivation tolerance.” We hypothesized that: cultivars with larger root mass and anchorage force would exhibit higher cultivation tolerance to tools that act primarily by uprooting due to greater anchorage in the soil. Furthermore, cultivars with larger shoot mass would have greater cultivation tolerance to hilling tools that move soil and bury plants.

Materials and Methods

Site Descriptions

Carrot early growth characteristics were assessed in greenhouse experiments at the University of Maine Roger Clapp Greenhouse in Orono, Maine (44°55′N, 68°40′W). Field experiments were conducted at the University of Maine Rogers Farm in Old Town, Maine (44°55′N, 68°41′W), residing in USDA Plant Hardiness Zone 4b, with an average annual high/low temperature of 20/-7°C, and average annual precipitation of 1,023 mm. The soil at the site is comprised of Nicholville fine sandy loam.

Greenhouse Growth Experiments

Seven commercial carrot cultivars were analyzed in 2019 to determine which cultivars and variables to assess in subsequent studies. With the assistance of carrot breeders, Drs. John Navazio and Phil Simon, we selected nine cultivars in 2020 (Table 4.1) based on their mid- to late-season root and shoot growth. Our goal was to include cultivars representing the spectrum of carrot growth profiles ranging from small to large roots and shoots. Cultivars were arranged in the greenhouse in a randomized complete block design with six replications. Average seed mass was determined for each cultivar prior to sowing. Seeds were passed through a sieve before sowing so that seed size would be relatively uniform across cultivars to reduce variability. Seeds were sown to a depth of 0.63cm in ConeTainers (Stuewe & Sons, Inc., Tangent, OR) filled with coarse pool sand and watered as necessary. Sand was selected as the growing media because it washes off roots easily, making root scans clearer and free of soil clods and organic matter. Cones were fertilized three times per week with Peter's Professional 20-20-20 general purpose fertilizer to avoid nutrient stress in the sand media. Cone location within a rack was randomly selected for each cultivar and growth stage and labeled appropriately. To minimize effects of temperature and air movement gradients within the greenhouse, racks were rotated one turn clockwise every week within each replicate. Three growth stages were tested: one-, two-, and four-true leaves. Two plants were seeded for each harvest date, one for anchorage force testing and one for destructive harvest and analysis of early growth characteristics, described in detail below.

Greenhouse Data Collection

Prior to sowing, seed weight was determined by weighing four samples each of 25 seeds to get a representative seed weight for each cultivar. At each harvest date, plant shoot height was recorded, and plants were removed from cones, carefully washed, and placed in a tray for scanning using a WinRHIZO™ system (Regent Instruments, Québec, Canada) to quantify root and shoot area. Roots and shoots were separated, dried at 65ºC for at least three days in a lab drying oven, and weighed. Additional plants were subjected to anchorage force testing using an Alluris® FMI-B150 Force Gauge (Alluris GmbH & Co., Germany). A metal clip was attached to the carrot stem at the soil level and attached to the force gauge. Plants were pulled straight up, while continuously recording force at the clip, until all roots had been removed from the soil

(Figure 4.1). The maximum and average force (Newtons) required to remove a plant from the soil were recorded.

Field Experiments

Carrot cultivars' tolerance to cultivation was assessed in field experiments in a 6 x 3 factorial, completely random design with four replications. Fertility was supplied based on soil test results using OMRI-approved materials. A phosphate deficiency was detected in year one (2020), and bone char (FedCo Seeds, Clinton, ME, USA) was applied at 200 kg ha^{-1} plant-available phosphorus. Nutri-wave™ 4-3-2 (Northeast Agricultural Sales, Inc., Detroit, ME, USA) granular fertilizer was applied prior to planting in both years at 50 kg ha^{-1} plant-available nitrogen. Pre-plant fertilizer was incorporated with a Perfecta® field cultivator. Feathermeal was sidedressed by hand at 33 kg ha^{-1} plant-available nitrogen four and six weeks after planting to meet N requirements. N applications were split to prevent carrot root forking.

Treatments consisted of six cultivars (Table 4.1) and three weed control treatments; finger weeder, tine harrow, and a hand-weeded, weed-free control. After pre-plant fertilizer application and seedbed preparation, soil was firmed with a cultipacker. Carrots were sown using a Jang six-row tractor-mounted seeder using recommended seed rollers and calibrations. Plots (3 m x 0.5 m) consisted of two rows of carrots on 50-cm rows sown at a depth of 0.63cm with 1.2cm in-row spacing. Six days after planting in both years, prior to crop emergence, all carrot beds were flame-weeded using a Pyroweeder® (Farmers Friend, Williamsport, TN). The flame weeder was centered over each bed and operated at 20 psi at a speed of 1.6 km h^{-1}, with burners adjusted to a 45° angle. Carrot stands were thinned at the cotyledon growth stage to a 2.5cm intra-row spacing.

When carrots reached the two to three true-leaf stage, they were subject to physical weed control by either the finger weeder or tine-harrow. Cultivars Bolero, Yellowstone, and Dragon were cultivated four weeks after planting, while cultivars SFF, NB8483, and NB8524 were cultivated five weeks after planting due to their slower emergence. Finger weeders (HAK Schoffeltechniek, Bleiswijk, Holland) were selected to represent a tool that acts primarily with an uprooting mode of action and were belly-mounted on a HAK cultivating tractor. Fingers were adjusted to touch tip-to-tip and operated at 3.2 km h^{-1}. A tine harrow (Tiny Treffler, Man@Machine, Grijpskerke, Netherlands) was selected to represent a tool that acts primarily with a burial mode of action. Tines were adjusted to a 62˚ angle relative to the soil and operated at a forward speed of 3.2 km h^{-1}.

Rainfall was supplemented with irrigation to provide 2.5 cm of precipitation per week. Raintowers (Irrigation King, Tualatin, OR) were centered at each replication and sprinkler heads adjusted to cover the entire replication. Soil moisture was measured the day of cultivation to assess the uniformity of precipitation across the experimental area. Three random measurements were made in each plot to a depth of 10 cm using a Delta-T HH2 Moisture Meter equipped with a Theta Probe (Delta-T Devices, Burwell, United Kingdom). Soil moisture data were non-significant across all treatments; therefore, data are not presented.

Field Data Collection

Prior to cultivation, carrot density was measured in the central 2.4 m of each row in each plot. Ambient weed density was also measured within the 10-cm intra-row zone centered on the crop row in each 2.4 m section. Approximately 24 h after cultivation, crop and ambient weed densities were again measured to assess post-cultivation effects.

Weed-free control treatments were hand-weeded every 10-14 d using stirrup hoes and hand pulling. The time to hand weed was recorded for each plot. In plots receiving cultivation treatments, timed hand-weeding was performed once 14 days after cultivation using the same method described above to give an estimate of labor requirements following a cultivation event.

Cultivar categories were harvested as they reached maturity. All carrots in each of the two rows were harvested by hand using a broad fork, briefly washed to remove soil, and separated into “marketable” and “unmarketable” based on USDA grading standards. Within each category the number of carrots was recorded, total weight determined, and root weight after removing shoots.

Statistical Analysis

Early growth characteristics and anchorage force were analyzed using goodness-of-fit Shapiro-Wilk tests and analysis of variance in JMP 16.0 (SAS Institute Inc., Cary, NC, USA). Cultivar, growth stage, and their interaction were tested, and year and block were used as random effects. Based on ANOVA results, Tukey-Kramer mean separations were performed at $\alpha = 0.05$.

Crop mortality, weed control efficacy, hand weeding time, and crop yield were analyzed using goodness-of-fit Shapiro-Wilk tests and analysis of variance in JMP 16.0. Cultivar, weed treatment, and their interaction were tested. Tukey-Kramer mean separations were performed at $\alpha = 0.05$. Orthogonal contrasts of cultivar category were performed to test responses to weed control treatments. Correlation analyses were also performed between early growth characteristics from the greenhouse and field trial response variables.

Results and Discussion

Early Growth Characteristics – Root and Shoot Mass

Root mass was surprisingly not different between cultivars at two-true leaves when cultivation occurred (Table 4.2, Table 4.3), and did not increase until four-true leaves (Figure 4.2). Mass was different between years at two-true leaves, averaging 3.1 mg (±0.3) and 7.2 mg (±0.5) across cultivars in 2020 and 2021, respectively. Root mass was highly correlated with the number of root tips and forks, indicating that factors such as root diameter (thickness) may vary between cultivars.

Shoot mass was also unexpectedly not different between cultivars at two-true leaves at the time carrots were cultivated (Table 4.2) and did not increase until four-true leaves (Figure 4.2). Shoot mass averaged 9.1 mg (±0.7) and 7.7 mg (±0.7) across cultivars in 2020 and 2021, respectively. Shoot growth characteristics such as area may not translate completely to mass. This may be due to differences in shoot morphology that contribute to mass, like shorter leaves, or leaves and stems with greater thickness, which could be important factors to consider for decreasing crop mortality from cultivation tools that act primarily by a burial mechanism. In field settings, differences in shoot mass may arise due to intra-specific competition; however, carrots in the greenhouse were grown individually to remove the effect of competition.

Early Growth Characteristics – Root Morphology

The number of root tips and forks were different between cultivars and cultivar interaction with year (Table 4.2, Table 4.3). Number of root tips was similar at the time of cultivation, but root forks were different between cultivars at two-true leaves, and both increased at four-true leaves (Figure 4.3). Ranked means of the number of root forks unexpectedly did not always correspond to designated cultivar categories, suggesting that other factors can influence root branching, such as the growing media or cultivar uptake and response to fertilization.

In other crops, seed mass can influence early growth characteristics. In canola, wheat, and sunflower, greater seed mass can result in quicker emergence, taller and thicker shoots, and greater early-season crop biomass and may be attributed, in part, to greater nutrient reserves (Ambika et al. 2014; Harker et al. 2015). Although seeds in this study were sieved to achieve uniformity, seed mass could be an important factor in future breeding efforts (Simon 2010). Embryo length may also be important, as greater embryo length results in quicker seedling emergence (Gray and Steckel 1983). Breeding for this trait could shorten carrot emergence time, thereby increasing competitive ability with weeds and allowing farmers to cultivate earlier.

Early Growth Characteristics – Shoot Morphology

Shoot height was different between cultivars at two-true leaves when carrots were cultivated in the field (Figure 4.4). At two-true leaves, cultivars in the “large” category (Bolero, Red Core Chantenay, Yellowstone) had similar shoot height to each other, but surprisingly did not have greater shoot height than some cultivars in the “average” and “small” categories (Figure 4.4). Contrasts of cultivar category were examined and found to be non-significant (data not shown). Genetic variability of shoot height can exist within carrot cultivars (Turner et al. 2018) and can also be influenced by the angle at which the petiole grows (Benjamin 1984), although this angle was not measured in our study. Shoots that prioritize height earlier in the season may be a desirable trait to select for to permit earlier and more aggressive cultivation with tools that throw soil and bury plants.

Shoot area was different between cultivars at two-true leaves (Table 4.2, Figure 4.4). At two-true leaves, when carrots were cultivated in the field, shoot area tended to be higher for cultivars in the “large” category, but cultivars in the “small” category, such as Mokum and NB8524, had comparable shoot area to Bolero and Red Core Chantenay at the second true-leaf (Figure 4.4). In crops such as potato and soybean, greater leaf area has shown increased crop competitiveness with weeds (Mohler, 2001). However, in carrots, selection of cultivars with greater shoot area may not be as important as previously thought for tools that act by a burial mechanism.

Anchorage Force

Average anchorage force was different between cultivars at two-true leaves but not different between years (Table 4.2). At two-true leaves, Bolero had higher average anchorage force, while NB8483 and SFF had a lower average anchorage force (Figure 4.5), but contrasts of cultivar category were found to be non-significant (data not shown). Further examination found that root area, tips, and forks were highly correlated with one another, but these variables showed weak (<0.20) correlations with anchorage force. While root morphology does play a role in anchorage force, other factors can influence anchorage force such as the growing media and soil moisture (Ennos 1990), and potentially the environmental conditions at the time of data collection (i.e., daily temperature and humidity fluctuations).

Cultivar Mortality From Cultivation

Despite carrot cultivar differences in root branching, anchorage force, and shoot morphology at two-true leaves, and contrary to our hypothesis motivating this work, mortality from cultivation was not different between carrot cultivars in either year (Table 4.4, Table 4.5), suggesting that early growth characteristic differences at two-true leaves may not be as important for cultivation tolerance as previously thought. Carrot mortality from cultivation was affected by the interaction of year, cultivar, and weed control treatment, but this was largely driven by year-to-year variability (Table 4.5). Mortality from finger weeders was not different between years, averaging 9% (±1) and 10% (±1) across cultivars in 2020 and 2021, respectively (Table 4.5). Mortality from tine harrows was higher in 2020 compared to 2021. Carrot mortality averaged 21% (±2) and 9% (±1) across cultivars in 2020 and 2021, respectively (Table 4.5). Mortality from tine harrows was greater than finger weeders in 2020 but was similar between the two cultivation tools in 2021. In comparison, Hitchcock-Tilton (2017) observed an average mortality of 16% from finger weeders and 17% from flextine harrows; however, the author notes evidence that carrot mortality of 10% can result in yield losses of 5-9% due to carrot density loss. Crop mortality of 10% or less is generally acceptable, supporting the aggressiveness of the tools used in our study.

Weed Control Efficacy and Selectivity

Intra-row weed control efficacy was different between cultivars, and also between years for certain cultivars and between years for weed control treatments (Table 4.4). Efficacy was higher in 2020 compared to 2021 for both finger weeders and tine harrows (Table 4.5), which may be attributed to the heavy rain following cultivation in 2021 that could have resulted in increased weed survival. Plots with Bolero, Yellowstone, and Dragon had comparable efficacy to each other, and higher efficacy compared to SFF, NB8483, and NB8524 (Table 4.5). This may be partially due to differences in cultivation timing, which would have affected weed size at cultivation. All cultivars were hand weeded at the cotyledon stage, but SFF, NB8483, and NB8524 were cultivated approximately one week later than the other cultivars due to their slower growth. While the timing of cultivation was appropriate for the carrot growth stage, weeds were likely larger, resulting in reduced efficacy. At the time of cultivation (two-true leaves), few differences in early growth characteristics were detected, which is a departure from Colquhoun et al. (2017) who observed quicker canopy development and larger shoots in Bolero compared to SFF. Factors other than crop competition due to morphological traits may influence efficacy, such as the present weed species and their growth traits; for example, weed species that have high leaf area or who grow by rhizomes.

Selectivity, calculated as percent crop survival divided by percent weed survival, showed a similar trend to efficacy, where selectivity was different between cultivars and cultivar interaction with year (Table 4.4). Bolero, Yellowstone, and Dragon had comparable selectivity to each other, and higher selectivity than SFF, NB8483, and NB8524 in both years (Table 4.5). Selectivity did not differ between finger weeders and tine harrows (p=0.201). Selectivity averaged 3.20 in 2020 and 2.25 in 2021 across Bolero, Yellowstone, and Dragon, showing a decrease in efficacy between years. Selectivity averaged 1.47 in 2020 and 1.68 in 2021 across SFF, NB8483, and NB8524. Cultivar traits that would confer greater tolerance to cultivation may not be larger roots and shoots, as shown by few differences in early growth characteristics despite differences in efficacy and selectivity. Examining different traits, such as root length and width, petiole angle, or embryo length may provide more insight into improving selectivity. Varying tool choice and aggressiveness may also help improve efficacy and selectivity given the lack of cultivar differences at the time of cultivation.

Hand-Weeding Time

Total time spent hand weeding was different between weed control treatments but unexpectedly was not different between cultivars despite differences in efficacy and selectivity

(Table 4.4). Hand-weeding time was higher in 2021 compared to 2020 (Table 4.5), likely caused by heavy rainfall in 2021 that delayed hand weeding, resulting in larger weeds that took more time to remove. In both years, time to hand weed averaged 240 h ha^{-1} (±13) in the hand-weeded control and was higher than the finger weeder and tine harrow treatments, which was expected due to the number of hand weeding events that took place in the control treatment to keep it weed-free. Hand-weeding time was not different between the finger weeder and tine harrow treatments in both years (Table 4.5). The finger weeder and tine harrow treatments reduced hand-weeding time by 36% across years compared to hand-weeding only. Labor requirements for the hand-weeded control are consistent with those of Sørensen et al. (2005) and Van Der Weide et al. (2008), who reported average hand-weeding time for carrots to be 100-300 h ha^{-1}, and tools like finger weeders or torsion weeders can reduce hand-weeding labor by 40-70% (Bleeker et al. 2002; Van Der Weide et al. 2008).

Cultivar Yield

Marketable root fresh weight was different between cultivars in 2020 but not in 2021, and also higher across cultivars in 2020 compared to 2021 (Table 4.4, Table 4.6). Marketable shoot fresh weight was different across cultivars, but not years or weed control treatments (Table 4.4, Table 4.6). Root and shoot fresh weight ranked means did not show a direct relationship with cultivar category. This suggests that yield differences may be attributed to several factors other than larger roots and shoots, such as cultivar responses to fertilization, precipitation, and weed competition.

Due to the unexpected differences in marketable root yield between cultivars in 2020, we hypothesized that cultivars may show biomass losses to cultivation earlier in the season but grow out of this injury by harvest. To test this, we planted a second plot for each cultivar and weed control treatment in 2021 where we measured carrot root and shoot dry biomass 14 days post-cultivation. However, no differences between cultivars, weed control treatments, or their interaction were detected for either root or shoot biomass (data not shown). Root area and number of root tips and forks were positively correlated with carrot marketable yield, suggesting that these traits are important for early season growth so that yield will not suffer even if some root damage occurs during cultivation.

Conclusions

For many of the early growth characteristics measured in this study, differences between cultivars were not detected until after the second true-leaf stage, and often these differences did not match predetermined cultivar categories and showed that high variability can exist both within cultivars and across years. Early growth characteristics that could aid in cultivation tolerance, thereby contributing to reduced mortality and greater selectivity, may not always be the biggest roots and shoots. For cultivation tools that primarily act by uprooting, breeding efforts could focus on selecting for cultivars that have smaller, but many roots (i.e., high degree of root branching) to increase crop anchorage force at earlier growth stages. For cultivation tools that primarily act by burial, selecting for cultivars with thicker shoots at earlier growth stages may aid in greater resistance to burial when carrots are still small. Selecting for traits at earlier growth stages may also permit cultivation prior to two-true leaves, which may aid in reduced hand-weeding labor. While carrot mortality was greater from tine harrows compared to finger weeders, unexpectedly, no differences between cultivars were detected. Contrary to this, cultivars in the “large” category, as well as Dragon, resulted in greater intra-row weed control efficacy and selectivity despite few differences in early growth characteristics that may have influenced crop competitive ability; however, this was likely due to differences in cultivation timing, which could affect cultivar selection. Total hand-weeding time was also surprisingly not different between cultivars, even though most early growth characteristic differences were not detected until later growth stages when additional post-cultivation hand weeding was performed. Differences in marketable yield were not consistent with predetermined cultivar growth categories and also varied by year, pointing to differences in cultivar responses to other factors, such as fertilization and environmental conditions. Future work could focus on exploiting cultivation tool selection rather than cultivar choice, selecting additional tools and tool settings to determine if cultivar cultivation tolerance can be improved in this manner.

Table 4. 1. Selected carrot cultivars, assigned by size category, and respective suppliers for greenhouse and field trials.

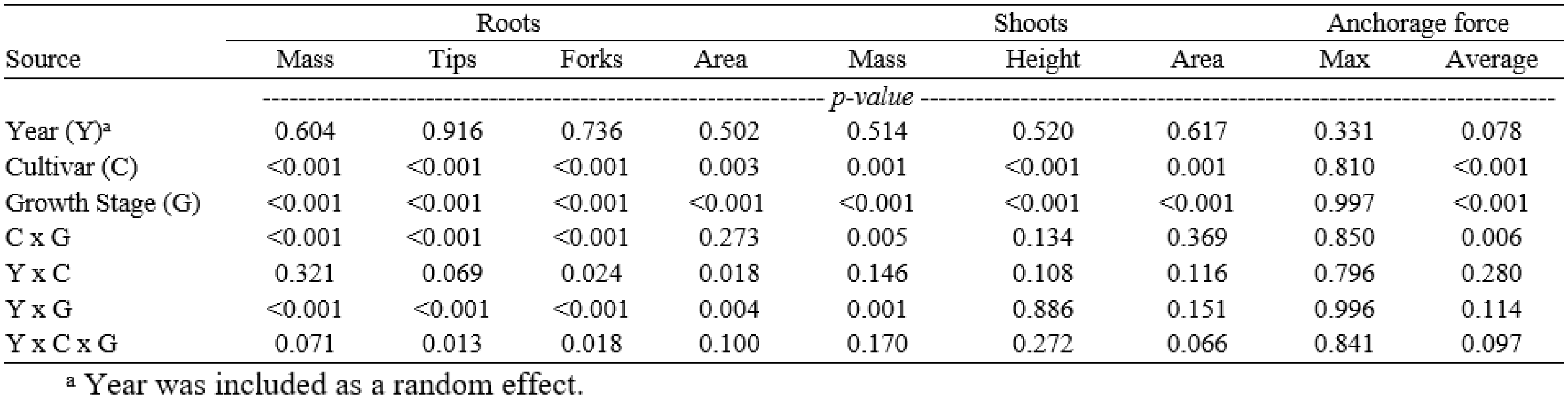
Category[a]	Cultivar	Supplier	Greenhouse Experiments	Field Experiments
Large	Bolero	Johnny’s Selected Seeds	Yes	Yes
Large	Red Cored Chantenay	John Navazio[b]	Yes	No
Large	Yellowstone	Johnny’s Selected Seeds	Yes	Yes
Average	Dragon	John Navazio	Yes	Yes
Average	Napoli	Johnny’s Selected Seeds	Yes	No
Average	SFF	Phil Simon[c]	Yes	Yes
Small	Mokum	Johnny’s Selected Seeds	Yes	No
Small	NB 8483	Phil Simon	Yes	Yes
Small	NB 8524	Phil Simon	Yes	Yes

[a] Category represents breeders’ expert opinions regarding root and shoot sizes.

[b] Carrot breeder, Johnny’s Selected Seeds

[c] Carrot breeder, University of Wisconsin-Madison

Table 4. 2. Effects of year, cultivar, growth stage, and their interactions on carrot early growth characteristics.



	Roots				Shoots			Anchorage force	
Source	Mass	Tips	Forks	Area	Mass	Height	Area	Max	Average
					p-value				
Year (Y)[a]	0.604	0.916	0.736	0.502	0.514	0.520	0.617	0.331	0.078
Cultivar (C)	<0.001	<0.001	<0.001	0.003	0.001	<0.001	0.001	0.810	<0.001
Growth Stage (G)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.997	<0.001
C x G	<0.001	<0.001	<0.001	0.273	0.005	0.134	0.369	0.850	0.006
Y x C	0.321	0.069	0.024	0.018	0.146	0.108	0.116	0.796	0.280
Y x G	<0.001	<0.001	<0.001	0.004	0.001	0.886	0.151	0.996	0.114
Y x C x G	0.071	0.013	0.018	0.100	0.170	0.272	0.066	0.841	0.097

[a] Year was included as a random effect.

Table 4. 3. Mean (±SE) root mass, tips, forks, and area at two-true leaves, and main effects of year, growth stage, and cultivar. [a]

Category	Cultivar	Root mass		Root tips		Root forks		Root area	
		2020	2021	2020	2021	2020	2021	2020	2021
		--------- *mg* ---------		------------------------ *No.* ------------------------				-------- *cm*^{2} --------	
Large	Bolero	3±1	9±1	36±15 b	85±28	66±44 b	216±96 ab	7±1	8±1
Large	Red Core Chantenay	2±1	7±1	20±10 c	125±7	61±10 ab	259±20 ab	6±1	7±1
Large	Yellowstone	2±1	6±1	50±17 a	81±16	108±54 a	200±48 ab	4±1	9±1
Average	Dragon	3±1	7±2	50±20 a	110±25	146±64 a	353±152 a	5±1	7±1
Average	Napoli	3±1	8±1	55±15 a	105±29	112±30 a	352±113 a	5±1	9±1
Average	SFF	4±1	9±2	45±8 ab	65±11	98±26 ab	149±10 b	4±1	6±1
Small	Mokum	3±1	5±1	53±21 a	60±7	81±37 ab	123±12 b	6±1	8±1
Small	NB8483	2±1	5±1	31±8 bc	55±9	34±10 c	110±20 c	4±1	6±1
Small	NB8524	4±1	11±2	66±12 a	98±3	168±51 a	253±32 a	5±1	7±1
Main Effects:									
Year	2020	11±2		107±16		465±112		6±1	
	2021	10±1		111±9		314±35		8±1	
Growth Stage									
	1-leaf	4±1 B		40±2 C		77±5 C		5±1 B	
	2-leaf	5±1 B		70±5 B		164±18 B		6±1 B	
	4-leaf	25±3 A		247±22 A		998±170 A		8±1 A	
Cultivar									
	Bolero	18±5 A		160±33 A		679±243 A		7±1 A	
	Red Core Chantenay	8±2 B		130±49 A		427±214 A		7±1 A	
	Yellowstone	6±1 B		100±21 AB		310±78 AB		7±1 A	
	Dragon	10±3 AB		142±40 A		594±274 A		6±1 AB	
	Napoli	9±1 B		110±18 AB		352±72 AB		7±1 A	
	SFF	10±3 AB		53±10 C		134±32 C		5±1 B	
	Mokum	12±3 AB		122±28 AB		472±220 A		7±1 A	
	NB8483	8±2 B		61±13 C		140±50 C		5±1 B	
	NB8524	11±2 AB		94±17 B		280±75 B		6±1 AB	

[a] Within column sections, means not followed by the same letter are significantly different ($p<0.05$).

Table 4. 4. Effects of year, cultivar, weed control treatment, and their interactions on carrot mortality, intra-row weed control efficacy, selectivity ratio, hand-weeding time, and carrot marketable yield.

Source	Carrot Mortality	Intra-row Weed Control Efficacy	Selectivity Ratio[b]	Hand-Weeding Time	Marketable Root Wt.	Marketable Shoot Wt.
	--	--	*p-value*	--	--	--
Year (Y)[a]	<0.001	0.556	0.526	0.053	0.594	0.958
Cultivar (C)	0.995	<0.001	<0.001	0.352	<0.001	0.002
Weed Control (W)	<0.001	0.856	0.201	<0.001	0.067	0.386
C x W	0.287	0.710	0.117	0.493	0.322	0.987
Y x C	0.983	<0.001	0.002	0.401	0.002	0.311
Y x W	0.009	<0.001	0.303	0.388	0.137	0.669
Y x C x W	0.005	0.593	0.159	0.182	0.484	0.849

[a] Year was included as a random effect.

[b] Calculated by dividing percent crop survival by percent weed survival.

Table 4. 5. Mean (±SE) carrot mortality when cultivated at the two-true leaf stage, intra-row weed control efficacy, selectivity, hand-weeding time, and main effects of year, weed control tool, and cultivar. [a]

Category	Cultivar	Carrot Mortality (%)				Intra-row Weed Control Efficacy (%)				Selectivity Ratio [b]				Hand-Weeding Time (h ha^{-1})			
		Finger Weeder		Tine Harrow		Finger Weeder		Tine Harrow		Finger Weeder		Tine Harrow		Finger Weeder		Tine Harrow	
		2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Large	Bolero	4±2	10±3	17±4	7±3	65±6	64±2	72±9	55±8	2.98	2.52	3.75	2.25	109±4	137±20	104±6	183±65
Large	Yellowstone	11±4	8±1	36±5	6±1	78±2	59±4	78±1	51±6	4.34	2.34	2.85	2.00	97±5	157±13	125±17	177±13
Average	Dragon	14±3	14±5	20±3	13±4	62±8	63±4	69±3	55±6	2.61	2.32	2.70	2.08	111±5	178±37	104±16	188±9
Average	SFF	9±1	9±3	13±3	12±1	34±6	53±7	43±6	42±7	1.41	2.12	1.60	1.58	185±32	162±21	134±13	196±16
Small	NB8483	7±2	10±2	18±2	10±4	31±5	40±6	40±4	41±5	1.37	1.58	1.38	1.56	141±5	222±30	127±11	240±28
Small	NB8524	10±1	11±3	24±7	8±2	36±5	47±6	54±5	36±6	1.42	1.77	1.70	1.50	132±9	183±19	128±7	185±14
Main Effects:																	
Year	2020	15±2 A				55±3				2.34				125±5 B			
	2021	10±1 B				51±2				1.97				184±7 A			
Weed Control	Hand-Weeded	-				-				-				240±13 A			
	Finger Weeder	10±1 B				53±3				2.23				151±7 B			
	Tine Harrow	15±2 A				53±2				2.08				157±7 B			
Cultivar																	
	Bolero	9±2				64±3 A				2.88 A				133±12			
	Yellowstone	15±3				67±4 A				2.89 A				139±10			
	Dragon	15±2				62±3 A				2.42 A				145±14			
	SFF	11±1				43±4 B				1.68 B				169±11			
	NB8483	11±2				38±2 B				1.47 B				182±16			
	NB8524	13±2				43±3 B				1.59 B				157±9			

[a] Within column sections, means not followed by the same letter are significantly different ($p<0.05$).

[b] Calculated by dividing percent crop survival by percent weed survival.

Table 4. 6. Mean (±SE) carrot marketable root and shoot yield, and main effects of year, weed control tool, and cultivar. [a]

Category	Cultivar	Marketable Root Fresh Wt.				Marketable Shoot Fresh Wt.			
		Finger Weeder		Tine Harrow		Finger Weeder		Tine Harrow	
		2020	2021	2020	2021	2020	2021	2020	2021
		Mg ha^{-1}							
Large	Bolero	17±1	6±1	12±2	6±2	4±1	6±2	5±1	3±1
Large	Yellowstone	10±1	8±2	7±2	8±1	7±1	7±1	5±2	6±2
Average	Dragon	16±2	9±2	17±3	7±2	7±1	8±2	7±2	5±2
Average	SFF	8±3	9±1	10±1	7±1	2±1	5±2	2±1	4±1
Small	NB8483	11±1	8±1	7±1	4±1	2±1	4±1	2±1	2±1
Small	NB8524	4±1	7±2	3±1	5±1	2±1	4±2	2±1	4±2
Main Effects:									
Year	2020	10±1				4±2			
	2021	8±1				5±1			
Weed Control									
	Hand-Weeding	9±1				5±1			
	Finger Weeder	9±1				5±1			
	Tine Harrow	8±1				4±1			
Cultivar									
	Bolero	10±1 A				5±1 ABC			
	Yellowstone	11±1 A				7±1 AB			
	Dragon	13±1 AB				8±1 A			
	SFF	9±1 AB				3±1 BC			
	NB8483	8±1 AB				3±1 BC			
	NB8524	5±1 B				2±1 C			

[a] Within column sections, means not followed by the same letter are significantly different ($p<0.05$).

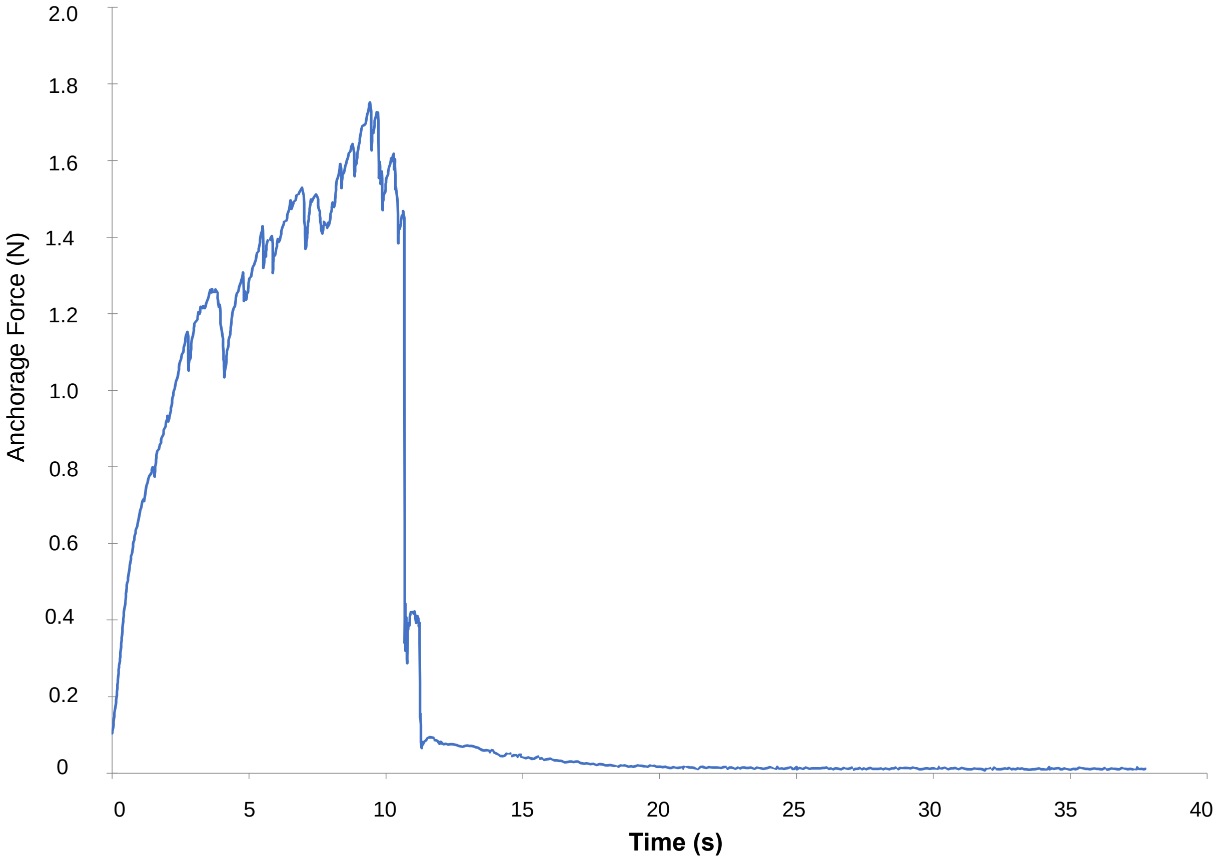


Figure 4. 1. Anchorage force profile of a two-true leaf Bolero seedling as it is uprooted. Force tended to increase until primary roots broke; a sharp decline is then observed.

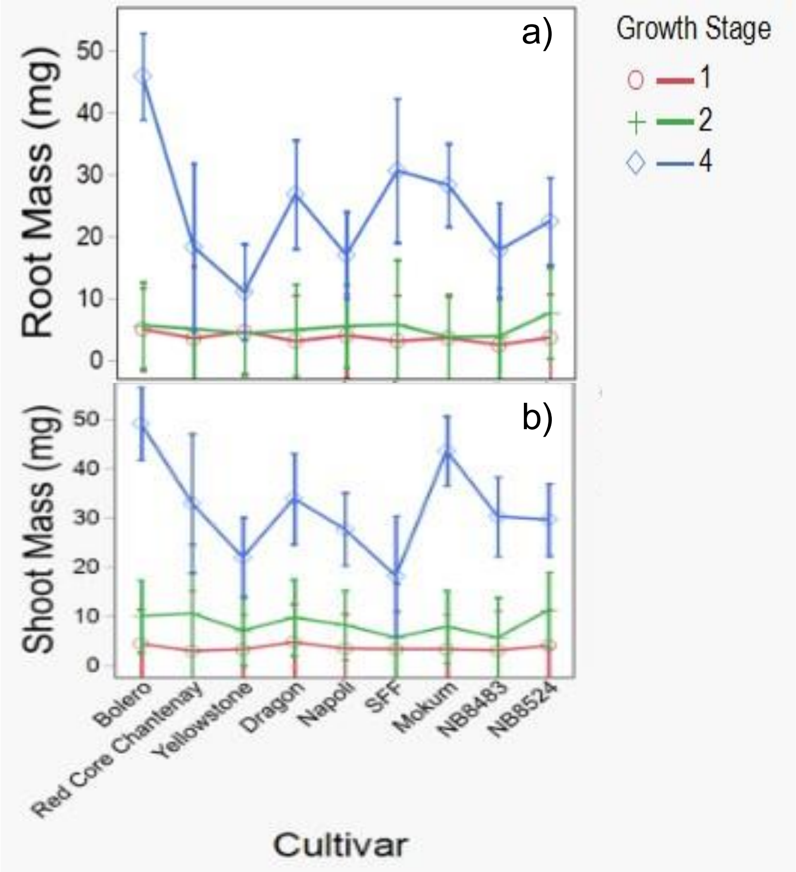


Figure 4. 2. Root mass (a) and shoot mass (b) by carrot cultivar and growth stage. Data were pooled across years. Error bars represent standard error of the mean.

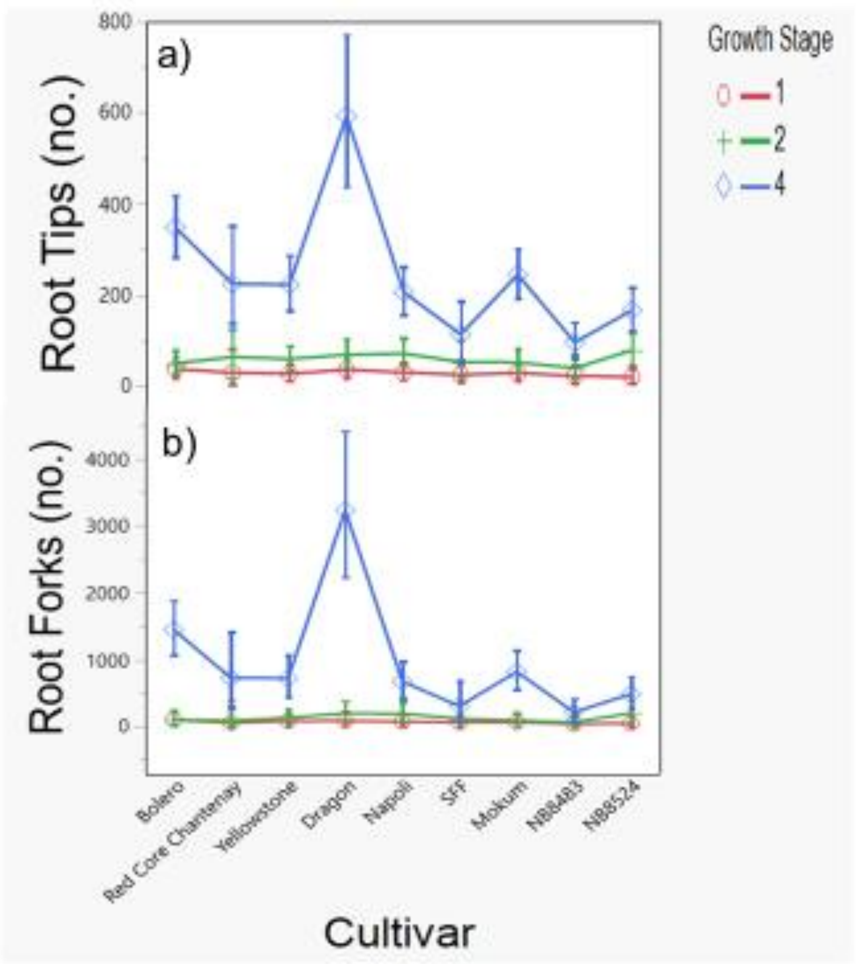


Figure 4. 3. Number of root tips (a) and root forks (b) by carrot cultivar and growth stage. Data were pooled across years. Error bars represent standard error of the mean.

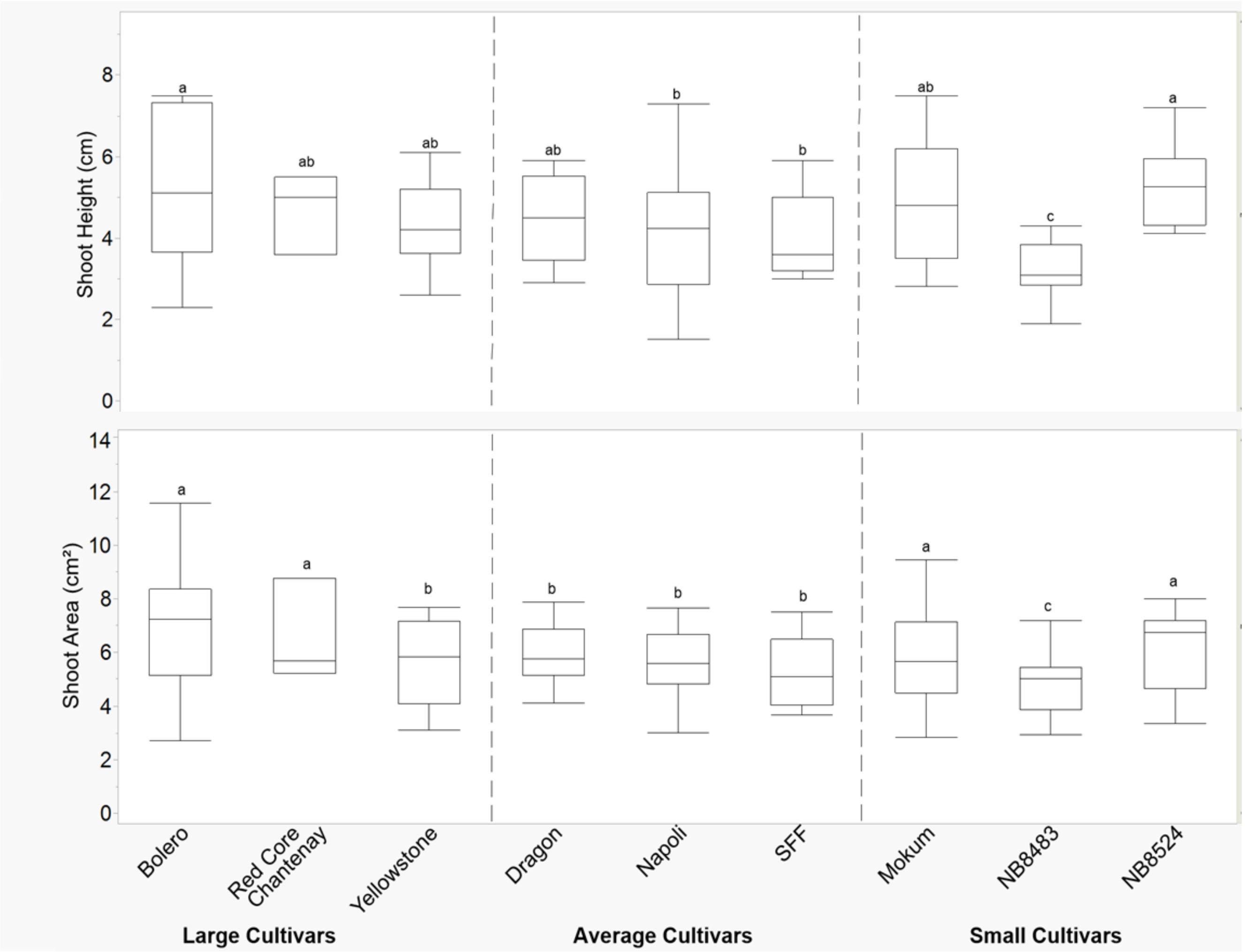


Figure 4. 4. Shoot height (cm) and shoot area (cm^2) by carrot cultivar at two-true leaves. Data were pooled across years. Error bars represent standard error of the mean. Different letters indicate significant differences in the main effect of cultivar at α=0.05.

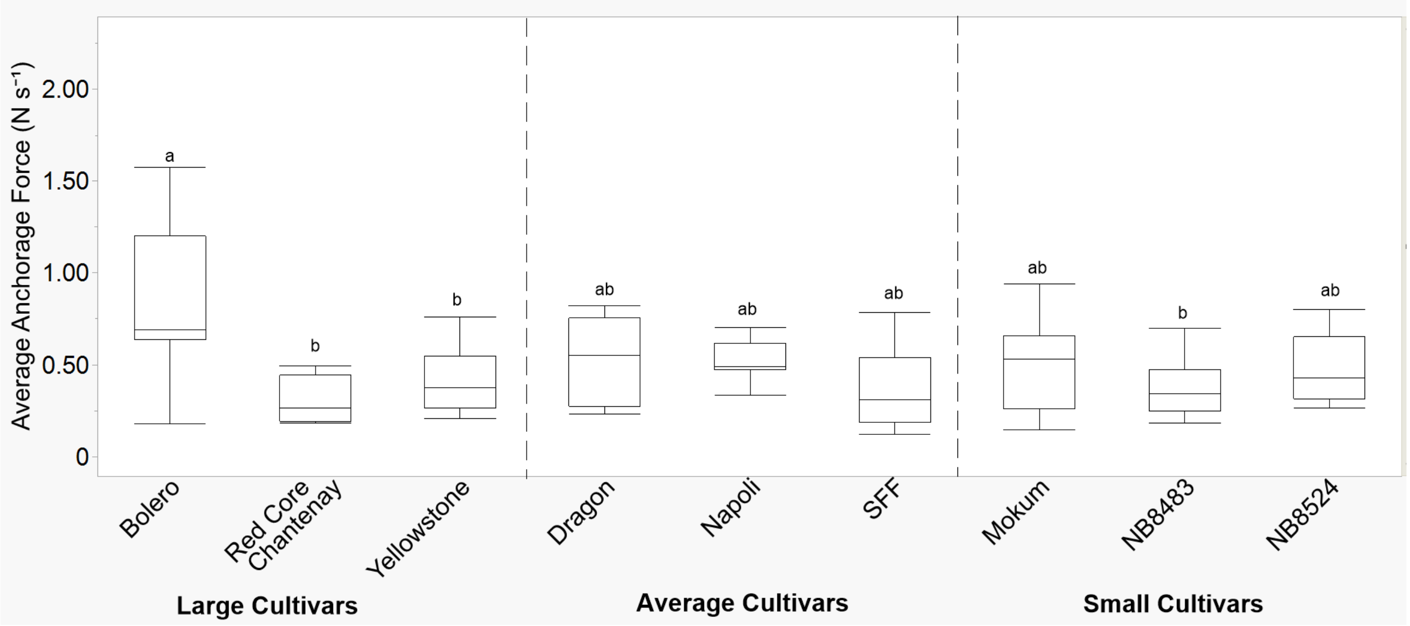


Figure 4. 5. Average anchorage force (N s^{-1}) by carrot cultivar at two-true leaves. Data were pooled across years. Error bars represent standard error of the mean. Different letters indicate significant differences in the main effect of cultivar at α=0.05.

REFERENCES

Ambika S, Manonmani V, Somasundaram G (2014) Review on effect of seed size on seedling vigor and seed yield. Res J of Seed Sci 7:31-38

Ascard J (1995) Effects of flame weeding on weed species at different developmental stages. Weed Res 35:397-411

Ascard J, Fogelberg F (2008) Mechanical in-row weed control in transplanted and direct-sown bulb onions. Biologic Agric & Hort 25:235-251

Ascard J, Mattsson B (1994) Inter-row cultivation in weed-free carrots: the effect on yield of hoeing and brush weeding. Biologic Agric & Hort 10:161-173

Barrios AN, Hoogenboom G, Nesmith DS (2005) Drought stress and the distribution of vegetative and reproductive traits of a bean cultivar. Sci Agric 62:18-22

Benjamin LR (1984) Role of foliage habit in the competition between differently sized plants in carrot crops. Ann Bot 53:549-557

Birthisel SK, Clements RS, Gallandt ER (2021) Review: how will climate change impact the ‘many little hammers’ of ecological weed management? Weed Res 61:327-341

Birthisel SK, Gallandt ER (2019) Trials evaluating solarization and tarping for improved stale seedbed preparation in the Northeast USA. Org Farm 5:38-51

Bleeker P, Van Der Weide RY, Kurstjens DAG (2002) Experiences and experiments with new intra-row weeders. In: *Proceedings, 2002 5th EWRS Workshop on Physical Weed Control*, Pisa, Italy, 97-100

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383-405

Boydston RA, Williams MM II (2015) Sweet corn hybrid tolerance to weed competition under three weed management levels. Renew Agric and Food Syst 31:281-287

Brainard SH, Ellison SL, Simon PW, Dawson JC, Goldman IL (2021) Genetic characterization of carrot root shape and size using genome-wide association analysis and genomic-estimated breeding values. Theor Appl Genet https://doi.org/10.1007/s00122-021-03988-8

Brown B, Gallandt ER (2019) To each their own: case studies of four successful, small-scale organic vegetable farmers with distinct weed management strategies. Renew Agric Food Syst 34:373-379

Brown B, Gallandt ER (2018a) Evidence of synergy with 'stacked' intrarow cultivation tools. Weed Res 58:284-291

Brown B, Gallandt ER (2018b) A systems comparison of contrasting organic weed management strategies. Weed Sci 66:109-120

Caldwell B, Mohler CL (2001) Stale seedbed practices for vegetable production. Hort Sci 36:703-705.

Chehade LA, Fontanelli M, Martelloni L, Frasconi C, Raffaelli M, Peruzzi A (2018) Effects of flame weeding on organic garlic production. Hort Tech 28:502-508

Cisneros JJ, Zandstra BH (2008) Flame weeding effects on several weed species. Weed Tech 22:290-295

Colby SR (1967) Calculating synergistic and antagonistic responses of herbicide combinations. Weeds 15:20-22

Coleman E (2018) The new organic grower. A master's manual of tools and techniques for the home and market gardener. Chelsea Green Publishing

Colquhoun JB, Bellinder RR, Kirkwyland JJ (1999) Efficacy of mechanical cultivation with and without herbicides in broccoli (*Brassica oleracea*), snap bean (*Phaseolus vulgaris*), and sweet corn (*Zea mays*). Weed Tech 13:244-252

Colquhoun JB, Rittmeyer RA, Heider DJ (2017) Tolerance and suppression of weeds varies among carrot varieties. Weed Tech 31:897-902

Cordeau S, Wayman S, Reibel C, Strbik F, Chauvel B, Guillemin JP (2018) Effects of drought on weed emergence and growth vary with the seed burial depth and presence of a cover crop. Weed Biol Manag 18:12-25

DeDecker JJ, Masiunas JB, Davis AS, Flint CG (2014) Weed management practice selection among Midwest U.S. organic growers. Weed Sci 62:520-531

Deese SD (2010) Economic analysis: weeding techniques for organic farms. https://digitalcommons.calpoly.edu/agbsp/14/. Accessed: August 23, 2021

Dessaint F, Barralis G, Caixinhas ML, Mayor JP, Recasens J, Zanin G (1996) Precision of soil seedbank sampling: how many soil cores? Weed Res 36:143-151

Dimitri C, Oberholtzer L (2009) Marketing U.S. organic foods: recent trends from farms to consumers. USDA ERS. https://www.ers.usda.gov/publications/pub-details/?pubid=44432. Accessed 18 November 2020

Diver S (2002) Flame weeding for vegetable crops. Appropriate Technology Transfer for Rural Areas. https://ucanr.edu/sites/Grown_in_Marin/files/298383.pdf. Accessed: October 22, 2021

Ennos AR (1990) The anchorage of leek seedlings: the effect of root length and soil strength. Ann Bot 65:409-416

Fennimore SA, Cutulle M (2019) Robotic weeders can improve weed control options for specialty crops. Pest Manag Sci 75:1767-1774

Fennimore SA, Slaughter DC, Siemens MC, Leon RG, Saber MN (2016) Technology for automation of weed control in specialty crops. Weed Tech 30:823-837

Fennimore SA, Tourte L (2019) Regulatory burdens on development of automated weeding machines and herbicides are different. Outlooks on Pes Management 4:147-151

Fogelberg F, Gustavsson AMD (1998) Resistance against uprooting in carrots (Daucus carota) and annual weeds: a basis for selective mechanical weed control. Weed Res 38:183-190

Forcella F (2003) Debiting the seedbank: priorities and predictions. Asp Appl Biol 69:151-162

Fortier JM (2014) The market gardener. New Society Publishers

Gallandt ER (2006) How can we target the weed seedbank? Weed Sci 54:588-596

Gallandt ER (2014) Weed management in organic farming. Pages 63-85 *in* Chauhan B, Mahajan G, eds. Recent Advances in Weed Management. New York, Springer

Gallandt ER, Birthisel SK, Brown B, McCollough M, Pickoff M (2018a) Organic farming and sustainable weed control. Pages 628-655 *in* Korres NE, Burgos NR, Duke SO, eds. Weed Control. Sustainability, Hazards, and Risks in Cropping Systems Worldwide. Florida, CRC Press

Gallandt ER, Brainard D, Brown B (2018b) Developments in physical weed control. Pages 261-283 *in* Zimdahl R, ed. Integrated Weed Management for Sustainable Agriculture. London, Burleigh Dodds Science Publishing

Gallandt ER, Liebman M, Corson S, Porter G, Ullrich S (1998) Effects of pest and soil management systems on weed dynamics in potato. Weed Sci 46:238-248

Gray D, Steckel JR (1983) Seed quality in carrots: the effects of seed crop plant density, harvest date and seed grading on seed and seedling variability. J Hort Sci 58:393-401

Grundy AC, Mead A, Burston S (2003) Modelling the emergence response of weed seeds to burial depth: interactions with seed density, weight and shape. J Appl Ecol 40:757-770

HAK L-Series. https://haknl.com/hoeing-machines/hak-l-series/?lang=en. Accessed 22 December 2020

Ham JM, Kluitenberg GJ, Lamont WJ (1993) Optical properties of plastic mulches affect the field temperature regime. J Amer Soc Hort Sci 118:188-193

Hanson J, Dismukes R, Chambers W, Greene C, Kremen A (2004) Risk and risk management in organic agriculture: views of organic farmers. Renew Agric Food Syst 19 218-227

Harker KN, O'Donovan JT, Smith EG, Johnson EN, Peng G, Willenborg CJ, Gulden RH, Mohr R, Gill KS, Grenkow LA (2015) Seed size and seeding rate effects on canola emergence, development, yield and seed weight. Can J Plant Sci 95:1-8

Hashim S, Marwat KB, Saeed M, Haroon M, Waqas M (2013) Developing a sustainable and eco-friendly weed management system using organic and inorganic mulching techniques. Pak J Bot 45:483-486

Hitchcock-Tilton SF (2018) Improving weed management in carrots with stacked in-row weeding tools and cultivation-tolerant cultivars. Master's Thesis. East Lansing, MI: Michigan State University. 138 p

Jabbour R, Zwickle S, Gallandt ER, McPhee KE, Wilson RS, Doohan D (2014) Mental models of organic weed management: comparison of New England US farmer and expert models. Renew Agric and Food Syst 29:319-333

Jerkins D, Ory J (2016) 2016 National Organic Research Agenda. Outcomes and Recommendations from the 2015 National Organic Farmer Survey and Listening Sessions, Santa Cruz, CA. p.126

Johnson MS, Fennimore SA (2005) Weed and crop response to colored plastic mulches in strawberry production. Hort Sci 40:1371-1375

Kar SK, Ghosh S, Manna I, Banerjee S, Dhara P (2003) An investigation of hand anthropometry of agricultural workers. J of Human Ecol 14:57-62

Knezevic SZ, Evans SP, Blankenship EE, Van Acker RC, Lindquist JL (2002) Critical period for weed control: the concept and data analysis. Weed Sci 50:773-786

Kumar B, Yaduraju NT, Ahuja KN, Prasad D (1993) Effect of soil solarization on weeds and nematodes under tropical Indian conditions. Weed Res 33:423-429

Kunz C, Weber JF, Peteinatos GG, Sökefeld M, Gerhards R (2018) Camera steered mechanical weed control in sugar beet, maize and soybean. Precis Agric 19:708-720

Kurstjens DAG, Perdok UD (2000) The selective soil covering mechanism of weed harrows on sandy soil. Soil and Till Res 55:193-206

Lati RN, Siemens MC, Rachuy JS, Fennimore SA (2015) Intrarow weed removal in broccoli and transplanted lettuce with an intelligent cultivator. Weed Tech 30:655-663

Lazarus W (2021) Farm machinery management. https://wlazarus.cfans.umn.edu/william-f-lazarus-farm-machinery-management. Accessed: February 24, 2022

Lee N, Thierfelder C (2017) Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. Agron Sustain Dev 37:48

Liebman M, Davis AS (2009) Managing weeds in organic farming systems: an ecological approach. Pages 173-196 *in* Francis C, ed. Organic farming: the ecological system. Madison, Agronomy, Crop, and Soil Science Society of America

Liebman M, Gallandt ER (1997) Many little hammers: ecological approaches for management of crop-weed interactions. Pages 291-343 *in* Jackson LE, ed. Ecology in Agriculture. San Diego, Academic Press

Lundkvist A (2009) Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. Weed Res 49:409-416

Malik VS, Swanton CJ, Michaels TE (1993) Interaction of white bean (*Phaseolus vulgaris* L.) cultivars, row spacing, and seeding density with annual weeds. Weed Sci 41:62-68

McErlic AF, Boydston RA (2013) Current state of weed management in organic and conventional cropping systems. University of Nebraska-Lincoln Digital Commons. https://digitalcommons.unl.edu/usdaarsfacpub/1387. Accessed 18 November 2020

Melander B (2000) Mechanical weed control in transplanted sugar beet. *In* Proceedings of the 4th EWRS Workshop on Physical Weed Control. Elspeet, Netherlands: European Weed Research Society

Melander B, Lattanzi B, Pannacci E (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. Crop Protec 72:1-8

Melander B, McCollough MR (2021) Advances in mechanical weed control technologies. Burleigh Dodds Series in Agricultural Science. https://bdspublishing.com/_webedit/uploadedfiles/All%20Files/Open%20Access/9781801462464.pdf. Accessed: October 26, 2021

Melander B, Rasmussen IA, Bàrberi P (2005) Integrating physical and cultural methods of weed control—examples from European research. Weed Sci 53:369-381

Merfield CN (2015) False and stale seedbeds: the most effective non-chemical weed management tools for cropping and pasture establishment. The BHU Future Farming Centre. Lincoln, New Zealand

Mirsky SB, Gallandt ER, Mortensen DA, Curran WS, Shumway DL (2010) Reducing the germinable weed seedbank with soil disturbance and cover crops. Weed Res 50:341-352

Mohammadian R, Moghaddam M, Rahimian H, Sadeghian SY (2005) Effect of early season drought stress on growth characteristics of sugar beet genotypes. Turk J Agric For 29:357-368

Mohler CL (2001) Mechanical management of weeds. Pages 139-209 *in* Liebman M, Mohler CL, Staver CP, eds. Ecological Management of Agricultural Weeds. Cambridge, Cambridge University Press

Mohler CL, Iqbal J, Shen J, DiTommaso A (2016) Effects of water on recovery of weed seedlings following burial. Weed Sci 64:285-293

Mudalagiriyappa H, Nanjappa V, Ramachandrappa B (1999) Effect of soil solarization on weed growth and yield of kharif groundnut (*Arachis hypogaea*). Indian J Agron 44:396–399

Mutch D (2012) Flaming as a method of weed control in organic farming systems. Michigan State University Extension E3038

Odero DC, Wright AL (2018) Critical period of weed control in snap bean on organic soils in south Florida. Hort Sci 53:1129-1132

Peachey RE, Pinkerton JN, Ivors K, Miller M, Moore L (2001) Effect of soil solarization, cover crops, and metham on field emergence and survival of buried annual bluegrass (*Poa annua*) seeds. Weed Tech 15:81-88

Peruzzi A, Martelloni L, Frasconi C, Fontanelli M, Pirchio M, Raffaelli M (2017) Machines for non-chemical intra-row weed control in narrow and wide-row crops: a review. J Agric Eng 48:57-70

Pietola L, Smucker AJM (1998) Fibrous carrot root responses to irrigation and compaction of sandy and organic soils. Pages 305-321 *in* Box JE, ed. Root Demographics and Their Efficiencies in Sustainable Agriculture, Grasslands and Forest Ecosystems. Developments in Plant and Soil Sciences, vol 82. Dordrecht, Springer

Pressman A (2011) Equipment and tools for small-scale intensive crop production. ATTRA National Sustainable Agriculture Information Service IP417

Price AJ, Norsworthy JK (2013) Cover crops for weed management in southern reduced-tillage vegetable cropping systems. Weed Tech 27:212-217

Priddy DM (2021) Soil surface characteristics and cultivar choice affect mechanical weed control efficacy in organic vegetables. M.S. Thesis. East Lansing, MI: Michigan State University. 73 p

Raffaelli M, Fontanelli M, Frasconi C, Sorelli F, Ginanni M, Peruzzi A (2011) Physical weed control in processing tomato in Central Italy. Renew Agric and Food Syst 26:95-103

Rasmussen J (1996) Mechanical weed management. Proceedings, Second International Weed Control Congress, 943-948

Rasmussen J, Mathiasen J, Bibby BM (2010) Timing of post-emergence weed harrowing. Weed Res 50:436-446

Rasmussen J, Nielsen HH, Gundersen H (2009) Tolerance and selectivity of cereal species and cultivars to postemergence weed harrowing. Weed Sci 57:338-345

Riemens MM, Groeneveld RMW, Kropff MJJ, Lotz LAP, Renes RJ, Sukkel W, Van der Weide RY (2010) Linking farmer weed management behavior with weed pressure: more than just technology. Weed Sci 58:490-496

Rodenburg J, Saito K, Irakiza R, Makokha DW, Onyuka EA, Senthilkumar K (2015) Labor-saving weed technologies for lowland rice farmers in sub-Saharan Africa. Weed Tech 29:751-757

Rylander H, Rangarajan A, Maher RM, Hutton MG, Rowley NW, McGrath MT, Sexton ZF (2020) Black plastic tarps advance organic reduced tillage I: Impact on soils, weed seed survival, and crop residue. Hort Sci 55:819-825

Samtani J, Derr J, Conway M, Flanagan R (2017) Evaluating soil solarization for weed control in strawberry (*Fragaria xananassa*) yield in annual plasticulture production. Weed Tech 3:1-9

Sanchez J, Gallandt ER (2020) Functionality and efficacy of Franklin Robotics’ Tertill™ robotic weeder. Weed Tech 35:166-170

Sarkar B, Sundaram PK, Dey A, Kumar U, Sarma K, Bhatt BP (2015) Traditional agricultural tools used by tribal farmers in Eastern India. Res J of Agric Sci 6:215-219

Sarrantonio M, Gallandt E (2003) The role of cover crops in North American cropping systems. J Crop Prod 8:53-74

Simon PW (2010) Breeding of carrot. Pages 157-190 *in* Janick J, ed. Plant Breeding Reviews, Volume 19. Canada, John Wiley & Sons, Inc

Singh R (2006) Use of soil solarization in weed management on soyabean under Indian conditions. Tropical Sci 46 (2):70-73

Smith RG, Atwood LW, Pollnac FW, Warren ND (2015) Cover-crop species as distinct biotic filters in weed community assembly. Weed Sci 63:282-295

Sørensen CG, Madsen NA, Jacobsen BH (2005) Organic farming scenarios: operational analysis and costs of implementing innovative technologies. Biosyst Eng 91:127-137

Stepanovic S, Datta A, Neilson B, Bruening C, Shapiro CA, Gogos G, Knezevic SZ (2015) Effectiveness of flame weeding and cultivation for weed control in organic maize. Biolog Ag & Hort 32:47-62

Stoller E, Wax L (1973) Periodicity of germination and emergence of some annual weeds. Weed Sci 21:574-580

Su SQ, Ahrens WH (1997) Weed management in Northeast China. Weed Tech 11:817-823

Swanton C, O'Sullivan J, Robinson D (2010) The critical weed-free period in carrot. Weed Sci 58:229-233

Tautges NE, Goldberger JR, Burke IC (2016) A survey of weed management in organic small grains and forage systems in the Northwest United States. Weed Sci 64:513-522

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392

Terpstra R, Kouwenhoven JK (1981). Inter-row and intra-row weed control with a hoe-ridger. J Agric Eng Res 26:127-134

Tilmor Power Ox. https://www.tilmor.com/en-us/products/259/powerox. Accessed 22 December 2020

Turner SD, Maurizio PL, Valdar W, Yandell BS, Simon PW (2018) Dissecting the genetic architecture of shoot growth in carrot (*Daucus carota* L.) using a diallel mating design. G3 8:411-425

USDA ERS (2022) Selected weekly fresh-market vegetable movement and price. https://www.ers.usda.gov/data-products/vegetables-and-pulses-data/selected-weekly-fresh-market-vegetable-movement-and-price/. Accessed: February 28, 2022

USDA ERS (2021) Farm structure. https://www.ers.usda.gov/topics/farm-economy/farm-structure-and- organization/farm-structure/. Accessed 11 January 2021

USDA NASS (2019) Census of agriculture. 2019 Organic survey. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Organics/index.php.Accessed 11 January 2021

Van der Weide RY, Bleeker PO, Achten VTJM, Lotz LAP, Fogelberg F, Melander B (2008) Innovation in mechanical weed control in crop rows. Weed Res 48:215-224

Vanhala P, Kurstjens D, Ascard J, Bertram A, Cloutier DC, Mead A, Raffaelli M, Rasmussen J (2004) Guidelines for physical weed control research: flame weeding, weed harrowing and intra-row cultivation. Pages 194-225 *in* Cloutier D, Ascard J, eds. Proceedings 6th EWRS Workshop on Physical and Cultural Weed Control. Lillehammer, Norway

Walsh MJ, Stratford K, Stone K, Powles SB (2012) Synergistic effects of atrazine and mesotrione on susceptible and resistant wild radish (*Raphanus raphanistrum*) populations and the potential for overcoming resistance to triazine herbicides. Weed Tech 26:341-347

Walters T, Pinkerton J (2012) Soil solarization: a perspective from cool northern regions. In Gamliel A, Katan J. Pensoft Publishers

APPENDIX

Appendix A. List of search terms and number of abstracts returned during preliminary literature searches for Chapter 1. The Web of Science database was used for all searches.

Search Terms	**No. Abstracts**
"organic weed management"	35
"physical weed control" AND "organic"	29
"ecological weed management" AND "organic"	16
"integrated weed management" AND "organic"	109
"hand weeding" AND "tools"	15
"hand tools" AND "weeds"	3
"weed management" AND "small scale"	38
"wheel hoe"	7
"weed management" AND “tarping”	1

Appendix B. Supplemental Table 2.1. Cultivation tool settings for each cultivation event.

	Cultivation Event 1				Cultivation Event 2			
	Single Tool		Stacked Tools		Single Tool		Stacked Tools	
Year	Tool	Tool Tip Distance[a] (cm)	Tool	Tool Tip Distance (cm)	Tool	Tool Tip Distance (cm)	Tool	Tool Tip Distance (cm)
2019	Finger Weeders	0[b]	Finger Weeders	0	Finger Weeders	0[b]	Finger Weeders	0
			Hilling Discs	10			Hilling Discs	10
2020	Finger Weeders	0	Finger Weeders	0	Finger Weeders	0	Finger Weeders	0
			Hoe Ridgers	15			Torsion Weeders	0
2021	Sweeps	10	Finger Weeders	0	Sweeps	10	Finger Weeders	0
			Torsion Weeders	0			Hoe Ridgers	15

[a] Indicates the working distance between tool tips, i.e., between finger weeder pairs.

[b] A tip distance of 0 indicates the tips of the tools were touching.

BIOGRAPHY OF AUTHOR

Rebecca Champagne was born in Augusta, Maine on February 23, 1993, and raised in West Gardiner, Maine by parents Karen and Mark Champagne. Rebecca graduated from the University of Maine in 2015 with a Bachelor of Science degree in Sustainable Agriculture. She graduated from the Pennsylvania State University in 2017 with a Master of Science degree in Agronomy. Prior to the start of her Ph.D. program, she worked as an analyst for an agricultural tech company, tracking and providing insight on global agriculture market data and trends. She plans on working in the intersection of science and policy to advocate for greater sustainability and equity within our agriculture and food systems. Rebecca is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in May 2022.