ADDRESSING WEED AND SOIL MANAGEMENT TRADE-OFFS IN VEGETABLES THROUGH INTEGRATED CULTURAL AND MECHANICAL STRATEGIES

By

Noelle Anne Connors

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Horticulture—Master of Science

2022

ABSTRACT

Mechanical cultivation is important for managing weeds in vegetables, but it can damage crops through uprooting or burial. We evaluated approaches to improve efficacy and selectivity of mechanical cultivation, and the impact of soil management practices on tool efficacy. Chapter 1 reports on experiments that test the effects of long-term reduced tillage and compost additions, as well as previous cultivation tool, on soil surface conditions, cultivation tool efficacy and yield in winter squash. Compost addition had variable effects on soil conditions and efficacy between the two years, but increased squash mid-season biomass in both years and squash yield in one of two years. Surprisingly, reduced tillage had no detectable effect on soil surface conditions, cultivation efficacy, or yield. In one year, hilling at the first event improved finger-weeding efficacy at later cultivation events. Chapter 2 reports on field experiments evaluating the effects of carrot seed size and cultivation tool on cultivation efficacy and crop yield. We tested if larger seed sizes could increase carrot anchorage force and height at the time of cultivation and increase tolerance to cultivation. We found that 1) carrots from large seeds had higher anchorage force and height at time of cultivation, 2) tool effects varied by year and in one year large seeds increased cultivation tolerance, 3) yields were 20% higher from larger seeds. Chapter 3 presents a model to provide insight into the effects of crop and weed characteristics on selectivity of cultivation tools that uproot or bury weeds. The model was parameterized using anchorage force and height data from carrots and five weed species grown in a greenhouse, and predicts the effects of cultural practices influencing the relative size of carrots and weeds. It suggests that selective potential in carrots varies with crop growth stage and weed species, but is generally higher for tools that bury weeds than for those that uproot. The model demonstrates the impact of cultural practices including stale seedbedding and seed size selection on selective potential.

ACKNOWLEDGEMENTS

My research was made possible by a USDA-OREI (Organic Agriculture Research and Extension Initiative) grant, Michigan State University's Project GREEEN (Generating Research and Extension to meet Economic and Environmental Needs), and from North Central SARE (Sustainable Agriculture Research and Education). I would like to thank my advisor Dr. Daniel Brainard for his mentorship and guidance in my research, and my committee members Dr. Erin Burns, Dr. Dan Chitwood, and Dr. Zachary Hayden. My projects would not have been possible without the help of Daniel Priddy and Johanna Flies, as well as all of the research aides that assisted me: Shane Adams, Lily Arriaga, Brandon Hall, Darla Martinez, and Brandon Scott. I would also like to thank the MSU CANR Statistical Consulting Center for their help with my data analysis. I would like to thank my friends and family for their support.

TABLE OF CONTENTS

CHAPTER ONE: Effects of Compost, Tillage and Cultivation Tool Sequence on Finger Weeder Efficacy and Yield in Organic Squash

ABSTRACT

Soil management practices may affect both crop growth and the efficacy of physical weed management practices through changes in soil surface properties. In field studies, we evaluated the impacts of contrasting compost (none vs annual spring applications), tillage (full width vs strip till) and cultivation tool sequence (hill-finger vs finger-finger) practices on soil surface characteristics (hardness, roughness and moisture content) and the selectivity of in-row mechanical cultivation. Surprisingly, reduced tillage (strip tillage) had few detected impacts on soil surface characteristics, finger weeder efficacy or crop yield. In contrast, depending on year, compost addition variously affected soil conditions, efficacy of finger weeding, and squash growth and yield. At the 2-leaf squash stage, compost addition had no detected impact on soil surface characteristics, but improved cultivation efficacy in one of two years (2021) and reduced crop mortality in the other (2022). At the 4-leaf squash stage compost addition reduced soil surface penetrometer resistance and increased soil water content in 1 of 2 years (2021) but had no detectable effect on finger weeder efficacy in either year. Compost addition increased early shoot biomass of squash in both years, and crop yield in one of two years (2021). In one of two years, hilling at the first cultivation event reduced soil hardness relative to finger weeding and resulted in greater soil disturbance and improved efficacy of finger weeding at the second cultivation. Overall, these results suggest that compost can improve squash yield and efficacy of mechanical cultivation depending on other conditions, but strip tillage is less likely to affect soil conditions or efficacy of in-row cultivation with a finger weeder. Additionally, cultivation with hilling disks early can improve future finger weeding efficacy compared to repeated finger weeding.

Keywords: soil surface conditions, reduced tillage, mechanical cultivation, finger weeder

Introduction

Michigan is a top producer of cucurbit crops with more acreage in processing cucumbers and winter squash than any other state (NASS 2017). Many cucurbit growers rely on mechanical cultivation either in addition to or instead of herbicides (Benzle 2019). Among organic growers, physical soil disturbance is particularly common for managing weeds. For example, a 2014 survey of Michigan organic farmers found that 50% of respondents who grew winter squash used row crop cultivators and 62% used rototillers (Lowry and Brainard 2019). They used an average of 6.5 total tillage operations, with 3.5 for field preparation and the rest for mechanical cultivation.

Tillage is a central weed management method, but when used excessively it can harm soil health. Primary tillage is important for disrupting weed life cycles and incorporating amendments, but it often leads to lower soil organic matter, loss of nitrogen through mineralization, and disruption of soil structure (Arriaga et al. 2017; Peigne et al. 2007). Many studies with long-term tillage reduction have shown benefits for soil characteristics including lower levels of compaction and increased aggregation (Arriaga et al. 2017; Peigne et al. 2007). Fewer studies have evaluated consequences of reduced tillage for weed management beyond shifts in weed community composition over time. Secondary tillage, shaping and leveling of beds, is often used intensively on vegetable farms to improve crop establishment through better soil-seed contact and uniform planting depth.

Compost is a commonly applied amendment in organic production systems with reported benefits for soil and pest management (Erhart & Hartl 2010; Martínez-Blanco et al. 2013). As with reduced tillage, it may improve soil physical, chemical and biological characteristics through increases in soil organic matter (Erhart& Hartl 2010). In a meta-analysis of effects of compost application, Martínez-Blanco et al. (2013) observed variable effects on crop yield, and benefits for soil physical and biological properties. Compost effects on yield were reported in only 40% of studies, and mid-term (<10 year) effects ranged from 138% decreases to 52% increases in yield. Compost increased soil structural stability between 29-65%, water holding capacity by up to 50%, and increased microbial activity 43-344%. They also found benefits for plant-available nutrients. Specifically, 5-60% of N applied in compost is mineralized, and 35-100% of applied P is mineralized, and 75-100% of applied K is mineralized depending on the time frame studied. They found no significant effects of compost on weed suppression, but compost decreased soil bulk density between 0.7-23%, which they suggested may increase soil workability for cultivation tools. Mohler et al. (2021) describes that compost can improve cultivation efficacy by improving soil tilth and reducing the formation of soil clods.

Overall, observed variation in cultivation efficacy suggest that it is highly dependent on the type of tool used, and soil characteristics and conditions including texture, moisture content and surface roughness (Gallandt et al. 2018). Understanding the interaction between soil surface conditions and cultivation tool efficacy can increase tool efficacy while minimizing unnecessary tillage.

Conventional wisdom says that cultivation tools are most effective in level beds with good tilth that allow uniform working tool depth (Mohler 1996; Bowman 1997). However, Priddy (2021) showed that rolling beds can have a negative effect on weed management by increasing soil moisture and penetrometer resistance (crusting), both of which reduced efficacy of flextine harrow cultivation. Evans et al. (2012) also found that cultivation efficacy was higher in beds that were not level, although the effect was dependent on tool. Surface conditions affected S-tine harrow and block cultivator efficacy, but not stirrup cultivator efficacy, which they concluded was likely because the stirrup cultivator is not as dependent on penetrating the soil surface. Mohler et al. (2000 cited in Evans et al. 2012) also found that cultivation was more effective when the seedbed was chiseled and disked than when it was also leveled and compacted from being culti-mulched. Evans et al. (2012) speculated that the observed benefits from having non-leveled soil is an indicator of lower compaction, since compaction decreases tool efficacy.

Several studies have examined the effect of soil moisture on cultivation tool efficacy. In laboratory experiments with a tine harrow, Kurstjens (2002) found that decreasing soil moisture levels from 16% to 5% increased weed mortality from 36 to 91%. Mohler et al. (2016) also found that recovery of weeds from burial depends on soil moisture. They found that weeds recovered best from burial if they were watered daily after cultivation, and worse if they were watered only immediately after cultivation.

The effect of soil texture on cultivation seems to depend on the mechanism used to kill weeds (Gallandt et al. 2018). For example, spring tine harrowing, which primarily uproots weeds, was more effective on sandy soils than clay soils (Van der Weide and Kurstjens 1996 cited in Gallandt et al. 2018). However, laboratory experiments studying burial showed that weeds could be killed by burial with less sand if the sand had a smaller particle size (Baerveldt and Ascard 1999).

Finger weeders are a commonly used tool but there is little research about how soil conditions affect their efficacy. Van der Schans et al. (2006) describe that the finger weeder works best in level and loose soil. They also suggest that it can be used successfully over a range of textures from light to medium heavy clay soils. The finger weeder is thought to primarily work by uprooting weeds (van der Schans et al. 2006; Peruzzi et al. 2017), although depending on its settings it can also be used to bury weeds (Hitchcock-Tilton 2018).

In this experiment, the finger weeder was tested in soils under different long-term management practices to determine how it functions in different soil conditions. Our first objective was to determine how compost addition, tillage practices, and cultivation tool sequence affect soil surface conditions and the efficacy of finger weeding in winter squash. We hypothesized that compost addition and conventional tillage practices would increase finger weeding efficacy compared to no compost addition and reduced tillage practices due to improved tilth and more uniform soil conditions. In addition, we hypothesized that finger weeding would be more effective after previous cultivation by hilling disks than following finger weeding, due to improved potential to disturb loosened soil above the crop root zone.

Materials and Methods

Field Site

A field experiment was conducted at Michigan State University's Horticulture Teaching and Research Center (HTRC) in Holt, MI (42.673705,-84.484900) during the 2021 and 2022 growing seasons. The soil type was 'Spinks Loamy Sand' with 74.8% sand, 17.8% silt, and 7.4% clay. The experiment was conducted in two seasons in adjacent plots within a long-term trial.

Experimental Design

Finger weeding efficacy under various soil conditions was studied in a field experiment with a split-split plot design. The main plot factor was long-term tillage treatment (conventional tillage vs. reduced tillage for 13 years), the sub-plot factor was long-term compost addition (13 years of either annual compost applications or no compost), and the sub-sub plot factor was cultivation tool sequence (finger weeding after hilling vs. finger weeding after finger weeding).

All combinations of factors were included for a total of 8 treatments (Table 1.1) replicated 4 times in the experiment.

Conventional tillage plots had a 13 year history of full width primary tillage with a rototiller, used either alone or in combination with subsoiling with an Unverferth 120 equipped with 3 shanks per bed spaced at 46 cm. Reduced tillage plots had a history of 13 years of strip tillage using a 2-row Hiniker 6000 equipped with row-cleaners, offset disks and a rolling basket to create strip-tilled zones approximately 30 cm wide and 30 cm deep, with approximately 46 cm of undisturbed soil between strips. In all years, in all plots, rye or rye-vetch cover crops were sown following crop harvest and then either incorporated with tillage (conventional till system) or retained on the surface in the between row zone (strip till system). For reduced tillage treatments during the 2019-2022 seasons, tarps were also used as a method to suppress weeds prior to crop planting, without tillage; in those years, cover crops were mowed and tarps applied in early spring and left on the soil surface for 2-3 weeks to suppress winter weeds and cover crop regrowth prior to crop planting. The compost factor included two levels: no compost addition, or annual spring applications of dairy-manure based compost (‘Dairy Doo’ from Morgan’s Composting, Sears, MI) at 5.4 dry MT ha^{-1} yr^{-1}.

Field operations during the squash producing season of 2021 and 2022 are summarized in Table 1.2. After primary tillage, 12.2 m x 1.5m plots were established. Squash was planted in four rows per main plot (two rows per sub-sub plot) spaced at 76 cm (corresponding to the center of the disturbed strip-till zone in reduced tillage treatments). In 2021, squash was direct seeded using Mater Macc vacuum seeder at 30 cm in-row spacing. However, transplants were used to fill in gaps from poor emergence and losses due to vole damage which were substantial (>20% in some plots). At 35 days after planting (DAP), squash were thinned to 76 cm spacing. In 2022, 23 day old squash seedlings were transplanted by hand at 46 cm in-row spacing. Between row weed management in both years consisted primarily of cultivation with rolling ‘spyder gangs’ on a Hillside cultivator. In 2021, plots were also flame weeded 3 DAP to control weeds before squash emergence, and again at 16 DAP in the between row zone of reduced tillage treatments, using shields to protect squash seedlings. However, due to safety concerns from flammability of surface residue, no flame-weeding was done in 2022.

Finger weeding treatments were done when squash had approximately 2-3 true leaves and approximately one week later, when squash had 5-6 leaves. Finger weeders (Fig 1.1; Tilmor) were belly mounted on a floating arm to a Tilmor cultivating tractor. They were set with the tips touching, and the floating arm angle set with the intention of ‘scrubbing’ soil from the in-row zone, uprooting weeds instead of burying them. Tractor speed was determined through calibration in practice beds, with speed adjusted gradually upward to maximize weed mortality while maintaining crop mortality of <5%. This corresponded to approximately 8 km hr^{-1} in all runs of the experiment. For the first cultivation event in each year, hilling disks (Kult Kress ‘Duo’ cutaway disks set to hill) were also used to set up contrasting soil topographies for the second cultivation event. They were belly-mounted on floating arm of Tilmor cultivating tractor, set with the front of disks at 17 cm and back at 11.5 cm.

Within each sub-plot, two adjacent 1.25 m x 0.1 m quadrats were established centered on the crop row to measure in-row weed density. In the first quadrat, surrogate weeds were sown at planting in 2022. Approximately 200 seeds each of ‘Red Spike’ red amaranth (*Amaranthus cruentus*) and ‘Mighty Mustard Pacific Gold’ condiment mustard (*Brassica juncea*) (Johnny’s Selected Seeds) were mixed with sand and sown in the 10cm in-row zone in each surrogate quadrat and covered with a thin layer of soil. Surrogates were also sown after the first cultivation event in both years to measure weed mortality from the second cultivation event.

Soil Surface Roughness and Soil Movement Measurements

Soil surface conditions before and after all cultivation events other than the first event in 2021, were measured using 3D images to assess topography (surface roughness and soil movement). Prior to the first cultivation event, a 1 m long permanent quadrat was established across the full width of each bed for photos of soil topography. All weeds and squash plants were removed before photos were taken. Images were taken using an Intel Realsense D455 Depth Camera mounted to the top of a dark box constructed from a lightweight metal frame covered by black plastic, measuring 1.14 x 0.87 x 1 m (Fig 1.2). The camera was mounted to the box approximately 0.9 m from the soil surface, following height recommended from Grundy et al. (2020). Images were taken before and after each cultivation event to characterize soil topography before each event, and to analyze changes in topography from the finger weeders and hilling disks. In addition, to provide a more direct measure of soil movement into or out of the crop row, wooden stakes were placed in the crop row of each plot and soil surface level was marked before and after each cultivation event. The difference between these heights was used to estimate the vertical soil movement into the crop row from each tool.

3D images were analyzed as point-clouds in CloudCompare (CloudCompare 2020). For each plot, the point-cloud was cropped to approximately 1 m x 0.1 m of the in-row zone centered on the crop row to represent the sampling area used for weed mortality. To adjust for any variation in slope within the plot, a 2D best-fit plane was fit through each point-cloud before calculating roughness (Thomsen et al. 2015). Roughness for each plot was calculated as the standard deviation of the point-cloud heights from the best fit plane (Martinez-Agirre et al. 2016; Cremers et al. 1996 as cited in Thomsen et al. 2015).

To calculate soil movement from cultivation, both the pre-cultivation and post-cultivation point clouds for each plot were cropped identically to approximately 1 m x 0.l m of the in-row zone. The average vertical distance between these two point clouds was used as an estimate of the amount of soil moved from the cultivation tool. These measurements were ground-truthed using the wooden depth stakes as described above.

Soil Penetrometer Resistance and Moisture Content Measurements

Before each cultivation event, we measured soil surface ‘hardness’ as micropenetrometer resistance using a Shimpo force gauge (Model #: FGV-100XY Shimpo, Kyoto, Japan). Ten measurements were collected from each plot randomly from the 10 cm in-row zone near the surrogate weed quadrat. The force gauge was slowly pressed into the soil until it went 1 cm deep or broke the top layer of the soil surface. The maximum force from each of these 10 readings per plot was averaged for a measure of soil hardness for each quadrat from which weed mortality was evaluated. Soil gravimetric water content (GWC) was calculated from soil samples collected with a trowel to a depth of 2.5 cm below the soil surface. This depth was selected to represent the approximate depth of tool penetration into the soil and the depth to which the majority of roots of surrogate weeds would extend. These samples were taken from the in-row zone adjacent to the weed count quadrats before each cultivation event. The soil was weighed, dried, and weighed again to calculate GWC.

Weed and Crop Mortality

Tool efficacy was measured as the difference between weed counts before and after cultivation events. Before each cultivation event, surrogate weeds in the in-row zone of the surrogate quadrat were counted by species. Surrogate weeds and ambient weeds for which at least 10-15 individuals were present per quadrat were included in each count. For the first cultivation event, ambient weeds meeting this criteria included common purslane (*Portulaca oleracea*), chickweed (*Stellaria media*), carpetweed (*Mollugo verticillata*), pigweed (*Amaranthus spp*.), large crabgrass (*Digitaria sanguinalis*), henbit (*Lamium amplexicaule*), and common lambsquarters (*Chenopodium album*) in 2021. In 2022 for the first cultivation event, weeds meeting this criteria were large crabgrass and common purslane. The surrogate species red amaranth and mustard were sufficient in the second event in 2021 and both events in 2022. Approximately two days after the cultivation event, counts were repeated in the same quadrats. Weed mortality was estimated as the percent difference between the pre and the post counts. Squash plants in one 40’ row of each plot were counted before and after each cultivation event to measure crop mortality.

Data Analysis

Data were analyzed using PROC MIXED procedures in in SAS 9.4 (Statistical Analysis Software 9.4 Cary, NC). For responses collected before cultivation events (soil hardness and gravimetric water content), the effects of long-term tillage, compost treatments and their interaction were evaluated. For responses evaluated after cultivation events (weed and crop mortality and biomass) the effects of tillage, compost, cultivation tool sequence and their interactions were evaluated. Tillage, compost, and cultivation sequence were considered as fixed effects and replication as a random effect in all cases. Tillage within replication was also considered a random effect. Assumptions of homogeneity of variance and normality of residuals were tested using Levene’s test and Shapiro-Wilks test respectively. If data did not fit assumptions, data was transformed using Box-Cox test to determine best transformation. When no suitable transformations were found, the PROC GLIMMIX procedure in SAS (Statistical Analysis Software 9.4 Cary, NC) was used to account for heterogeneity of variance in a mixed model with unequal variances (Milliken & Johnson 2009). When the main or interactive effects of tillage, compost, or tool were significant at $p<0.10$, means were separated using Tukey's HSD with a Tukey adjustment for multiple comparisons. Main effects means were discussed as significant when no interaction effects were significant.

Results

Soil and Plant Characteristics Before First Cultivation Event

At the time of the first cultivation event, surrogate weeds were at the cotyledon growth stage, and squash at the 2-3 leaf growth stage (Table 1.3). At this stage, we did not detect any impacts of tillage or compost additions on soil hardness, or surface roughness in the in-row zone, but gravimetric water content was higher in the strip till treatment in 1 of 2 years (Table 1.4). In 2022, soil moisture was higher in the strip tilled (6.8%) plots than the rototilled plots (5.2%).

Impacts of First Cultivation Event on Weeds and Squash

At the first cultivation event, when squash was at the 2-3 leaf stage, the efficacy of mechanical cultivation differed based on soil management (compost and tillage) depending on the year and weed species (Table 1.5). In 2021, finger weeder efficacy was higher in the compost (61%) than in the no-compost treatment (51%), and higher in conventional till (69%) compared to strip till (45%) for the ambient weed community. In 2022, neither ambient, surrogate, nor total weed mortality was influenced by either compost or tillage practices.

Squash mortality from the first cultivation event was influenced by compost application and tillage in 2022, but not in 2021 (Table 1.5). In 2022, within the strip till plots, squash mortality was lower in the compost treatment (5%) than the no compost treatment (11%). In

2022 in plots where no compost was applied, squash mortality was lower in rototilled treatments (3%) than strip till treatments (11%).

Soil and Plant Characteristics Before the Second Cultivation Event

At the time of the second cultivation event, weeds were at the cotyledon stage in 2021 and cotyledon to two-leaf stage in 2022 and crop at the 5-6 leaf stage in both years (Table 1.3).

At this stage, tillage, compost and tool treatments from the first cultivation event affected soil characteristics differently depending on the year (Table 1.6). At the second cultivation event, soil hardness was higher in the previously finger weeded treatment than in the previously hilled treatment in both years. In 2021, the soil was also harder in the rototill than the strip till treatment, but soil hardness was not influenced by tillage in 2022. In 2021 at the second cultivation event, the soil was less hard and had higher moisture in the compost treatment than in the no compost treatment. In 2022, the effect of tillage on soil moisture depended on the previous tool (Table 1.6; significant tillage x tool interaction): contrary to expectations, conventionally tilled treatments had higher soil moisture (20%) than strip tilled treatments (11%) following initial finger weeding; however no effects of tillage on soil moisture were detected following hilling (data not shown (p=0.054)).

Soil roughness before cultivation events did not differ by tillage or compost treatment. In 2021, soil roughness at the second cultivation event was higher following hilling than following finger weeding at the first cultivation event, but it did not differ by tool sequence in 2022.

Impacts of Second Cultivation Event on Weeds and Squash

At the second cultivation event, finger weeder efficacy was influenced by tool sequence and tillage in 2021, but no effects of these factors were detected in 2022 (Table 1.7). In 2021, finger weeder efficacy on total weeds was higher in the previously hilled treatment (65%)

compared to the previously finger weeded (46%) treatments. Similarly, in 2021, mustard mortality was higher in the previously hilled than the previously finger weeded treatment. In 2021 the effects of previous tool treatment on amaranth mortality were only detected in the rototilled treatments: in rototilled treatments the finger weeder was more effective following hilling (78%) than following finger weeding (43%); a similar (but non-significant) effect was observed in strip-till treatments. No compost effects on finger weeding efficacy were detected in either year. Squash mortality from the second cultivation event was under 2% and was unaffected by tillage, compost, or tool sequence in either year.

Soil Movement from Cultivation

No effects of tillage, compost or tool sequence on soil movement from finger weeding were detected for either cultivation event (Tables 1.4 and 1.6). At the first cultivation event in both years, soil movement to the crop line and in-row zone ranged from approximately 0.4 cm to 1.1 cm, so soil was moved into the crop line and in-row zone in both years. At the second cultivation event in 2021, soil movement to the crop line was negative, suggesting that the finger weeders removed soil from within the crop row regardless of the previous tool used. At this same event, soil movement into the in-row zone averaged 0.3 cm, so the soil removed from the crop line mostly stayed in the in-row zone. For the second cultivation in 2022, soil movement ranged from an average of 0.5 cm 1.7 cm per plot, suggesting that the finger weeder—contrary to expectations—moved soil into both the crop row and the in-row zone, regardless of the previous tool used.

Mid-Season Biomass

In both years, squash midseason biomass (measured 26 and 12 days after cultivation 2 in 2021 and 2022 respectively) was 32% higher in the compost than the no compost treatment

(Table 1.8). No difference in squash biomass between cultivation sequence or tillage was detected. In 2022, no biomass difference was detected between cultivated and uncultivated squash 12 days after cultivation, suggesting that there was not observable cultivation damage.

In both years, alternating tool treatments reduced total midseason weed biomass compared to the finger weeded treatment (Table 1.8). In 2021, alternating tool treatments decreased ambient weed biomass compared to finger weeder treatment, but there was no detectable effect of tool treatment on ambient weed biomass in 2022. In 2022, alternating tool treatments decreased surrogate weed biomass compared to repeated finger weeding, but surrogate weed biomass did not differ in 2021. No differences in weed biomass were detected between tillage and compost treatments.

Yield

In 2021, squash final stand density was affected by tillage and compost, but there were no tillage, compost, or tool effects on stand density in 2022 (Table 1.9). In 2021, within the strip till treatments, stand density was higher where compost was applied compared to no compost. In the no compost treatments, stand density was higher in the rototill treatment than the strip till treatment.

In both years, tillage and tool treatments did not affect squash yield (Table 1.9). Squash total yield was higher in the compost (2.14 kg/row m) than in the no compost treatment 1.64 kg/row m) in 2021, but did not differ in 2022 despite differences in midseason biomass. In 2021, squash marketable yield was also higher in the compost treatment, and the total and marketable number of fruit per row was higher in the compost than in the no compost treatment.

Discussion

Effects of long-term soil management history on soil surface conditions at the time of cultivation were variable. We expected that long-term history of reduced tillage would reduce soil hardness, increase surface roughness, and increase soil moisture compared to long-term rototilling. However, these expectations were met only for moisture content, and only at the first cultivation event in 2022 (Table 1.4). At the other timings, tillage history had no detected effect on soil surface conditions at time of cultivation. Previous studies have found that strip tillage reduces soil hardness compared to rototilling (Licht and Al-Kaisi 2005; Jaskulska et al. 2020) and may increase soil moisture (Haramoto and Brainard 2012; Jaskulska et al. 2020). In a study of Iowa soils Licht and Al-Kaisi (2005) observed that strip tilled soils had greater moisture than rototill treatments at all depths tested (0-30 cm and 0-120 cm). However, when compared at those two depths, they were unable to detect significant differences between no-till, strip-till, and rototill treatments.

Compost addition also impacted soil surface conditions, but results were inconsistent across years and timings (Tables 1.4 & 1.6). As expected, compost reduced soil hardness and increased soil moisture before the second cultivation event in 2021, but at all other timings had no detectable effect on soil hardness or moisture. Others have found that adding compost can improve soil bulk density and porosity (Evanylo et al. 2008) and increase soil moisture retention (Evanylo et al. 2008; Zemanek 2011).

The impact of finger weeding on vertical soil movement was inconsistent and generally did not follow expected patterns. Although we attempted to calibrate the finger weeder to uproot weeds by pulling soil from the in-row zone, finger weeding resulted in *positive* in-row vertical soil movement in most cases. Moreover, even though there were differences in soil conditions at the time of cultivation from both compost and tillage management practices, there were no detectable effects of these conditions on vertical soil movement from finger weeding. Surprisingly, even when hilling occurred at the first cultivation event, subsequent finger weeding does not appear to have removed soil from the in-row zone. However, it should be noted that changes in vertical soil movement may reflect reductions in soil bulk density following finger weeding, rather than movement of soil into the row.

In one of two years, cultivation efficacy at the first event was higher in the compost compared to no compost and higher in rototill than strip till, but at other events there was no difference from compost. Previous studies document the benefits of compost for soil health (Erhart & Hartl 2010; Martínez-Blanco et al. 2013), including improving tilth which is thought to increase cultivation efficacy (Mohler 2001). Priddy (2021) also did not observe any increase in flextine efficacy in compost treatments within this same long-term study, which he suggested may have been due to similar levels of organic matter regardless of historic compost addition. .

Results partially support the hypothesis that mechanical cultivation would be less effective in strip till treatments, but the mechanism for that effect was not clearly linked to measured soil surface conditions. Efficacy was reduced after strip till in 2021, but the soil moisture and hardness were not different from the rototill. Other studies have found in-row cultivation to be less effective in strip till treatments than rototilled (Luna and Staben 2002). Cultivation in strip till systems is generally expected to be more difficult than in rototilled systems because of cover crop residue (Mohler 2001) and the narrower cultivation area (Brainard et al. 2013). However, in our study, relatively little cover crop residue was present in-row following strip tillage, and the in-row zone was apparently sufficiently wide to support adequate performance of the finger weeder.

Results of this study provide some support for the concept of alternating in-row tools to improve efficacy. At the second cultivation event in 2021, finger weeding efficacy was higher in the previously hilled treatments than in previously finger weeded, especially in the rototilled treatments. In addition, in both years, weed biomass after the second cultivation event was reduced in the alternating treatment compared to the finger weeded treatment. These differences might be partially explained by differences in soil hardness and roughness at the time of cultivation. In both years, previously hilled treatments had reduced soil hardness compared to previously finger weeded treatments. In 2021, when this difference was more pronounced in the rototill treatments, rototoill treatments had harder soil than strip till.

Other studies have found that harder soil leads to decreased cultivation efficacy. For example, Priddy (2021) found decreased efficacy of flextine harrow where soil had been hardened by molasses. Evans et al. (2012) observed that cultivation was less effective after soil had been leveled, likely due to compaction which decreases tool efficacy.

Several studies have specifically observed that finger weeders work better in looser soil. Kurstjens and Bleeker (2000) found that finger weeders could not penetrate compact soil, but they were effective after torsion weeders had already loosened soil. Brown and Gallandt (2018) tested ‘stacked’ cultivation tools-using torsion weeders, finger weeders, and harrows in one pass. They found evidence of synergy- efficacy from all three tools together was higher than would be expected by combining the three individual tool efficacies. Based off slow motion video, they suggested that one reason for this effect is that finger weeders seemed to work better in previously disturbed soil. Peruzzi et al. (2017) also notes that finger weeders are most effective in dry soil that is readily workable.

Squash mortality due to finger weeding was generally low. In 2022 at the first cultivation event, compost addition reduced mortality within strip till compared to no compost. At that event, strip till plots had higher soil moisture than rototill plots, but there were no compost effects or interactions on soil conditions. The lower squash mortality in strip-till compost treatments could be due to more rapid squash root growth in compost compared to no compost treatments.

Compost increased mid-season squash biomass in both years. In 2021, compost also led to increased yield and greater fruit number, but there was no detectable difference in fruit yield or number in 2022. Other studies have found variable responses of winter squash yield to compost. In a two year, multi-site study, Rowley (2018) found that at one site in one year, compost increased fruit number and weight compared to no compost, but in other years and locations they found no difference between compost and other fertilizer treatments. Evanylo et al. (2008) found that compost did not affect pumpkin or bell pepper yields compared to no soil amendments, which they attributed to most likely sufficient nutrients already present in the soil.

Overall, these results show that compost may have benefits for cultivation efficacy and crop yield. Reduced tillage treatments had no effect on soil conditions at the time of cultivation, and little effect on cultivation efficacy. Hilling increased soil hardness at future cultivation events which in one year increased finger weeding efficacy. Future research could further investigate the mechanism of compost increasing cultivation efficacy through analysis of other soil conditions or soil clumping from cultivation.

LITERATURE CITED

Arriaga FL, Guzman, J, and Lowery, B (2017) Conventional agricultural production systems and soil functions. In Al-Kaisi, M.M. and Lowery, B. (eds.), Soil Health and Intensification of Agroecosystems: 109-125

Baerveldt S, Ascard J (1999) Effect of soil cover on weeds. Biol Agric Hortic 17:101-111

Benzle MM (2019) Integrated cultural and mechanical weed management for organic winter squash systems. MS Dissertation. East Lansing, MI: Michigan State University. 135 p

Brainard DC, Peachey RE, Haramoto ER, Luna JM, Rangarajan A (2013) Weed ecology and nonchemical management under strip-tillage: implications for Northeastern U.S. vegetable cropping systems. Weed Technol 27:218-230

Brown B, Gallandt ER (2018) Evidence of synergy with ‘stacked’ intrarow cultivation tools. Weed Res 58(4):284-291

Cloudcompare (2020). [GPL software]. version 2.11.3. Retrieved from http://www.cloudcompare.org. Accessed November 2, 2022

Erhart E, Hartl W (2010) Compost use in organic farming in Lichtfouse E (ed) Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming. Sustainable Agriculture Reviews, vol 4, Spring, Dordrecht 311-345

Evans GJ, Bellinder RR, Hahn RR (2012) An evaluation of two novel cultivation tools. Weed Technol 26(2):316-325

Evanylo G, Sherony C, Spargo J, Starner D, Brosius M, Hearing K (2008). Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. Agric Ecosyst Environ 127(1-2):50-58

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

Grundy L, Chimire C, Snow V (2020) Characterisation of soil micro-topography using a depth camera. MethodsX, 101144

Haramoto ER, Brainard DC (2012) Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience 47(11):1596-1602

Hithcock-Tilton S (2018) Improving Weed Management in Carrots With Stacked In-Row Weeding Tools and Cultivation-Tolerant Cultivars. MS Dissertation. East Lansing, MI: Michigan State University. 127 p

Jaskulska I, Romaneckas K, Jaskulski D, Galezewski L, Breza-Boruta B, Debska B, Lemanowicz J (2020) Soil properties after eight years of the use of strip-till one-pass technology. Agronomy 10:1596

Kurstjens D, Bleeker P (2000) Optimising torsion weeders and finger weeders. 4th workshop of the EWRS working group Physical Weed control. https://library.wur.nl/WebQuery/wurpubs/fulltext/40584 Accessed October 27, 2022

Kurstjens DAG (2002). Mechanisms of selective mechanical weed control by harrowing. PhD Dissertation. Wagenigen University. 156 p

Licht MA, Al-Kaisi M (2005) Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil and Tillage Res 80: 233-249

Lowry CJ, Brainard DC (2019) Organic farmer perceptions of reduced tillage: a Michigan farmer survey. Renewable Agric Food Systems 34(2):103-115

Luna JM, Staben ML (2002) Strip tillage for sweet corn production: yield and economic return. HortScience 37(7):1040-1044

Martinez-Agirre A, Álvarez-Mozos J, Giménez R (2016) Evaluation of surface roughness parameters in agricultural soils with different tillage conditions using a laser profile meter. Soil and Tillage Research 161:19-30

Martínez-Blanco J, Lazcano C, Christensen TH, Muñoz P, Rieradevall J, Møller J, Antón A, Boldrin A (2013) Compost benefits for agriculture evaluated by life cycle assessment. A review. Agron Sustainable Dev 33:721-732

Milliken GA, Johnson DE (2009) Analysis of Messy Data Vol 1: Designed Experiments. CRC Press

Mohler, C (1996) Ecological bases for the cultural control of annual weeds. J Prod Agric 9(4):468-474

Mohler CL, Teasdale JR, DiTommaso A (2021). Manage weeds on your farm: a guide to ecological strategies. SARE

Mohler CL, Iqbal J, Shen J, DiTommaso A (2016) Effect of Water on Recovery of Weed Seedlings Following Burial. Weed Sci 64:285-293

National Agricultural Statistics Service (NASS) (2017) Quick Stats. https://quickstats.nass.usda.gov/results/B8FCEB40-4E3F-30C0-AED8-716AC4820CA7. Accessed October 27, 2022

Peigne J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use and Manage 23(2):129-144

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(2):57-70

Priddy D (2021) Soil surface characteristics and cultivar choice affect weed control efficacy in vegetable crops. MS Dissertation. East Lansing, MI: Michigan State University. 63 p

Rowley, NW (2018) Optimizing fertilizer and compost rates in organic reduced till agriculture. MS Dissertation. Orono, ME: University of Maine. 109 p

Thomsen LM, Baartman JEM, Barneveld RJ, Starkloff T, Stolle J (2015) Soil surface roughness: comparing old and new measuring methods and application in a soil erosion model. Soil 1:399-210

van der Schans D, Bleeker PO, Molendijk L, Plentinger M, van der Weide RY, Lotz B, Bauermeister R, Total R, Baumann DT (2006). Practical weed control in arable farming and outdoor vegetable cultivation without chemicals. Lelystad, The Netherlands: Applied Plant Research Wageningen University. 77p

Zemanek P (2011) Evaluation of compost influence on soil water retention. Acta Uni Agri Silvi Mendel Brunen 59 (3):227-232

APPENDIX

Tables and Figures

Table 1.1. Treatments, 2021 and 2022.

Treatment	Long-term Tillage	Long-term Compost	Tool Cultivation 1	Tool Cultivation 2
1	Rototill	None	Finger weed	Finger weed
2	Rototill	None	Hill	Finger weed
3	Rototill	Compost	Finger weed	Finger weed
4	Rototill	Compost	Hill	Finger weed
5	Strip till	None	Finger weed	Finger weed
6	Strip till	None	Hill	Finger weed
7	Strip till	Compost	Finger weed	Finger weed
8	Strip till	Compost	Hill	Finger weed

Table 1.2. Schedule of field operations, 2021 and 2022.

	Event	**2021**	**DAP**[a]	**2022**	**DAP**
Pre-Testing Plot Maintenance	Flail mow	5/19	-27	5/20	-27
	Apply compost RT[b]	5/19	-26	6/9	-7
	Tarp	5/19	-27	5/23	-24
	Subsoil/fertilize/rototill CT[c]	5/23	-23	5/24	-23
	Rototill CT	6/1	-14	NA[d]	NA
	Tarp removal	6/7	-8	6/9	-7
	Apply compost CT	6/7	-8	6/10	-6
	Fertilizer (Pre Plant)	6/7	-8	6/10	-6
	Rototill CT			6/10	-6
	Strip till RT	6/7	-8	6/11	-5
	Strip till 2 RT	6/9	-6	NA	NA
	Planting[d]	6/15	0	6/16	0
	Cultivation maintenance				
	Flame weeded pre-emergence	6/18	3	NA	NA
	Flame weeded BR[f]	6/19	4	NA	NA
	Hillside cultivated[g] BR	6/20	5	6/26	10
Cultivation Event 1	Sow surrogate weeds	6/21	NA	6/16	0
	3D images pre-cultivation 1	6/22	7	6/21	5
	PRE count 1	6/23	8	6/21	5
	Cultivation testing 1	6/24	9	6/21	5
	3D images post- cultivation 1	6/25	10	6/22	6
	POST count 1	6/26	11	6/23	7
Cultivation Event 2	Sow surrogate weeds	6/27	12	6/22	6
	3D images pre-cultivation 2	6/28	13	6/30	14
	PRE count 2	6/29	14	6/28	12
	Cultivation testing 2	6/30	15	6/30	14
	3D images post- cultivation 2	7/1	16	6/30	14
	POST count 2	7/2	17	7/1	15
	Handweed[h]	7/3	18	7/7	21
	Biomass sample of crop and weeds	7/4	19	7/12	26
	Harvest	9/30	107	9/23	99

[a] Days after planting.

[b] Reduced tillage treatment

[c] Conventional tillage treatment

[d] Not applicable

[e] 2022 planting was date we planted the transplants. Seeds were sown 5/26/22.

[f] Between row

[g] Lilliston Hillside cultivator used between row.

[h] Quadrats with surrogate weeds were not handweeded.

Table 1.3. Weed and crop growth stages at time of cultivation 2021 and 2022.

	Surrogate Weed Growth Stage		Squash Growth Stage	
	2021	2022	2021	2022
	----leaf number----		----leaf number----	
Cultivation 1	NA[a]	C[b]	2-3	2-3
Cultivation 2	C	C-2	5-6	5-6

[a] No surrogate weeds present. Ambient weeds at varying stages.

[b] Cotyledon

Table 1.4. Effects of tillage and compost on soil surface conditions before first cultivation event and vertical soil movement from finger weeding, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Before cultivation					After cultivation [a] Vertical soil movement		
	Hardness		GWC[b]		Roughness [c]	Crop Line [d]		IR Zone[e]
	2021	2022	2021	2022	2022	2021	2022	2022
	----------N------		--------%--------		--mm--	-----------cm----------		
Tillage Main Effect								
Rototill	25.84	3.58	5.71	**5.19** a	4.89	0.76	1.09	0.47
Strip Till	26.31	3.71	4.77	**6.78** b	6.44	0.45	0.79	0.83
Compost Main Effect								
Compost	25.65	3.52	5.16	6.15	5.56	0.58	0.96	0.65
None	26.50	3.76	5.33	5.82	5.63	0.64	0.91	0.59
ANOVA	-- p-value--							
Tillage	0.860	0.785	0.350	**0.045**	0.191	0.366	0.277	0.207
Compost	0.727	0.348	0.843	0.425	0.638	0.720	0.823	0.657
Tillage x Compost	0.712	0.276	0.571	0.597	0.704	0.408	0.246	0.441

[a] All data is from finger-weeded treatments.

[b] Soil gravimetric water content.

[c] Data only measured in 2022.

[d] Crop line data measurement is from depth stakes, reflects vertical soil movement in one location per plot in center of crop row.

[e] In-row zone, reflects soil movement into 1.25 x 0.1 m zone centered on crop row.

Table 1.5. Effects of tillage and compost on weed and squash mortality from finger weeder at first cultivation, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

			Weeds			
	Squash		Ambient [a]		Surrogates[b]	Total
	2021	2022	2021	2022	2022	2022
	-- %					--
Tillage Main Effect						
Rototill	3.02	3.08	**69.23** a	87.42	33.17	57.50
Strip Till	2.47	7.87	**44.52** b	85.32	50.19	66.26
Compost Main Effect						
Compost	1.87	3.91	**61.22** a	84.32	36.93	63.69
None	3.70	7.04	**50.58** b	88.75	44.77	60.07
Tillage x Compost Interaction						
Rototill + Compost	0.91	**3.13** b	70.88	86.00	27.61	64.46
Rototill	5.14	**3.03** b	64.64	91.00	38.74	50.54
Strip till + Compost	2.83	**4.69** b	51.55	82.67	52.41	62.92
Strip till	2.18	**11.05** a	32.92	88.00	50.81	69.61
ANOVA	-- p-value					--
Tillage	0.824	0.094	**0.074**	0.646	0.327	0.412
Compost	0.410	0.066	**0.029**	0.458	0.753	0.708
Tillage x Compost	0.266	**0.061**	0.253	0.991	0.676	0.306

[a] In 2021, weeds included common purslane (*Portulaca oleracea*), chickweed (*Stellaria media)*, carpetweed (*Mollugo verticillata)*, pigweed (*Amaranthus spp.)*, large crabgrass (*Digitaria sanguinalis)*, henbit (*Lamium amplexicaule)*, common lambsquarters (*Chenopodium album)*. In 2022, weeds included common purslane and large crabgrass.

[b] Includes mustard and red amaranth sown 5 days before cultivation.

Table 1.6. Effects of tillage, compost and previous cultivation tool on soil surface conditions before second finger weeding event and soil movement from finger weeding, 2021 and 2022. Statistical significance (p<0.1) is indicated by different letters in the same column.

	Before cultivation						After cultivation			
							Soil movement			
	Soil Hardness		GWC[a]		Roughness		Crop line[b]		IR Zone[c]	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	-------N-------		----------%----------		-------mm-------		--------------------cm--------------------			
Tillage Main Effect										
Rototill	**17.4** a	6.4	11.7	16.8	4.9	5.4	-0.13	0.67	0.34	1.20
Strip Till	**14.1** b	6.7	12.3	12.6	4.7	5.5	-0.29	0.76	0.26	1.58
Compost Main Effect										
Compost	**14.9 b**	6.7	**12.9 a**	15.3	4.8	5.2	-0.13	0.69	0.36	1.52
None	**16.7 a**	6.4	**11.1 b**	14.1	4.8	5.8	-0.29	0.73	0.25	1.15
Tool Main Effect[d]										
Finger	**17.8** a	**8.1** a	11.7	15.5	**3.4** a	5.2	-0.23	0.84	0.39	1.08
Hill	**13.8** b	**5.0** b	12.3	13.8	**6.2** b	5.7	-0.19	0.59	0.21	1.67
ANOVA	-- p-value --									
Tillage	**0.038**	0.680	0.595	0.168	0.514	0.879	0.476	0.744	0.708	0.542
Compost	**0.058**	0.422	**0.0742**	0.576	0.854	0.850	0.468	0.880	0.580	0.739
Tool	**<0.001**	**<0.001**	0.576	0.443	**<0.001**	0.203	0.983	0.321	0.395	0.558
Tillage x Compost	0.462	0.770	0.520	0.110	0.714	0.959	0.100	0.763	0.847	0.427
Tillage x Tool	0.212	0.235	0.318	**0.046**[f]	0.146	0.966	0.597	0.880	0.697	0.810
Compost x Tool	0.702	0.777	0.186	0.321	0.202	0.447	0.379	0.725	0.429	0.316
T x C x T[e]	0.709	0.440	0.415	0.898	0.714	0.870	0.132	0.763	0.720	0.366

[a] Soil gravimetric water content

Table 1.6 (cont'd)

[b] Crop line data measurement is from depth stakes, reflects vertical soil movement in one location per plot in center of crop row

[c] In-row zone, 1.25 x 0.1 m zone centered on crop row.

[d] Refers to tool sequence, first tool was used at prior cultivation. Only finger weeder used in second cultivation event. See Table 1.1 for treatments.

[e] Tillage x compost x tool interaction.

[f] See text for explanation of this interaction.

Table 1.7. Effects of compost, tillage, and previous cultivation tool on weed and squash mortality from finger weeder at second cultivation event, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

			Weeds [a]					
	Squash		Mustard		Amaranth		Total	
	2021	2022	2021	2022	2021	2022	2021	2022
	---------- % ----------							
Tillage Main Effect								
Rototill	-1.30	-0.52	43.00	43.45	60.75	31.35	51.70	35.40
Strip Till	0.69	0.45	48.52	50.39	68.40	44.73	58.94	47.80
Compost Main Effect								
Compost	-1.14	-0.52	46.11	44.59	68.84	38.59	58.17	41.60
None	0.52	0.45	45.40	48.19	60.30	37.56	52.47	40.74
Tool Main Effect								
Finger-Finger	-0.78	0.00	**38.77** a	51.15	52.94	36.09	**46.04** a	41.47
Hill-Finger	0.16	-0.07	**52.75** b	39.19	76.20	39.99	**64.60** b	40.87
Tillage x Tool Interaction[b]								
Rototill x Finger-Finger	-2.35	0.00	34.65	44.70	**43.28** b	29.25	38.81	35.73
Rototill x Hill-Finger	-0.26	-1.04	51.34	40.85	**78.21** a	31.30	64.59	35.01
Strip till x Finger-Finger	0.79	0.00	42.90	56.04	**62.61** a	42.09	53.28	46.73
Strip till x Hill-Finger	0.590	0.890	54.15	37.88	**74.20** a	45.11	64.60	46.59
ANOVA	---------- p-value ----------							
Tillage	0.313	0.245	0.319	0.703	0.310	0.211	0.193	0.228
Compost	0.318	0.166	0.978	0.837	0.110	0.977	0.194	0.931
Tool	0.570	0.913	**0.006**	0.293	**<0.001**	0.769	**<0.001**	0.955
Till x Compost	0.385	0.913	0.140	0.541	0.476	0.669	0.212	0.587
Till x Tool	0.489	0.166	0.471	0.486	**0.031**	0.955	0.101	0.970
Compost x Tool	0.272	0.166	0.845	0.492	0.897	0.472	0.720	0.277

Table 1.7 (cont'd)

T x C x T[c]	0.604	0.913	0.282	0.724	0.439	**0.0542[d]**	0.243	0.292

[a] In 2021, mustard and red amaranth were sown 6 days before cultivation. In 2022, mustard and red amaranth were sown before the first cultivation, 14 days before this event.

[b] Refers to tool sequence, first tool was used at prior cultivation event. Only finger weeder used at second cultivation. See Table 1.1 for treatments.

[c] Tillage x compost x tool interaction

[d] None of the interaction means are significantly different when adjusted for multiple comparisons.

Table 1.8. Effects of tillage, compost and tool sequence on squash and weed biomass after second cultivation event, 2021 and 2022. Measured 26 days after cultivation in 2021 and 12 days after cultivation in 2022.

	Squash		Weeds					
	Total shoot biomass		Surrogate[a]		Ambient[b]		Total	
	2021	2022	2021	2022	2021	2022	2021	2022
Tillage Main Effect	-----g per plant-----		-----------g m^{-1c}----------		-----------g m^{-1}-----------		---------g m^{-1}---------	
Rototill	74.2	67.7	5.1	10.3	9.6	10.1	14.6	20.8
Strip Till	69.9	58.7	4.6	11.9	16.3	13.6	20.8	25.8
Compost Main Effect								
Compost	**82.2 a**	**70.4** a	4.0	12.1	14.4	9.0	18.4	21.3
None	**62.3 b**	**55.9** b	5.7	10.2	11.3	14.7	17.0	25.3
Tool Main Effect								
Finger-Finger	69.5	60.4	5.2	**16.4** a	**16.1** a	14.7	**21.3** a	**31.4** a
Hill-Finger	74.8	63.6	4.5	**5.9** b	**9.5** b	9.0	**14.0** b	**15.2** b
ANOVA	--- p-value							--
Tillage	0.724	0.197	0.723	0.763	0.120	0.459	0.237	0.476
Compost	**0.058**	**0.014**	0.222	0.638	0.280	0.175	0.561	0.519
Tool	0.774	0.449	0.641	**0.018**	**0.023**	0.188	**0.0047**	**0.017**
Tillage x Compost	0.425	0.870	0.668	0.325	0.968	0.426	0.906	0.907
Tillage x Tool	0.577	0.752	0.848	0.656	0.419	0.724	0.489	0.621
Compost x Tool	0.130	0.845	0.325	0.770	0.128	0.589	0.267	0.855
T x C x T[d]	0.760	0.739	0.932	0.513	0.802	0.967	0.577	0.671

[a] In 2021 surrogate was 33 days old mustard sown before second cultivation event, in 2022 it was red amaranth combined from both cultivation events (20 and 26 days old).

[b] Ambient weeds included common purslane (*Portulaca oleracea*), chickweed (*Stellaria media)*, carpetweed (*Mollugo verticillata)*, pigweed (*Amaranthus spp.)*, large crabgrass (*Digitaria sanguinalis)*, henbit (*Lamium amplexicaule)*, common lambsquarters (*Chenopodium album)*.

c Grams per meter row in the 10 cm in-row zone.

[d] Tillage x compost x tool interaction.

Table 1.9. Effects of tillage, compost and cultivation sequence on final plant density, fruit weight, and fruit number, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Plant Density		Fruit Weight				Fruit Number			
			Total		Marketable		Total		Marketable	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Tillage Main Effect	--# per row m--		--------------kg per row m -------------------				----------------# per row m---------------			
Rototill	1.00	1.04	1.95	2.07	1.59	1.91	4.06	3.04	3.02	2.79
Strip Till	0.95	1.04	1.84	2.16	1.54	2.01	3.71	3.13	2.83	2.91
Compost Main Effect										
Compost	1.00	1.05	**2.14** a	2.16	**1.77** a	2.06	**4.34** a	3.25	**3.32** a	3.00
None	1.00	1.03	**1.64** b	2.07	**1.34** b	1.85	**3.43** b	2.92	**2.54** b	2.71
Tool Main Effect										
Finger-Finger	1.00	1.05	1.92	2.22	1.58	2.03	3.93	3.22	2.99	2.95
Hill-Finger	1.00	1.03	1.87	2.01	1.54	1.88	3.84	2.95	2.87	2.76
Tillage x Compost Interaction										
Rototill + Compost	**1.05** a	1.03	2.26	2.03	1.86	1.93	4.59	3.03	3.52	2.81
Rototill	**1.11** a	1.05	1.64	2.11	1.31	1.89	3.52	3.05	2.53	2.78
Strip till + Compost	**0.98** a	1.07	2.02	2.29	1.68	2.20	4.08	3.47	3.13	3.19
Strip till	**0.83** b	1.00	1.63	2.03	1.37	1.81	3.34	2.80	2.54	2.63
ANOVA	--p-value--									
Tillage	0.073	1.000	0.497	0.634	0.693	0.558	0.344	0.689	0.485	0.584
Compost	0.424	0.496	**<0.001**	0.582	**0.002**	0.156	**<0.001**	0.124	**0.001**	0.228
Tool	0.260	0.496	0.646	0.181	0.558	0.333	0.647	0.209	0.571	0.359
Tillage x Compost	**0.095**	0.176	0.380	0.294	0.401	0.242	0.427	0.113	0.378	0.181
Tillage x Tool	0.614	0.496	0.687	0.608	0.713	0.951	0.547	0.884	0.455	0.905
Compost x Tool	0.186	0.496	0.967	0.817	0.725	0.399	0.828	0.383	0.700	0.703
T x C x T[a]	0.730	0.496	0.939	0.672	0.920	0.352	0.754	0.409	0.768	0.324

[a] Tillage x compost x tool interaction

Figure 1.1. Image of Tilmor finger weeders in squash.

Figure 1.2. Image of box used to take 3D photos of soil surface before and after cultivation. Orange stakes were centered on crop rows and middle of the bed. Plastic covered all sides of box when photos were taken.

CHAPTER TWO: Effects of Seed Size and Cultivation Tool Choice on Cultivation Efficacy and Yield in Carrots

ABSTRACT

Weed management in carrots (*Daucus carota)* is difficult due to their poor competitiveness and lack of effective herbicide options. Mechanical cultivation is important for managing weeds in carrots but can also damage crops through uprooting or burial. One approach to improving carrot tolerance to mechanical cultivation at early growth stages is to use high quality seeds of competitive cultivars. We hypothesized that larger seed size would lead to taller, better rooted carrots at the time of cultivation, which would increase their tolerance to cultivation. We also hypothesized that carrots that had higher anchorage force at time of cultivation would be more tolerant to the finger weeder—a tool believed to kill weeds primarily through uprooting — while carrots that were taller at the time of cultivation would be more tolerant to hilling disks — a tool which is designed to selectively bury small weeds. We found that carrot seedlings from large seeds had 20% greater anchorage force and 12% greater height than those from smaller seeds at the time of early cultivation. In one of two years, carrots from larger seeds were more tolerant of cultivation than carrots from small seeds. Yields were 20% greater from larger seeds than smaller seeds. Tool effects on carrots and weeds varied by year, with inadequate selectivity observed at the 1-2 leaf stage. Aggressive finger weeding resulted in stand loss, yield loss and loss of quality in 1 of 2 years. Future research will explore additional traits to improve carrot tolerance to early cultivation.

Keywords: seed size, mechanical weed cultivation, selectivity

Introduction

Weed management in young carrots is a major challenge for vegetable growers. Many growers rely heavily on herbicides, but these may have environmental and human health consequences including decreased soil species diversity, carry-over suppression of future crops, and potential health problems in mammals (Pimentel and Burgess 2014). Herbicide resistance is a serious challenge for carrot growers because overreliance on a few products has led to herbicide failures (Heap 2020). In carrots, several species of weeds have developed resistance - including linuron resistant common purslane (*Portulaca oleracea*) (Masabni and Zandstra 1999) and Powell amaranth (*Amaranthus powellii*) (McNaughton et al. 2005). Weeds are particularly challenging for organic production of carrots (Perruzi et al. 2007) which represented 14% of all carrots grown in the United States in 2017 (NASS 2019). Organic growers often rely on mechanical cultivation as one of their main approaches to managing weeds (Bond and Grundy 2001; Melander et al. 2005). Due to limited herbicide options growers often rely on tillage and hand-weeding escaped weeds. However, these methods increase soil degradation and require high labor costs (Zwickle et al. 2016). Low availability of farm workers and rising wages place greater pressure on carrot growers to find alternatives.

Mechanical cultivation can be used to help manage weeds in carrots. Several tools are effective for between-row weeds. However, in-row weeds are more challenging to manage with cultivation in young carrots without damaging or killing the carrots. To gain insight into practical approaches for managing weeds with cultivation tools in close proximity to the crop, Rasmussen (1992) defined cultivation selectivity as the ratio of weed mortality to the ratio of crop covered by soil (or crop mortality) as a measure of the ability of a tool to kill weeds without killing the crop. Kurstjens et al. (2004) predicted selectivity of a specific tool with a crop-weed combination by measuring plant traits relevant to the tool's mode of action. They modeled anchorage force of crop and weeds at the time of cultivation to predict selectivity of uprooting tools, and suggested that a similar approach could be used to predict the selectivity of tools that bury weeds based on crop and weed height. In a greenhouse experiment to test uprooting force, Fogelberg and Gustavsson (1998) found that because carrots are better rooted than most weeds at early growth stages, there is potential for selectivity of tools that utilize uprooting. However, information on the relative height of crops and weeds, and their tolerance to burial have not been extensively studied (Mohler et al. 2016).

Finger weeders and hilling disks are tools that can be used in young carrots, although few studies have evaluated the optimal timing for using these tools. In a study comparing selectivity of various tools in carrots, the finger weeder and hilling disks were found to be more selective than the torsion weeder or flextine harrow in most site-years (Hitchcock-Tilton 2018). Given the specific tool settings used in their studies, hilling disks were usually found to be overall more selective, but the finger weeder caused the lowest carrot mortality. However, variability in results across experiments was often quite large. Champagne (2022) found that finger weeders and flextine harrows did not differ in selectivity in a two-year study of in-row weed tools in carrots. Both tools resulted in about 53% in-row weed mortality. They found that in one year of the study, carrot mortality was higher from tine harrows than finger weeders, although in the second year no differences were detected. Peruzzi et al. (2007) tested vibrating tines and torsion weeders as in-row tools for carrots at early growth stages and found that both averaged 74% reduction in in-row weeds. Despite these studies that in-row cultivation can help manage weeds in carrots, a 2016 informal survey showed that few Michigan growers had tried using finger weeders in carrots (Hitchcock-Tilton 2018), likely in part due to limited availability of finger weeders and other in-row tools on organic farms during that time (Lowry and Brainard 2017). Increased availability and affordability of these tools, coupled with rising labor costs have resulted in greater interest in how to optimize their use.

Experiments evaluating mechanical cultivation tools are often highly variable, making specific recommendations for growers challenging. Sources of this variation include differences in soil conditions, tool settings, and the relative size and identity of weed-crop combinations evaluated all of which interact with tool efficacy (Gallandt et al. 2018). For example, Fogelberg and Dock Gustavsson (1998) showed that the force required to uproot carrots and weeds depends on soil type, plant development stage, and species.

To improve recommendations, a more mechanistic understanding of the efficacy of tools is needed. In particular, greater understanding of the relative tolerance of weeds and crops to forces applied by cultivation tools should help growers choose the optimal tool and timing for their situation. The hilling disks and finger weeder utilize different modes of primary action which affect their ability to manage weeds. Hilling disks bury weeds, so they take advantage of a height difference between the crop and weed to selectively kill weeds. Finger weeders—depending in part on how they are set and the soil conditions—more often kill weeds through uprooting (van der Schans et al. 2006; Peruzzi et al. 2017), so their selectivity likely depends more on a difference in anchorage force between crops and weeds. Building on the work of Kurstjens et al. (2004), we hypothesize that measurements of the anchorage force and height of carrots and weeds at the time of cultivation, may help predict the relative cultivation efficacy and selectivity of finger weeders and hilling disks.

Cultural weed management strategies that increase carrot size or strength compared to the weeds can be utilized to improve selectivity (Kurstjens and Perdok 2000). For example, Colquhoun et al. (2020) showed that adjusting cultivars, plant spacing and timing can improve weed management outcomes in carrots. Other studies have found that tolerance to cultivation may depend on carrot cultivar and seed size (Hitchcock-Tilton 2018; Champagne 2022). Specifically, Hitchcock-Tilton (2018) found that specific cultivars, like Bolero, were more tolerant of in-row cultivation tools than other cultivars. However, Champagne (2022) found no significant difference in mortality of nine carrot cultivars from cultivation at the two-leaf stage with a tine harrow or finger weeder, even though the cultivars had significant differences in root branching, anchorage force, and shoot morphology.

One approach to improving carrot early vigor and tolerance to cultivation, may be to use only the large seed classes within a seedlot. For example, Hitchcock-Tilton (2018) found that large seed size classes of the cultivar ‘Bolero’ resulted in larger plants at early stages relevant to cultivation compared to small seed size classes; in one case, larger seed size was correlated with increased tolerance to the finger weeder, but this result was not observed in other locations or with other tools. Several earlier studies have demonstrated that carrot seed sizes from a single seedlot often vary by a factor of 2-3 times (Currah and Salter 1973, Bedford and Mckay 1973 as cited in Gray and Ward 1985) and that such differences may result in greater early biomass or yield. Austin and Longden (1967) found that at similar densities, large seeds led to larger carrot yields than small seeds, and that yield of roots between 15-18 weeks was 15-20% higher from large seeds than small seeds. Hole et al. (1987) found that early absolute growth rate for different carrot cultivars was related to the initial seed weights. However, they also found that variation in root yield could not be explained by variation in seed size. However, very few studies have examined the interactions between seed size and stress from mechanical cultivation on carrot yield and profitability.

Our primary objectives were to 1) evaluate the efficacy and selectivity of finger weeders and hilling disks in organic carrot production; 2) determine if carrot seed size selection improves carrot tolerance to cultivation with either of these tools. Secondary objectives included evaluating the impacts of tools and seed size on carrot quality and yield. We hypothesized that larger seed size would lead to taller, better rooted carrots at the time of cultivation, which would increase their tolerance to cultivation. We also hypothesized that carrots that had higher anchorage force at time of cultivation would be more tolerant to the finger weeder—a tool believed to kill weeds primarily through uprooting — while carrots that were taller at the time of cultivation would be more tolerant to hilling disks — a tool which is designed to selectively bury small weeds.

Materials and Methods

Experiment Site

This study was conducted at the Michigan State Horticultural Teaching and Research Center (HTRC) in Holt, MI (42.673705,-84.484900) in 2021 and 2022. The soil was a 'Spinks loamy-sand' with pH 6.5 and 74.8% sand, 17.8% silt, and 7.4% clay. Adjacent fields were used in the two years.

Experimental Design

This experiment evaluated the effects of cultivation tool sequence and carrot seed size on crop and weed mortality, biomass and crop yield. Plots were arranged in a split plot design with cultivation tool sequence as the main plot factor, and seed size as the sub-plot factor. Three cultivation tool sequences were evaluated: 1) finger weeding for all events; 2) finger weeding alternated with hilling disks for two (2021) or three (2022) cultivation events; and 3) an uncultivated control. Seed size factor had two levels: 'large' and 'small' seed size classes from the same seedlot, separated using a seed blower. Treatments consisted of all 6 combinations of tool sequence and seed size (Table 2.1), replicated 4 times, for a total of 24 plots. ‘Bolero’ (Johnny’s Selected Seeds, Winslow ME) seeds were separated using a model 757 seed blower (Seedburo Equipment Co. Chicago, Il). For each batch of seeds, a two-step process was implemented: 1) air pressure was adjusted upward (opening top of seed blower tube to about 2.6 cm) until approximately 25% of the seeds were collected at the top of the blow tube (‘small seeds’); 2) small seeds were removed from the top and the air pressure adjusted upward (by opening the top to about 3.8 cm) until approximately 25% of the seeds were left at the bottom of the blow tube (‘large seeds’). Our seed separation method resulted in mean seed weights of 2.53 mg (SD 0.06) for the large seeds and 1.93 mg (SD 0.08) for the small seeds ($p<0.001$).

Carrots were sown using a Jang tractor mounted seeder (Jang Automation Co. Seoul, South Korea) belly mounted to a 520 Series Cultivating Tractor (Tilmor, Dayton OH). Plots were 20 feet long with three rows, spaced 38 cm and 1.3-2.5 cm in-row spacing, thinned to approximately 1.3 cm at 14 days after planting (DAP). Each plot had three adjacent permanent quadrats (1.25 x 0.1 m each) in the middle row to track weed and carrot densities throughout the experiment. From approximately 6 to 12 DAP, carrot emergence was counted daily in one quadrat from each plot to determine if seed size influenced the rate of emergence. In 2021, six days after planting, prior to carrot emergence, the plots were flame weeded using a propane flame-weeder, a common practice in organic carrots. In 2022, carrots emerged before flame weeding could be accomplished, so no flame weeding occurred. Carrots were hand-weeded and thinned to approximately 40 plants per m row 14 DAP in 2021. In 2022, carrots were hand-weeded in-row 16 DAP, but thinning was not needed due to low emergence. Basket weeding (Tilmor) was used to manage between row weeds as needed (Table 2.2). ‘Surrogate’ weeds were sown 12-13 DAP to evaluate mortality given the low and inconsistent densities of ambient weeds. Approximately 200 seeds of "Red Spike" red amaranth (*Amaranthus cruentus)* and 200 "Mighty Mustard Pacific Gold" condiment mustard (*Brassica juncea*) (Johnny's Selected Seeds) were mixed with sand, sown in the center 10 cm in one quadrat per plot and covered with a thin layer of loose soil.

Cultivation Treatments

In-row cultivation used either finger weeders (Fig. 2.1a; Tilmor) or hilling disks (Fig 2.1b; Kult Kress 'Duo' cutaway disks set to hill) belly-mounted to a manually-steered Tilmor cultivating tractor. Fingers were calibrated with the goal of 'scrubbing' soil from the in-row zone to uproot weeds, rather than pushing soil into the row to bury them. This involved raising the toolbar and adjusting the toolbar angle such that the floating arm sloped downward slightly (approximately 10-15^{o} from horizontal) until soil was observed moving out of the crop row in the calibration area. Tips of fingers were set to leave an approximately 1 cm minimum gap between tips of the fingers, centered on the crop row. Tractor speed was determined in practice beds by gradually increasing speed in order to maximize weed mortality while targeting less than 10% crop mortality. For all cultivation events in both years, with the exception of the second cultivation event in 2022, the speed required to attain approximately this level of crop mortality was estimated at 8.6 km hr^{-1}. However, for the second cultivation event in 2022, the speed was reduced to approximately 7 km hr^{-1} to reduce crop damage observed in the calibration area. In 2021, finger weeded treatments at the first cultivation event were not aggressive enough to penetrate the soil surface and kill weeds consistently in the experimental area, so the finger weeder was run a second time through each plot with the same settings within 1 hour of the first cultivation event. Cutaway disks were set with 12 cm distance between the front of disks, and 17 cm between the back with driving speed adjusted in the calibration area such that soil moved fully into the crop row with peak height at the crop line. The speed required to achieve this outcome ranged from 2-3 km hr^{-1} depending on soil conditions. However, in all cases, differences in soil conditions between the calibration area and the experimental area resulted in variation in the amount of soil movement in or out of the row.

In the uncultivated control treatments, no in-row weeding was done between the pre and post cultivation counts as a control to evaluate potential weed and carrot mortality independent of cultivation tools. These treatments were handweeded after post counts of each cultivation event to minimize competition with carrots. Cultivated treatments were also handweeded 3-4 days after the last in-row cultivation to minimize competition.

Data Collected

Before each cultivation event, the height and anchorage force were measured for six carrots in each plot. The height of both the tallest leaf and the growing point were measured, then each plant was uprooted using a Shimpo force gauge (Fig. 2.2; Model #: FGV-100XY Shimpo, Kyoto, Japan) to measure anchorage force. To measure anchorage force, a clip (Outus "Crocodile Mouth" Tarp Clips-004, 9 x 3 x 2cm) was attached to the plant stem directly above the soil surface and the plant was pulled up slowly until the plant was uprooted. Maximum force used per plant was recorded as the anchorage force. In 2022, surrogate weed heights and anchorage force were measured for three of each species per plot at the same time as the carrot measurements. In 2021, surrogate weed evaluations were limited to prior to the second cultivation event.

Carrot and surrogate weeds were counted in the in-row zone of one 1.25 x 0.10 m quadrat per plot before each cultivation event to measure initial density. For the second cultivation event in 2021, crabgrass (*Digitarius sanguilas)*, common purslane (*Portulaca oleracea),* and common lambsquarters (*Chenopodium album)* were also counted in the 10 cm in-row zone of a 1.25 m quadrat adjacent to the surrogate quadrat. The same counts were repeated 2-3 days after cultivation to evaluate mortality. Approximately 10 days after the last cultivation event, 10 carrots were sampled to measure root and shoot biomass.

In 2022, immediately before each cultivation event, soil samples were taken from each plot to a 2.5 cm depth to evaluate gravimetric water content (GWC) at the approximate working depth of tools. Samples were weighed, then dried and weighed again to calculate gravimetric water content. In 2021, for the first cultivation event, water content was monitored with a Decagon sensor, placed at approximately 2 cm depth to evaluate volumetric water content (VWC). For comparison with other events, VWC was converted to GWC by dividing by the soil's bulk density.

To evaluate soil movement into the crop row, wooden stakes were placed in the crop row of each plot and soil surface level was marked before and immediately after each cultivation event. The distance between these lines was used to estimate approximate vertical soil movement into the crop row due to each tool.

Carrots were harvested around 80 DAP. A random sample of 15 carrots were selected from the three quadrats in each plot. For this sample, fresh root and shoot biomass were collected, and the plants were dried to measure dry root and shoot biomass. Then, the remaining carrots in the three quadrats (3.75m total) were harvested from each plot. Carrots were separated into marketable vs. unmarketable. The categories for unmarketable carrots were: undersized (<15 cm diameter), forked, small and forked, nubs, and other unmarketable (including insect damage, cracked carrots, or other visible defects). In 2022, an unmarketable category for bent carrots (visually categorized based on deviation of approximately 1 cm or more from linear) was also included. For each plot, the number of carrots within each category was counted, then total fresh weight and total root weight were measured.

Data Analysis

Data were analyzed using PROC MIXED procedures in SAS (Statistical Analysis Software 9.4 Cary, NC). For responses evaluated before cultivation events (anchorage force and height), only the fixed effects of seed size were evaluated. For responses evaluated after cultivation events (weed and crop mortality, biomass and yield) the effects of seed size, cultivation tool sequence and their interactions were evaluated. Seed size and cultivation tool were considered as fixed effects. To account for the split plot design, replicate and replicate x tool were random effects. Data were analyzed separately in each year. Shapiro-Wilks and Levene's tests were used to check for normality and homogeneity of residuals. As necessary, responses were transformed to meet those assumptions, and Box-Cox test was used to find best transformation. When no transformation was possible (due to heterogeneity of residuals), a linear mixed model with unequal variances in PROC GLIMMIX in SAS was used to account for heterogenous structure (Milliken & Johnson 2009). When the main or interactive effects of seed size or tool were significant ($p < 0.1$), means were separated using Tukey's HSD with a Tukey adjustment for multiple comparisons. Main effects were discussed as significant when no interactions were significant.

Results & Discussion

Carrot Emergence

Seed size affected total emergence in one of two years (2021) and affected timing of emergence in 2022 (Table 2.3). In 2021, small seed carrots had approximately 20% greater total emergence than large seed carrots, but emergence did not differ by seed size in 2022. Although total emergence was higher for small seeds than large seeds in 2021, this affect was likely an artifact of our seeding method. In particular, the seed disk on the planter resulted in less consistent singulation of small seeds than large seeds in 2021. In 2022, a slightly larger percentage of the large seeds (95%) than small seeds (87%) had emerged on Day 9. However, no other effects of seed size on emergence timing were detected.

In contrast to our findings, several studies have shown that carrot seed grading can increase total emergence and uniformity of the timing of emergence. Uniform and early emergence may increase carrot competitiveness with weeds and reduce damage from cultivation. Austin and Longden (1967) found that large seeds had higher germination and percent seedling emergence than small seeds. Smaller seeds also had more variable seedling emergence, leading the authors to speculate that smaller seeds may be more sensitive to soil conditions at planting.

Martins et al. (2013) found that seed size significantly affected germination speed for 76% of 50 progenies tested, and a significant effect on total germination for 70% of progenies tested. However, the effect of seed size on seed germination timing and percentage varied by progeny- for some progenies smaller seeds germinated more, and for other progenies large seeds had higher germination. Therefore, they recommended that in contrast to traditional practices, small seeds should not always be removed, since seed size effect depends on the genotype. Gray and Steckel (1983a) found that grading had no effect on mean emergence time in all cases except with one group of seeds, where grading to select for larger seeds reduced mean emergence time. They also found that grading early-harvested seeds increased total emergence, but it was lower than emergence for graded or ungraded later-harvested seeds. For seeds harvested later, there was no effect of seed grading on emergence. Currah and Salter (1973) found that grading had no effect on time to 50% emergence for three of the four cultivars studied, but it did decrease that time for ‘Nantes 20’.

Field Conditions at Time of Cultivation

Prior to cultivation, soil moisture ranged from 5-11% (Table 2.4). Surrogate weeds were sown prior to each cultivation event (Table 2.2), so weeds were typically at the cotyledon stage at the time of cultivation (Table 2.4). However, for the second and third cultivation events in 2022, red amaranth as at the cotyledon to 2-leaf stage. The average height of both surrogate species was under 1 cm for all cultivation events in 2021, and the first two cultivation events in 2022 (Table 2.5). Before all cultivation events, average anchorage force was under 0.4 N for red amaranth and under 0.6 N for mustard.

Carrot Early Growth Characteristics

As expected, seed size had a significant effect on mean carrot height and anchorage force at the time of early cultivation events (Table 2.6). At the time of the first cultivation event, when carrots were in the 1-2 leaf stage, averaged over both years, the top leaf was 12% taller and the anchorage force 20% greater for carrot seedlings from large compared to small seeds. This early difference was also seen in the mean shoot biomass, which was 38% greater than that from small seed carrots in both years.

The effects of seed size on carrot growth characteristics at the time of later cultivation events differed by year (Table 2.6 and 2.8). In 2021, at the time of the second cultivation event, when carrots were in the 4-6 leaf stage, seedlings from large seeds had 50% greater shoot biomass, 23% greater height and 44% greater anchorage force than those from small seeds. However, in 2022 seed size had no detectable effect on carrot growth at either the second or third cultivation events when carrots had 2-3 or 4-6 leaves, respectively.

Previous studies have also demonstrated varying effects of carrot seed size on early growth. Gray and Steckel (1983b) also found that seed grading increased mean seedling weight. Hitchcock-Tilton (2018) found that seed size predicted plant biomass at the cotyledon and 1-true leaf stage among different carrot cultivars, but that seed size did not correlate with plant size at the time of cultivation for later-stage carrots. Seedling size uniformity is also important, since more uniform seedlings will compete less with each other and have similar tolerance to cultivation. Salter et al. (1980) and Gray and Steckel (1983a) noted that seedlings from uniform seed sizes will not necessarily be more uniform because seedling size is more dependent on embryo size than seed weight. However, Gray and Ward (1985) found that seed weight and endosperm volume are closely linearly related, which suggests that seed weight may be correlated with seedling size. They did note that the correlation between seed weight and endosperm size was different in different years of the study, suggesting that it can be affected by environmental conditions.

Carrot Cultivation Tolerance

Carrots from large seeds were more tolerant of cultivation than carrots from small seeds at the first cultivation in one of two years (Table 2.7). In 2022 at the first cultivation event (carrots at 1-2 leaf stage), carrot mortality from large seeds (27%) was lower than for carrots from small seeds (35%). However, at all other cultivation timings in both years, there was no detectable effect of seed size on carrot tolerance to either cultivation tool (Tables 2.7 and 2.9; no significant tool x seed size interactions). Cultivation tool had no detectable effects on carrot survival at any timing (Tables 2.7 and 2.9). In 2021, we did not detect any difference in carrot mortality from the finger weeder and hilling disk at the first cultivation; average mortality was 13% across both tools. In 2022, carrot mortality from the finger weeder and hilling disk at the first cultivation did not differ from each other; both cultivation tools resulted in approximately 30% carrot mortality. For later cultivation events—when carrots were at the 2-6 leaf stages--mortality from both tools was low (<5% in all cases), and there were no significant differences in carrot survival between tools.

Although carrot seed size increased anchorage force and height at the time of first cultivation, it only improved carrot tolerance to cultivation in one of two years. Similarly, Hitchcock Tilton (2018) found inconsistent effects of carrot seed size or cultivar on tolerance to cultivation; in one of two years, carrot seedlings from large seeds were more tolerant to cultivation from a torsion weeder than those from small seeds; however, they observed no effect in the second year, nor any effect on tolerance to finger weeders or hilling disks Champagne (2022) found that although carrot cultivars differed in their anchorage force, root branching and shoot morphology at the two-leaf stage, they did not differ in their cultivation tolerance. Champagne (2022) suggests that perhaps larger roots and shoots do not lead to improvements in cultivation tolerance, and that improving other traits like root length or width, petiole angle, or embryo length could improve selectivity. Alternatively, improvements in mechanical cultivation precision and consistency may be needed to take advantage of anchorage force or height differences to improve selectivity in carrots and other crops (Gallandt et al. 2018).

Tool and Seed Size Effects on Weed Mortality and Selectivity (First and Third Cultivation Events)

Weed mortality at the first cultivation event—when carrots were at the 1-2 leaf stage--was affected by tool and carrot seed size in one of two years (Table 2.7). The effects of tool on weed mortality at that timing varied by year and species. In 2021, at the first cultivation event, weed mortality did not differ between the finger weeder and hilling disk, averaging 36% for red amaranth and 23% for mustard. In 2022, red amaranth mortality was higher (72%) for the hilling disk than for the finger weeder (44%). In 2022, mustard mortality did not differ between the two tools (approximately 57% for both). In 2022 only, tool and seed size effects on surrogate weed mortality were also evaluated at the third cultivation event (Table 2.7) when carrots were at the 4-6 leaf stage, and surrogates at the 1-2 leaf stage (Table 2.4). At that timing, mustard mortality was higher (84%) in the small seed carrots than in the large seed carrots. At the third cultivation event, efficacy did not differ between finger weeders and hilling disks, with tools killing 88% of red amaranth and 77% of mustard surrogates on average.

Our results imply that the selectivity of both finger weeders and hilling disks was low at the first cultivation event. Although a larger fraction of weeds were killed compared to carrots at this early stage in both years (Table 2.7), crop mortality was likely unacceptably high for most growers, particularly in 2022, when it averaged 31%. Using crop survival divided by weed survival as a measure of selectivity (see Hitchcock-Tilton 2018) we found average selectivity of approximately 1.5 over the two years of the experiment, with little or no meaningful impact of seed size or tool. Unsurprisingly, selectivity was much higher (5-10) at the third cultivation event in 2022, when carrots had a substantial size advantage compared to weeds (Tables 2.5 and 2.6).

Tool Sequence and Seed Size Effects on Weed Mortality and Selectivity (Second Cultivation Event)

At the second cultivation event, we evaluated the effects of seed size and previous cultivation tool (finger weeder or hilling disk) on finger weeder efficacy, finding that results differed by year (Table 2.9). In 2021, finger weeders were roughly twice as effective at killing weeds at the second cultivation event when they followed hilling disks rather than finger weeders at the first cultivation event. However, this difference was not observed in 2022. Given no difference in crop mortality due to tool in 2021, these results correspond to an increase in selectivity of finger weeding of approximately 40% when following a hilling disk then when following a finger weeder.

Although we had expected carrot seed size to increase carrot tolerance to cultivation, it is not surprising that it did not affect weed mortality at most events, since tools were run at the same intensity (same speed, depth, angle, etc.) across carrot seed size treatments.

These results illustrate the ongoing challenge of achieving selectivity in the in-row zone of carrots at the 1-2 leaf stage. High carrot mortality from the hilling disks and finger weeders at the carrot 1-2 leaf stage, combined with inadequate efficacy on weeds in both years of our study demonstrates an ongoing need to identify methods to improve early carrot establishment relative to weeds, or the precision of cultivation tools. In addition to seed grading and cultivar choice, other approaches may be helpful for improving carrot vigor at the time of early cultivation. For example, seed priming or other seed treatments may increase early carrot growth. For example, Brocklehurst and Dearborn (1983) found that priming carrot seeds with polyethylene glycol increased rate of emergence and increased average plant weights by up to 33% at early stages. Munawar et al. (2013) found that priming carrot seeds with a 1.5% zinc solution could increase percent emergence, rate of emergence, seedling size, and vigor index. However, more rapidly emerging carrots may interfere with grower’s ability to flame weed to kill weeds before carrot emergence.

Improved selectivity at early growth stages of carrots may also be attained through improvements in the precision of tools used. In organic carrot production, most growers rely on handweeding at early stages to selectively remove weeds. Rapid improvements in camera vision systems, AI and robotic weeding hold promise for approximating levels of selectivity attainable by such hand-weeding operations (Fennimore et al. 2016). However, they are currently expensive, slow and insufficiently precise to be of practical benefit to carrot growers. Shorter-term approaches to improve precision of more traditional tools like those tested in this study, include more precise bed preparation and planting, as well as improvements in steering and depth control to improve the precision and reduce the variance of tool forces applied to weeds (Gallandt et al. 2018). For example, in our study, carrots were planted and weeded using human steering on a belly mounted tractor. More precise steering for both operations is possible with RTK-GPS and camera guidance systems currently available and would improve the selectivity of these tools.

Although we did not detect consistent differences between tool type on crop and weed mortality, our results support previous work suggesting that the choice of tools and tool sequence can have important impacts on selectivity. Under the conditions of our study, hilling improved efficacy relative to finger weeding in 1 of 2 years (Table 2.7). Hilling at the first cultivation event also improved the efficacy of finger weeding at the second cultivation event in 1 of 2 years (Table 2.9). Other studies in carrots have shown inconsistent results of tool choice. For example, Champagne (2022) and Peruzzi et al. (2007) both compared two different in-row tools (finger weeder vs. tine harrow and torsion weeder vs. vibrating tines), and found that when used at the same timings, tool choice did not affect weed mortality. However, Hitchcock-Tilton (2018) found that efficacy and selectivity varied with tool- with hilling disks provided greater selectivity than finger weeders for broadleaf weeds in 1 of 3 trials. He also found that stacked tools generally showed greater selectivity than single tools, although often at the expense of high crop mortality.

Carrot Yield

In both years, carrots from large seeds produced a higher total yield than those from small seeds (Table 2.10). In 2021, large seeds produced 18% greater total yield than small seeds, and in 2022 large seeds produced 15% greater yield than small seeds. A similar seed size effect was also seen in marketable yield in both years. In 2021, marketable yield was 23% higher in large seed carrots than small seed carrots, and in 2022 marketable yield was 17% higher in large seed carrots than small seed carrots. In 2021, large seed carrots also had significantly higher total and marketable fresh root weights per plant than small seed carrots, although fresh root weight was not different between seed sizes in 2022.

The effect of tool sequence on carrot yield was different between the two years but did not vary by seed size (Table 2.10; no significant tool x seed size interactions). In 2021, total and marketable yield were not different between the tool treatments. In 2022, however, total and marketable yield were significantly lower in the finger weeded treatment than in the handweeded control or alternating tool treatments. The average marketable yield in the finger weeded treatment was only 62% of the yield of the handweeded control, but the alternating tool yield did not differ from the handweeded control.

In both years, more carrots were harvested from the handweeded control than from the finger weeded treatment, but neither differed from the alternating tools treatment (Table 2.10). In 2021, the number of marketable carrots did not differ by tool, but in 2022 finger weeded plots had fewer marketable carrots than the alternating tool plots or handweeded controls. In 2021, both the total and marketable fresh root weights per plant were higher in the finger weeded treatment than in the alternating tool treatment and handweeded treatment. In 2022, total and marketable root fresh weights per plant were higher in both the finger weeded and alternating tool treatments than in the handweeded treatment.

Tool and seed size significantly affected carrot shoot, root, and total dry weight per plant at harvest, but the effects varied by year (Table 2.11). In 2021, carrot shoot, root, and total dry weights per plant were higher for large seed carrots, but in 2022 carrot dry weights did not differ by seed size. In 2021 dry root weight and dry total weight per plant were higher in the finger weeded treatment than the alternating tool and handweeded treatments. In 2022, carrot dry shoot weight was higher in the finger weeded treatment than the handweeded treatment. Biomass allocation, as measured by the root to shoot ratio at harvest, did not differ by seed size or tool in either year.

Larger carrot seed sizes did not consistently increase tolerance to cultivation, but larger seed sizes produced larger yields in both years. Other studies have found similar yield benefits from large seed sizes. Austin and Longden (1967) found that when grown at the same density, carrots from larger seed sizes had higher average yields than carrots from small seeds. They attributed this effect mostly to low yields from the two smallest seed sizes, suggesting that removing the smallest seeds might have the biggest yield effect. Salter et al. (1981) also found that root weight at harvest was increased by grading. However, Hole et al. (1987) found that in a study of nine carrot cultivars, seed weight did not correlate with root yield. Currah and Fellows (1981 cited in Gray and Steckel 1983a) explain that most of the variation in carrot root weight is associated with variation in seedling weight. As noted above, seedling weight is more strongly correlated with embryo size than seed weight (Gray and Steckel 1983a), suggesting that embryo size may have more of an effect on root yield than seed weight.

Although carrot mortality from cultivation may have been higher than many growers would tolerate —especially at the first cultivation event in 2022—yield loss resulting from this crop damage was observed only for the finger weeder treatment in 2022 (Table 2.10). As observed in previous studies (Hitchcock-Tilton 2018; Ascard & Mattsson 1994), the negative effects of cultivation on plant population density appear to have been partially or completely overcome by greater growth of individual carrots in several cases (Tables 2.10 and 2.11), presumably due to reduced intraspecfic competition for water, nutrients or light in the presence of fewer neighbors. Individual carrot fresh root weight was 20-24% higher in the fingerweeded treatments than the handweeded control. Other studies have found similar results in onions and beets- early cultivation can reduce stand density without significant yield effects (Ascard & Bellinder 1996).

Carrot Quality

The effect of carrot seed size on carrot quality varied between the two years. In 2021, 28% of the small seed carrots were unmarketable compared to only 22% of the large seed carrots (Table 2.12). However, in 2022, no effects of seed size on percent marketable carrots were detected. In 2021, more carrots from small seeds were undersized than from larger seeds, however in 2022 the percentage of undersized carrots did not differ by seed size. In 2022, there was a larger percent of bent carrots from small seeds than from large seeds. In 2021, there were a larger number of unmarketable ‘other’ carrots from large seeds than small seeds, although the number of ‘other’ unmarketable carrots did not differ by seed size in 2022.

The effect of tool treatment on carrot quality also varied between the two years (Table 2.12). In 2022 the finger weeded treatment had more unmarketable carrots (32.9%) than the hilling disk treatment (19.6%), but in 2021 there was no detectable tool effect on carrot quality.

In 2021, there was a higher percent of nub carrots from the small seeded alternating tool (6%) treatments than from the large seed handweeded or large seeded alternating tool treatments (0% from both).

The varying effects of tool sequence on carrot quality are likely due to a combination of direct and indirect effects of cultivation. Cultivation may directly reduce carrot quality by physically damaging carrot tap roots which results in more forks and nubs, although those differences were not consistently detectable in our study. Cultivation may also indirectly affect root quality through changes in plant density that may influence intraspecific competition and carrot growth. In our study, high carrot mortality from early cultivation events reduced carrot stand density. In 2021, this resulted in larger carrot size, and hence fewer carrots in the 'small' unmarketable category. However, in 2022, no such cultivation effects on size class were detected. In that year, our results suggest direct physical damage from the finger weeder was responsible for reduced carrot quality. Previous studies have shown similarly inconsistent effects on quality. White and Strandberg (1978) found that at optimal temperatures, taproots reach full length within the first 24 days after seeding, and that any root injury or disruption of the rapid early growth can lead to forking or stubbed roots. Ascard and Mattsson (1994) observed a higher proportion of branched carrots in inter-row cultivated treatments by a hoe and brush-weeder compared to uncultivated treatments, which they attributed to damage from lateral soil movement from the implements. In a three-year study of carrots with an 'innovative' cultivator that had vibrating tines and torsion weeders to manage weeds in row, Peruzzi et al. (2007) found no decrease in carrot quality from the innovative system compared to the standard system without torsion weeders or tines. In some years, the innovative system led to higher carrot density and yield than the standard system. Trembley (1997) found no decrease in carrot yield or quality when comparing treatments mechanically cultivated with torsion weeders, basket hoe, or tine harrow with herbicide and weed-free treatments. In one year of their experiment, they applied an herbicide over mechanically cultivated plants which decreased the stand density, but similar to our findings this did not reduce yield.

Carrot mortality from cultivation is a concern from growers, especially since carrots grow slowly and are vulnerable to damage from cultivation tools. Growers' willingness to accept carrot morality depends on the density of the carrots at the time of cultivation (e.g. thick stands may benefit from thinning) and the perceived costs of weed escapes. As the cost of hand weeding increases, growers are likely to accept greater stand losses in order to control a larger percentage of the weeds. In our study, carrot mortality from finger weeders and hilling disks ranged from 10% to 33% from our first cultivation event, while weed mortality ranged from 21-72%. Champagne (2022) observed only 9-10% carrot mortality and 53% weed mortality from cultivation with finger weeders in carrots at the two-true leaf stage, and Hitchcock-Tilton (2018) observed an average of 6-26% carrot mortality and 9-88% weed mortality from finger weeders. These comparisons suggest that our tools may have been set more aggressively than previous studies or typical grower practice. The reason for large difference in carrot mortality from the same tools used on similar sized carrots between the two years are unclear, but may have been due to differences in soil conditions or tool settings. For example, soil moisture was lower before all cultivation events in 2021 than 2022 (Table 2.4). Other research suggests that cultivation selectivity is highly dependent on conditions including soil moisture (Gallandt et al. 2018). Kurstjens et al. (2000) showed that susceptibility to uprooting varies with soil moisture, and Mohler et al. (2016) demonstrated that recovery of plants from burial depends on soil moisture.

Overall, our results suggest that both finger weeder and hilling disks can be valuable tools for managing in-row weeds in carrots, but both carry considerable risks when applied at the 1-2 leaf stage. In one of two years, carrot yield was lower in the finger weeded treatment than the hilling disk treatment, and in some cases it was less effective at killing weeds. Finger weeding was also associated with an increase in unmarketable carrots in one of two years. Seed size selection did improve early growth characteristics, and in one of two years large seeds improved cultivation tolerance. Large seed sizes increased yield by 20% compared to small seed sizes, suggesting that growers might benefit from purchasing larger seed grades if available, and seed companies might set higher size limits when grading seeds. Additional research could focus on other seed improvements to increase tolerance to cultivation.

LITERATURE CITED

Ascard J, Bellinder RRB (1996) Mechanical in-row cultivation in row crops. Second International Weed Control Congress, Copenhagen

Ascard J, Mattsson B (1994) Inter-row cultivation in weed-free carrots: the effect on yield of hoeing and brush weeding, Biol Agric Hortic 10(3):161-173

Austin RB, Longden PC (1967) Some Effects of Seed Size and Maturity on the Yield of Carrot Crops, Journal of Horticultural Science 42(4):339-353

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

Brocklehurst PA, Dearman J (1983) Interactions between seed priming treatments and nine seed lots of carrot, celery and onion. II. Seedling emergence and plant growth. Ann Appl Biol 102(3):585-593

Champagne R (2022) Evaluating Physical and Cultural Methods to Improve Weed Management in Organic Vegetables. PhD Dissertation. Orono, ME: University of Maine. 105 p

Colquhoun JB, Rittmeyer RA, Heider DJ (2020) A holistic carrot production system for season-long weed management. Weed Technol 34(6):876-881

Currah IE, Salter PJ (1973) Some combined effects of size grading and 'hardening' seed on the establishment, growth, and yield of four varieties of carrots. Annals of Botany 37(152):709-719

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

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

Gray D, Ward JA (1985) Relationships between seed weight and endosperm characteristics in carrot. Ann Appl Biol 106:379-384

Gray D, Steckel JRA (1983a) Some effects of umbel order and harvest date on carrot seed variability and seedling performance, Journal of Horticultural Science 58(1):73-82

Gray D, Steckel JRA (1983b) Seed quality in carrots: the effects of seed crop plant density, harvest date and seed grading on seed and seedling variability, Journal of Horticultural Science 58(3):393-401

Heap I (2020) The international survey of herbicide resistant weeds. www.weedscience.org Accessed April 5, 2021

Hithcock-Tilton S (2018) Improving Weed Management in Carrots With Stacked In-Row Weeding Tools and Cultivation-Tolerant Cultivars. MS Dissertation. East Lansing, MI: Michigan State University. 127 p

Hole CC, Morris GEL, Cowper AS (1987) Distribution of dry matter between shoot and storage root of field-grown carrots. I. Onset of differences between cultivars. Journal of Horticultural Science 62(3):335-341

Kurstjens DAG, Perdock UD (2000) The selective soil covering mechanism of weed harrows on sandy soil. Soil and Tillage Res 55(3-4):193-206

Kurstjens DAG, Kropff MJ, Perdock UD (2004) Method for predicting selective uprooting by mechanical weeders from plant anchorage forces. Weed Sci 52:123-132

Martins CC, Silva ND, Machado CG (2013) Carrot seed size and progenies influence on seed physiological quality and plant productivity performance. Journal of Food, Agriculture & Environment 11 (3&4):1143-1147

Melander B, Rasmussen IA, Bàrberi P (2005) Integrating physical and cultural methods of weed control—examples from European research. Weed Sci 53:369–38

Milliken GA, Johnson DE (2009) Analysis of Messy Data Vol 1: Designed Experiments. CRC Press

Mohler CL, Iqbal J, Shen J, DiTommaso A (2016) Effect of Water on Recovery of Weed Seedlings Following Burial. Weed Sci 64:285-293

Munawar M, Ikram M, Iqbal M, Raza MM, Habib S, Hammad G, Najeebullah N, Saleem M, Ashraf R (2013) Effect of seed priming with zinc, boron and manganese on seedling health in carrot (Daucus carota L.). International Journal of Agriculture and Crop Sciences 5(22):2697

National Agricultural Statistics Service (NASS) (2019) Certified organic vegetables grown in the open harvested and value of sales: 2019. https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Organics/organics_1_002%20_002.pdf Accessed October 30, 2022

Peruzzi A, Gianni M, Fontanelli M, Raffaelli M, Barberi P (2007) Innovative strategies for on-farm weed management in organic carrot. Renewable Agric Food Syst 22(4):246-259

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. Journal of Agricultural Engineering, 48(2):57-70

Pimentel D, Burgess M (2014) Environmental and economic costs of the applications of pesticides primarily in the United States. Pages 47-71 *in* Pimentel D, Peshin R, eds. Integrated Pest Management. Dordrecht: Springer

Rasmussen J (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. Weed Res 32:267-274

Salter PJ, Currah IE, Fellows JR (1981) Studies of some sources of variation in carrot root weight. J Agric Sci 96:549-556

Trembley ML (1997) The effect of mechanical weed cultivation on crop yield and quality, disease incidence, and phenology in snap bean, carrot and lettuce crops. MS Thesis. Montreal: McGill University

van der Schans D, Bleeker PO, Molendijk L, Plentinger M, van der Weide RY, Lotz B, Bauermeister R, Total R, Baumann DT (2006). In: D. van der Schans and P. Bleeker (Eds.), Practical weed control in arable farming and outdoor vegetable cultivation without chemicals. Applied plant research, Wageningen, UR.

White JM, Strandberg JO (1978) Early root growth of carrots in organic soil. J Amer Soc Hort Sci 103(3):344-347

Zwickle S, Wilson R, Bessette D, Herms C, Doohan D (2016) Facilitating ecological weed management decisions by assessing risk-benefit tradeoffs. Agroecol and Sustainable Food Syst 40(7):635-659

APPENDIX

Tables And Figures

Table 2.1. Seed size and cultivation tool sequence for experimental treatments, 2021 and 2022.

		Cultivation Tool and Sequence		
Treatment Number	Seed Size[a]	Event 1	Event 2	Event 3[b]
1	Small	Uncultivated	Uncultivated[c]	Uncultivated
2	Large	Uncultivated	Uncultivated[c]	Uncultivated
3	Small	Finger weed	Finger weed	Finger weed
4	Large	Finger weed	Finger weed	Finger weed
5	Small	Hill	Finger weed	Hill
6	Large	Hill	Finger weed	Hill

[a] Seed size refers to separated 'Bolero' carrot seeds from one seed lot. Seeds were separated by weight, small is smallest 25% of sample, large is largest 25%.
[b] Only occurred in 2022.
[c] Handweeded in 2021.

Table 2.2. Schedule of field operations, 2021 and 2022.

		2021		2022	
	Operation	**Date**	**DAP**[a]	**Date**	**DAP**
Pre-plant	Rototill to kill cover crop	4/27	-36	4/27	-27
	Subsoiling	5/11	-22	NA[b]	NA
	Fertilize	5/11	-22	NA	NA
	Rototill to work in fertilizer	5/11	-22	NA	NA
	Treffler	5/27	-6	5/24	0
	Basket Weeded			5/24	0
Pre-emergence	Plant carrots	6/2	0	5/24	0
	Basket weeded	6/4	2	NA	NA
	Propane flame weeder	6/7	5	NA	NA
Early post-emergence	Basket weeded			5/31	7
	Thin to 1.3 cm spacing	6/14	12	NA	NA
	Handweed ambient weeds	NA	NA	6/9	16
	Basket weeded			6/10	17
Cultivation Event 1	Sow surrogate weeds	6/14	12	6/6	13
	Pre cultivation counts	6/24	22	6/15	22
	Cultivation 1 (finger weeder and hilling disks)	6/24	22	6/15	22
	Post cultivation counts	6/28	26	6/20	27
	Carrot biomass	6/29	27	6/24	31
	Surrogate weeds biomass	6/30	28	6/22	29
	Sidedress & Basket weeded	7/7	35	7/1	38
Cultivation Event 2	Sow surrogate weeds	7/7	35	6/16	23
	Pre cultivation counts	7/17	45	6/27	34
	Cultivation 2 (finger weeder)	7/15	43	6/27	34
	Post cultivation counts	7/19	47	6/29	36
	Carrot biomass	NA	NA	7/7	44
Cultivation Event 3	Sow surrogate weeds	NA	NA	6/29	36
	Pre cultivation counts	NA	NA	7/8	45
	Cultivation 3 (finger weeder and hilling disks)	NA	NA	7/8	45
	Post cultivation counts	NA	NA	7/11	48
Post Cultivation	Timed handweeding and/or biomass of ambient	7/19	45	7/11	48
	Carrot biomass	7/27	55	7/18	55
	Harvest	8/23	82	8/9	77

[a] Days after planting

[b] Not applicable

Table 2.3. Effect of seed size on carrot total emergence and uniformity of emergence, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Total Emergence		% Emerged by Day After Planting													
			Day 6		Day 7		Day 8		Day 9		Day 10		Day 12		Day 13	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	------# m^{-1}-----		---% ---													
Seed Size Main Effect																
Large	**45** a	30	2	NA[a]	NA	8	80	67	89	**95** a	NA	95	100	NA	NA	100
Small	**55** b	31	3	NA	NA	12	80	63	88	**87** b	NA	95	100	NA	NA	100
ANOVA	---p-value---															
Seed Size	**0.003**	0.754	0.205	NA	NA	0.167	1	0.580	0.83	**0.081**	NA	0.96	1	NA	NA	1

[a] Not applicable

Table 2.4. Gravimetric soil moisture and leaf stage of carrots and seeds before cultivation events, 2021-22.

	Gravimetric Soil Moisture		Leaf Stage					
			Red Amaranth		Mustard		Carrots	
	2021	2022	2021	2022	2021	2022	2021	2022
Cultivation Event	------%------		--leaf # per plant--		--leaf # per plant--		--leaf # per plant--	
First Cultivation	8.3[a]	5.0	Cot[b]	Cot	Cot	Cot	1-2	1-2
Second Cultivation	11.0	8.7	Cot	Cot-2	Cot	Cot-2	4-6	2-3
Third Cultivation	NA	8.0	NA	Cot-2	NA	Cot	NA	4-6

[a] approximated from volumetric water content

[b] cot = cotyledon

[c] Not applicable

Table 2.5. Summary of surrogate weed height and anchorage force before cultivation events, 2021 and 2022. Weeds sown approximately 5 days before cultivation, see Table 2.2 for timing.

	First Cultivation[a]				Second Cultivation[b]								Third Cultivation[c]			
	Height		Anchorage Force		Height				Anchorage Force				Height		Anchorage Force	
	2022		2022		2021		2022		2021		2022		2022		2022	
	Mean	SD[d]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Species	-----cm-----		------N------		---------------cm-------------				------------N------------				-------cm-----		-------N-------	
Red Amaranth	0.79	0.20	0.35	0.11	0.54	0.17	1.53	0.62	0.18	0.15	0.25	0.11	1.40	0.59	0.25	0.23
Mustard	0.86	0.23	0.55	0.19	0.75	0.24	1.00	0.36	0.40	0.20	0.37	0.11	1.19	0.51	0.40	0.22

[a] For first cultivation event no weed size data was collected in 2021. In 2022, both weed species at cotyledon stage.

[b] In 2021, both weeds at cotyledon stage. In 2022, both weeds at coteldyon-2 leaf stage.

[c] Third cultivation event only done in 2022. Red amaranth at cotelydon-2 leaf stage, mustard at cotyledon stage.

[d] SD= standard deviation

Table 2.6. Effects of carrot seed size on carrot seedling shoot biomass, anchorage force and height at the time of first and third cultivation events, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Pre-Cultivation 1[a]												Pre-Cultivation 3[b]					
	Shoot Biomass				Height				Anchorage Force				Shoot Biomass		Height		Anchorage Force	
	2021		2022		2021		2022		2021		2022		2022		2022		2022	
	Mean	SD[c]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Seed Size	-----------mg-------------				-------------cm------------				---------------N------------				-----mg------		----cm----		------N-----	
Large	**11.27** a	2.64	**10.67** a	2.38	**3.75** a	0.90	**3.68** a	0.61	**1.30 a**	0.40	**1.35 a**	0.28	589.60	217.94	21.82	4.94	13.78	5.17
Small	**8.18** b	1.42	**8.15** b	2.38	**3.70** b	1.04	**3.41** b	0.78	**1.04 b**	0.31	**1.12 b**	0.23	563.14	201.06	21.29	4.85	13.34	5.53
ANOVA	------------------------------------p-value------------------------------------																	
Seed Size	**<0.001**		**<0.001**		**0.003**		**0.005**		**<0.001**		**<0.001**		0.662		0.384		0.431	

[a] Carrots at 1-2 true leaf stage.

[b] Only occurred in 2022. Carrots at 4-6 leaf stage.

[c] SD= Standard deviation

Table 2.7. Effects of carrot seed size and tool on carrot and weed mortality at first and third cultivation events, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Cultivation 1						Cultivation 3		
	Carrots		Red Amaranth		Mustard		Carrots	Red Amaranth	Mustard
	2021	2022	2021	2022	2021	2022	2022	2022	2022
Seed Size Main Effect									
Large	14.2	**26.9** b	33.9	58.4	20.5	58.2	1.1	86.5	**70.0** b
Small	12.5	**35.3** a	38.2	57.2	26.0	57.4	1.6	90.5	**84.3** a
Tool Main Effect									
Finger	10.0	28.9	30.1	**44.0** b	20.8	55.1	-1.2	88.8	74.9
Hilling Disk	16.7	33.3	42.0	**71.6** a	25.8	60.6	3.9	88.1	79.0
ANOVA	--p-value--								
Seed Size	0.608	**0.071**	0.568	0.867	0.332	0.912	0.863	0.114	**0.070**
Tool	0.132	0.552	0.189	**0.031**	0.542	0.490	0.357	0.866	0.582
Seed Size x Tool	0.475	0.144	0.771	0.107	0.281	0.742	0.498	0.121	0.600

[a] Hilling Disk

Table 2.8. Effects of carrot seed size on carrot seedling shoot biomass, anchorage force and height at the time of second cultivation event, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Pre-Cultivation 2[a]											
	Shoot Biomass				Height				Anchorage Force			
	2021		2022		2021		2022		2021		2022	
	Mean	SD[b]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	----------------------mg-------------------------				--------------------cm----------------				----------------N--------------			
Seed Size Main Effect												
Large	**211.35** a	55.84	86.02	36.36	**12.4** a	2.75	10.09	2.20	**7.48** a	2.80	3.85	1.72
Small	**143.28** b	57.02	80.40	26.44	**10.1** b	5.18	9.67	1.92	**5.18** b	2.06	3.77	1.58
ANOVA	---p-value--											
Seed Size	**0.008**		0.590		**<0.001**		0.151		**<0.001**		0.874	

[a] In 2021, carrots at 4-6 leaf stage. In 2022, carrots at 2-3 leaf stage.

[b] SD= standard deviation

Table 2.9. Effects of previous tool and carrot seed size on finger weeder efficacy and crop mortality at second cultivation, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Carrot mortality		Weed mortality[a]	
	2021	2022	2021	2022
Seed Size Main Effect	----------------------------	---------------%---------------	----------------------------	
Large	-1.7	7.7	35.5	61.8
Small	-0.5	10.0	27.7	53.6
Tool[b] Main Effect				
Finger-Finger	-2.8	9.5	**19.1** b	53.8
Hill-Finger	0.6	9.7	**44.1** a	62.9
ANOVA	----------------------------	-------------p-value-------------	----------------------------	
Seed Size	0.463	0.433	0.380	0.445
Tool	0.457	0.251	**0.057**	0.271
Seed Size x Tool	0.202	0.452	0.827	0.360

[a] Weeds in 2021 included red amaranth, mustard, carpetweed, purslane, and crabgrass. In 2022, weeds included red amaranth and mustard. These were combined due to insufficient numbers of any single species.

[b] Note that at second cultivation, the finger weeder was used for both tool sequences (see Table 2.1).

Table 2.10. Effects of carrot seed size and cultivation tool on yield and final number of carrots, 2021 and 2022. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Yield				Carrot Number				Root fresh weight per plant			
	Total		Marketable		Total		Marketable		Total		Marketable	
Factors	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
	------------- g m^{-1} ----------				---------- # m^{-1} ----------				---------- g per plant ----------			
Seed Size Main Effect												
Large	**1189** a	**1136** a	**1059** a	**867** a	23.3	24.6	18.2	18.1	**52.2** a	47.3	**59.7** a	49.2
Small	**1006** b	**988** b	**862** b	**744** b	24.8	22.1	17.8	16.4	**40.6** b	44.3	**47.9** b	46.4
Tool Main Effect												
Finger-Finger	1088	**840** b	959	**572** b	**21.3** b	**17.6** b	16.8	**11.7** b	**52.3** a	**48.4** a	**58.6** a	**49.9** a
Hill-Finger(-Hill)[a]	1035	**1143** a	903	**936** a	23.2 ab	23.8 ab	16.8	**18.8** a	**44.8** b	**48.2** a	**53.3** b	**49.8** a
Handweeded	1168	**1203** a	1020	**910** a	**27.5** a	**29.7** a	20.5	**21.1** a	**42.2** b	**40.3** b	**49.5** b	**43.7** b
ANOVA	------------------------------p-value------------------------------											
Seed Size	**0.036**	**0.098**	**0.027**	**0.098**	0.374	0.318	0.804	0.360	**0.0006**	0.250	**0.0001**	0.219
Tool	0.520	**0.026**	0.526	**0.027**	**0.052**	**0.010**	0.126	**0.007**	**0.036**	**0.080**	**0.077**	**0.087**
Seed Size x Tool	0.203	0.589	0.227	0.774	0.230	0.324	0.129	0.450	0.445	0.738	0.276	0.790

[a] Hilling disk used for third cultivation event which was only done in 2022, see Table 2.1 for treatments.

Table 2.11. Effect of carrot seed size and cultivation tool on carrot biomass per plant and root-shoot ratio at harvest, 2021-22. Statistical significance ($p < 0.1$) is indicated by different letters within the same column.

	Total Dry Weight		Shoot Dry Weight		Root Dry Weight		R:S Ratio[a]	
	2021	2022	2021	2022	2021	2022	2021	2022
Seed Size Main Effect	--g per carrot ---------------------------------							
Large	**11.54** a	9.57	**4.65** a	3.85	**6.89** a	5.72	1.53	1.52
Small	**8.95** b	9.74	**3.51** b	4.02	**5.44** b	5.67	1.58	1.48
Tool Main Effect								
Finger-Finger	**11.74** a	10.12	4.66	**4.34** a	**7.08** a	5.69	1.53	1.36
Hill-Finger (-Hill)[b]	**9.48** b	10.10	3.76	4.09 ab	**5.71** b	6.01	1.55	1.52
Handweeded	**9.50** b	8.80	3.82	**3.42** b	**5.69** b	5.38	1.60	1.59
ANOVA	--p-value --							
Seed Size	**<0.001**	0.803	**<0.001**	0.541	**<0.001**	0.869	0.498	0.274
Tool	**0.042**	0.169	0.150	**0.092**	**0.018**	0.346	0.917	0.163
Seed Size x Tool	0.490	0.919	0.538	0.627	0.435	0.969	0.997	0.285

[a] Root: shoot ratio.

[b] Hilling disk used for third cultivation event only in 2022, see Table 2.1 for treatments.

Table 2.12. Effects of carrot seed size and tool on carrot quality measures at harvest, 2021 and 2022. Statistical significance (p < 0.1) is indicated by different letters within in the same column.

	% Forked		% Bent [a]	% Undersized[b]		% Nub		% Other[c]		% Unmarketable[d]	
	2021	2022	2022	2021	2022	2021	2022	2021	2022	2021	2022
Seed Size Main Effect											
Large	6.1	9.0	**7.5** b	**10.2** b	4.3	0.3	5.2	**5.5** a	0.7	**22.1** a	26.7
Small	4.3	7.1	**9.5** a	**17.8** a	3.5	2.4	5.9	**3.2** b	0.4	**27.7** b	26.3
Tool Main Effect											
Finger-Finger	6.0	11.1	9.8	9.4	3.3	0.4	8.2	5.6	0.6	21.4	**32.9** a
Hill-Finger(-Hill)[e]	6.2	5.6	7.4	15.2	2.9	3.1	3.6	2.7	0.2	27.2	**19.6** b
Handweeded	3.4	7.6	8.1	17.3	5.8	0.5	4.7	4.8	1.0	26.0	27.2 ab
ANOVA	--p-value--										
Seed Size	0.209	0.412	**0.052**	**0.004**	0.510	0.102	0.610	**0.087**	0.429	**0.026**	0.875
Tool	0.260	0.252	0.633	0.100	0.371	0.314	0.148	0.215	0.335	0.134	**0.099**
Seed Size x Tool	0.334	0.298	0.937	0.354	**0.056**[f]	**0.084**[g]	0.629	0.270	0.391	0.400	0.119

[a] Only included as a category in 2022.

[b] Undersized carrots were ≤ 15 cm diameter.

[c] Other unmarketable included insect damage, cracked carrots, or other visible defects

[d] Total percent unmarketable.

[e] Hilling disk used for third cultivation event in 2022 only, see Table 2.1 for treatments.

[f] No interaction means significantly different when adjusted for multiple comparisons.

[g] See text for description of interaction

Figure 2.1. Image of cultivation tools used in experiment, including a) finger weeders (Tilmor) and b) hilling disks (Kult Kress ‘Duo’ cutaway disks set to hill).

Figure 2.2. Anchorage force gauge used to uproot plants.

CHAPTER THREE: Modeling Effects of Crop and Weed Characteristics and Cultural Practices on Selective Potential of Cultivation

ABSTRACT

Selectivity, the ability to kill weeds without killing the crop, is a challenge for in-row mechanical cultivation, especially in slow-growing crops like carrots. To gain insight into the optimal tool type and timing for cultivation given different weed species, we adapted a model from Kurstjens et al. (2004) to predict “potential efficacy”—the greatest weed mortality attainable with an idealized cultivation tool— based on early growth characteristics of carrots and weeds. We parametrized the baseline model using anchorage force and height data of carrots and five weed species grown in a greenhouse, and used it to predict potential efficacy for tools that either uproot or bury weeds. We also used the model to predict the impact on potential efficacy of cultural practices which increased carrot size relative to weeds (e.g. stale seedbed and large carrot seed size). Overall, we found that for our baseline model, selective potential depends on weed species and time, but is typically higher for burial than uprooting, especially for grass weed species. We also found that cultural practices that increase the size differential between crops and weeds generally increase selective potential, but that the magnitude of those effects vary considerably based on weed species. The model provides useful insights for developing and testing hypotheses that will have greatest potential impact for improving selectivity of cultivation and reducing weed management costs in carrots and other crops.

Keywords: modelling, selective potential, cultural practices

Introduction

Mechanical cultivation can be used to manage weeds in vegetable crops. In-row cultivation is more challenging because it risks damaging or killing the crop, especially for slow-growing crops like carrots (Hitchcock Tilton 2018; Champagne 2022). Tool efficacy varies depending on the crop, weeds present, tool settings, and soil conditions (Gallandt et al. 2018). Rasmussen (1992) first introduced the concept of selectivity to quantify cultivation success in grain crops as the ability to kill weeds without killing the crop. He measured selectivity as the "ratio between weed control and crop burial" from harrowing, although other definitions with varying properties have been proposed (Kurstjens et al. 2001; Hitchcock-Tilton 2018). Selectivity typically relies on a difference in size and relevant growth characteristics between the crop and weed (Rasmussen et al. 2010). For example, Fogelberg and Gustavsson (1998) suggested that tools that uproot weeds (e.g. brush weeders) may be selective based on measured differences in anchorage force between crop and weeds.

Kurstjens et al. (2004) provided additional helpful insight regarding the critical concept of selectivity for mechanical cultivation tools by developing a predictive model of selectivity based on crop, weed and tool characteristics including anchorage force. They expanded the definition of selectivity to include "selective potential" and "selective ability" of the tool. They defined selective *potential* for tools that kill weeds primarily by uprooting (e.g. tine harrows) as the maximum possible selectivity that could be achieved for a given crop and weed combination with an ideal tool (one that can apply a uniform uprooting force at the level required to maximize selectivity). Their model was based on the measured distribution of the crop and weeds anchorage forces (forces required to uproot). Selective *ability* of the tool was defined as the selectivity that could be achieved given the actual variability in the uprooting force applied by the tool. Kurstjens et al. (2004) modeled potential selectivity for uprooting tools through measurements of anchorage force of crops and weeds. They generated plant anchorage force frequency distributions for specific crop and weed combinations, which they used to calculate selective potential and selective ability of uprooting, to gain insight into key factors influencing selectivity.

While Kurstjens et al. (2004) used their model primarily to gain insight into selectivity of tools that work by uprooting, they suggest that the same basic framework may be used to evaluate tools with other modes of action, including those that bury weeds. In vegetable crops, growers often have multiple tool options, but lack information needed to determine which will provide greatest selectivity for a given weed-crop-soil combination (Gallandt et al. 2018). For example, in young carrots, finger weeders and hilling disk may both be used to manage weeds in the crop row, but their efficacy varies (Hitchcock-Tilton 2018; Champagne 2022). These tools have different primary modes of action, so different characteristics of the crop and weed are needed to predict their selectivity. The finger weeder is reported to work primarily by uprooting weeds (van der Schans et al. 2006; Peruzzi et al. 2017), so selectivity likely depends on a difference in the anchorage force of the crop and weed as described by Kurstjens et al. (2004). Hilling disks primarily bury weeds, so their selectivity might be predictable by comparing the tolerance of crops and weed to burial.

Knowledge regarding crop and weed tolerance to burial is critical for modelling selectivity of tools that function primarily by covering plants with soil, including hilling disks. Unfortunately, studies evaluating this kind of tolerance are surprisingly rare. Mohler et al. (2016) found that for most annual plants at early growth stages, covering the tallest plant part with as little as 2 cm of soil was lethal, but that recovery depended on soil moisture following burial.

Baerveldt and Ascard (1999) found that for 0.5-1 cm covering of common lambsquarters (*Chenopodium album*) was sufficient. They also suggested that common lambsquarters likely required more soil covering than other species in the study because of its upright growth habit and larger seed sizes. Other studies with artificial soil covering showed that for most species at the 1-2 leaf stage, covering with only 10-15 mm of soil was sufficient to kill 90% of weeds (Habel 1954, Kees 1962, Koch 1964b cited in Kurstjens and Perdok 2000). Kurstjens and Perdok (2000) also concluded that weeds are more likely to die from burial if they are bent as they're buried which often occurs during cultivation, suggesting that burial might not have to be as deep to be effective. Merfield et al. (2020) found that in a study of 6 species representing a range of grass and broadleaf plants, very few plants of any species recovered when they were completely covered with soil. Although plants differ in their tolerance to burial, and recovery from burial depends on soil characteristics (Mohler et al. 2016; Baerveldt and Ascaard 1999), for most annual plants at early growth stages, covering the tallest plant part completely is likely lethal (Merfield et al. 2020).

In addition to tool choice, growers often are challenged with determining the optimal timing of mechanical cultivation. Previous studies have shown that cultivation timing can be critical to achieving high selectivity. Growers are often advised to "weed early, shallow, and often" (Mohler et al. 2021) since smaller weeds are easier to kill than larger weeds (Kurstjens and Perdock 2000; Mohler et al. 2021). In several reviews of mechanical cultivation, it is well established that smaller weeds are easier to kill than larger weeds, and therefore cultivation should be done earlier (Melander et al. 2005; Van Der Weide et al. 2008). However, the effect of cultivation timing likely depends on the crop and weed combination. For example, in contrast to most findings, Rasmussen et al. (2010) found that in young barley, selectivity was not affected by timing within the two-week period studied. They found that regardless of timing, 80% weed control led to 25-30% crop damage. In contrast to typical expectations, Fogelberg and Gustavsson (1998) also found that the difference in uprooting force between carrots and weeds increased as they developed. This suggests that a tool that uproots, like the finger weeder, might become more effective when plants are older. Given that previous studies show varying effects of time on selectivity, we were interested in developing a model to help predict how potential efficacy of the finger weeder and hilling disks changes over time depending on the weed species present.

Other studies have found weed species present to have varying effects on cultivation efficacy. In a study of mechanisms of weed mortality from harrowing, Kurstjens and Kropff (2000) found that the effect was species dependent. For example, they found that ryegrass (*Lolium perenne)* had more damage from burial, but burial did not affect even white thread weeds of quinoa (*Chenopodium quinoa)*. Baerveldt and Ascard (1999) also found that when plants were upright at the time of burial, plant size influenced the amount of soil needed to kill them. They observed differences by species: bent plants were more sensitive to soil cover than upright plants, and less soil was needed to bury them. They also found that larger seeded plants (like *S. alba* in their study) were able to regrow through 3 cm of soil even at the cotyledon stage if they were not bent during burial. Mohler et al. (2016) also found that weed species with larger seed mass were more likely to recover from burial.

To further understand potential selectivity from cultivation, measurements of anchorage force and heights are needed for relevant crop and weed species. Anchorage force has been extensively studied in field crops, like wheat (*Triticum aestivum)*, to understand lodging, and in trees to improve stability (Ennos 2000). However, few studies have focused on anchorage force of vegetables and weed species. Fogelberg and Gustavsson (1998) measured uprooting force for carrots and annual weed species in four different soil types from the two-leaf to six-eight leaf stage, but did not include height data or weeds common to US carrot production other than common lambsquarters.

Our objectives were 1) to develop a model that can be used to calculate selective potential of mechanical cultivation tools that uproot or bury weeds based on anchorage force and height data of crops and weeds; 2) collect greenhouse and field data for carrots and common weeds to parametrize this model; and 3) use the model to generate hypotheses regarding optimal tool choices and impacts of cultural practices on selective potential in carrots. We hypothesized that the optimal tool choice for weeding carrots could be predicted based on the height and anchorage force of carrots and weeds and changes over time depending on weed species. We also hypothesized that cultural practices that increase the size of carrots relative to weeds (e.g. stale seedbedding or grading for larger seed size) improve selectivity, but that the magnitude of those improvements depends critically on weed species and timing.

Methods

Model Overview

The model, based on that of Kurstjens et al. (2004) uses crop and weed characteristics to estimate selective potential. Selective potential is the maximum possible selectivity that can be achieved for a given crop and weed combination assuming an idealized tool that exerts a uniform force on each plant (Kurstjens et al. 2004). Our model expands on that of Kurstjens et al. (2004), developed only for tools that uproot, to include crop and weed height to predict selectivity of tools that bury weeds.

To simplify model development and interpretation, we adjusted the model of Kurstjens et al. (2004) to evaluate ‘potential efficacy’ of tools that uproot or bury for a fixed level of crop mortality, rather than their ‘selective potential’ that can be evaluated over a range of crop mortalities. Since most growers accept only a narrow range of crop mortality, optimization of selectivity based on definitions like that of Rasmussen (1992) may not be desirable. Therefore, as a starting point in our baseline model, we set crop mortality at five percent, reflecting the fact that most carrot growers would not choose a high level of selectivity if it required a higher level of crop mortality.

To calculate potential efficacy, our model uses the same basic procedure for both burial and uprooting tools. It first uses anchorage force data of crops and weeds to predict potential efficacy of uprooting, then height data to predict potential efficacy of burial. The below explanation describes the procedure for calculating uprooting efficacy, but the same methods are then used for height to predict burial efficacy.

Calculating Potential Efficacy of Uprooting and Burial

Experimental data on individual anchorage forces for the weed and crop species are inputs into the model, and the date and species of interest are selected. Our model software generates graphs consisting of probability density functions of the anchorage force or height of carrots and weeds for a given sampling date (Fig 3.1), similar to Kurstjens’ et al. (2004) to illustrate the selectivity of the tool. Then, for each sampling date (T) the model uses the distribution of crop anchorage force data to calculate the uprooting force (F) that would cause five percent crop mortality ($F_{5,T}$), based on the assumption that individual carrots with anchorage force < $F_{5,T}$ would die, and those with > $F_{5,T}$ would survive (Fig. 3; $F_{5,T}$ line). The model then calculates weed mortality given this uprooting force (Fig. 3; area under the weed anchorage force probability density function to the left of $F_{5,T}$)) based on the weed's anchorage force distribution, assuming again that individual plants will die if and only if they have anchorage forces $<F_{5,T}$. The 'Potential Efficacy' of uprooting (PE_U) for each weed species at time T ($PE_{U,T}$) is therefore the percent of individual weeds of that species that would be killed if the uprooting force $F_{5,T}$ were applied.

The potential efficacy of burial ($PE_{B,T}$) is calculated exactly as described above for uprooting, except that crop and weed height distributions are used to calculate the burial depth required to attain five percent crop mortality at each time T ($D_{5,T}$). In this case the assumption is that plants will die if and only if their height is $<D_{5,T}$.

The model was written in R (R Studio 1.4.1106).

Assumptions of the Model

Baseline Assumptions

To calculate potential efficacy in our baseline model, we assumed that for calculating potential efficacy of uprooting, plants would be killed if and only if they had an anchorage force less than the tool uprooting force. Similarly, we assumed that for calculation of potential efficacy of burial, plants would be killed if and only if they were shorter than the burial depth of the tool. Although these are useful simplifying assumption that appears to hold true for many annual weed species (Merfield et al. 2020; Mohler et al. 2016; Habel 1954, Kees 1962, Koch 1964b cited in Kurstjens and Perdok 2000), it should be noted that some plants may recover from greater levels of burial (Mohler et al. 2016; Bervelt and Asgaard 1999), depending in part on soil conditions following burial. Likewise, uprooting forces less than those required to uproot a plant may nonetheless cause substantial crop injury.

Our baseline model also assumes that the plant height and anchorage force data from the greenhouse studies used to parameterize the model provide a reasonable approximation of plant growth under field conditions. Of course in reality, the plant genotypes, soil conditions (texture and moisture), fertility and watering regime and light conditions in the greenhouse are artificial and may deviate substantially from field conditions. For our baseline model, we also assumed that carrots and weeds were sown simultaneously as might be expected in a field situation where carrots are sown into a weed-free bed with ungerminated weed seeds. In reality, poor bed preparation, or delayed planting might result in weeds emerging more rapidly than carrots. On the other hand, weed species with dormancy mechanisms may have delayed emergence relative to the crop. Growers also often use stale seedbed practices, or residual herbicides that delay weed emergence.

Variations in Assumptions

To illustrate simple uses of the model for generating hypotheses, baseline assumptions were adjusted to gain insight into the potential impact on potential selectivity of different tools on weeds when: 1) weed emergence was delayed relative to carrots (as in a stale seedbed) and 2) carrot height and anchorage forces varied relative to those measured in the greenhouse (as expected based on different carrot cultivars or seed sizes).

To evaluate the potential benefits of stale seedbed for selectivity, weed anchorage force and height measurements from 100 degree days (approximately seven days) prior to the carrot anchorage force and height measurements were used. This assumption reflects typical grower practice of waiting until just before carrot emergence to flame weed or spray emerging weeds, giving the crop a 5-7 day advantage relative to weeds.

To test how differences in carrot seed size or cultivar would affect potential selectivity, carrot height and anchorage force were increased by 10% increments from 50% smaller to 50% larger than our measurements from ‘Bolero’ seedlings (Chapter 1). For example, at 22 days after planting, we found that carrots from large seed size classes had 20% greater anchorage force, and 12% greater height than those from small seed size classes. This range of variation also reflects data from previous studies comparing differences in height and anchorage forces for different commercially available cultivars of carrots. For example, Hitchcock Tilton (2018) found that the cultivar ‘Bolero’ was 22-53% larger than that of other cultivars including Danvers and Napoli at the one true-leaf stage.

Greenhouse Experiments to Parameterize the Model

Experimental Design

Plant growth measurements used to parameterize the model were collected from experiments in Michigan State University’s Plant Science Greenhouses in East Lansing, MI. Our experimental factors were species with 6 levels (carrots and 5 weeds), and sampling timing with 6 levels (6-22 days after seeding (DAS)). The treatments were arranged in a split plot design with 10 replicates, each containing 15-20 plants used for evaluating anchorage force and height. The study was conducted twice, once from September 21-October 7 (Run 1), 2021 and from November 4-26, 2021 (Run 2). Greenhouse temperatures were set at 24/18^{o}C day/night temperatures on 16 hour photoperiod. However, actual temperatures were higher in Run 1 (27/19 ^{o}C) compared to Run 2 (22/18 ^{o}C) due to higher external temperatures during Run 1 coupled with inadequate insulation and ventilation to maintain temperature settings.

Species included ‘Bolero’ carrots (Johnny’s Selected Seeds), ‘Mighty Mustard Pacific Gold’ condiment mustard (*Brassica juncea*, Johnny’s Selected Seeds), ‘Red Spike’ red amaranth

(*Amaranthus cruentus*, Johnny's Selected Seeds), large crabgrass (*Digitaria sanguinalis*), common lambsquarters (*Chenopodium album*), and giant foxtail (*Setaria faberi*). Crabgrass seeds were collected in 2008 in Michigan, lambsquarters seeds were collected in 2015, and foxtail seeds were collected in 2011. All species had over 50% germination in petri-dish tests prior to the experiment.

Plants were grown in 10.5 cm diameter round pots filled with a 3:2:1 mixture of field soil ('Sphinks loamy sand'), greenhouse potting mix and compost. The greenhouse potting mix was a 40:40:20 mixture of Suremix Perlite (peat, perlite, lime) (Michigan Grower Products Inc, Galesburg, MI). Compost was 'Dairy Doo' (Morgan's Composting, Sears, MI). Each pot was sown with one species. The number of seeds varied between 20-100 seeds based on germination percentage, and thinned to attain 18 seedlings per pot. Pots were watered after seeding and regularly as they started to dry out.

Measurements

Anchorage force and height of three plants per pot were first measured shortly after emergence at 4-6 DAS, then approximately every three days. At each sampling date, the height of the tallest leaf was measured. Then, the anchorage force of each of the three plants was estimated by clamping the shoot with a tarp clip (Fig 3.2, Outus Crocodile Mouth Tarp Clips-004, 9 x 3 x 2cm) and pulling slowly upward using a force gauge (Fig 3.3, Alluris FMI-S30) to measure the maximum force required to uproot. Pots were weighed before each anchorage force measurement, and again after being dried out after the experiment, to calculate soil gravimetric water content (GWC). GWC was calculated for the entire pot, so may not have accurately represented moisture content in the shallower rooting zone. The purpose of these GWC measurements was to understand potential sources of variation in anchorage force measurements between sampling dates.

Data Analysis

Data were analyzed using PROC MIXED procedures in in SAS 9.4 (Statistical Analysis Software 9.4 Cary, NC). Differences in anchorage force and height by species were evaluated separately at each measurement date. To account for the split-plot design, replication was a random effect and species x replication was a random effect. Assumptions of homogeneity of variance and normality of residuals were tested using Levene's test and Shapiro-Wilks test respectively. If data did not fit assumptions, data was transformed using Box-Cox test to determine best transformation. When no suitable transformations were found, the PROC GLIMMIX procedure in SAS (Statistical Analysis Software 9.4 Cary, NC) was used to account for heterogeneity of variance in a mixed model with unequal variances (Milliken & Johnson 2009). When the main effect of species was significant at $p<0.10$, means were separated using Tukey's HSD with a Tukey adjustment for multiple comparisons.

Given differences in temperature between the two greenhouse studies, data was expressed in terms of growing degree days ('GDD'; base temp 5 C) using the average of the maximum and minimum temperatures for that day from Hobo Pendant sensors set to log on 1 hour intervals. Mean height and anchorage forces for the two runs were combined for sampling dates in cases where the GDD were similar (+-5 GDD), but only measurements for the second run were used for the last two measurement dates because the GDDs differed and because the final data from the first run of the experiment clearly diverged substantially from field grown plants (e.g. Chapter 1) due to insufficient lighting and etiolation of plants.

Results and Discussion

Species Differences in Anchorage Force and Height

For all species studied, anchorage force and height increased throughout the experiment (Table 3.1). Mustard had higher anchorage force than all other species tested at all dates measured. It was also taller than all other species until 19 DAS when it was not different from carrots. Carrots had equal or greater mean anchorage force and height compared to all weed species other than mustard throughout their measured growth.

In addition to differences in mean height and anchorage force, notable differences in the variability of those measures—a key parameter affecting predicted selectivity in our model—were observed (Table 3.1). For carrots, the variability in plant height was generally less than the variability in anchorage force. For example, at 263 degree days (approximately 2 weeks after planting) the coefficient of variation in carrot height was approximately ½ that of anchorage force (Fig 3.4). A similar trend was observed for the surrogate weeds (red amaranth and condiment mustard), but not for the wild species, which were generally more variable, especially in terms of plant height.

Our measurements of carrot anchorage force and height in the greenhouse diverged somewhat from those measured in our field study (Table 3.1). For example, at the time of the first cultivation carrots in the field were slightly more advanced (1-2 leaf stage) than the largest plants measured in the greenhouse (cot-1 leaf stage), and therefore, as expected, slightly higher anchorage forces (1.0-1.3 N). However, the height of field grown carrots at that stage (3.4-3.8 cm) was less than that of those grown in the greenhouse (5.3 cm). Similarly, surrogate weeds (condiment mustard and red amaranth) that were present in the greenhouse study tended to be taller than those in the field at similar growth stages (Table 3.1)

Mean anchorage force measurements in our experiment were similar to those in some previous studies, though diverged considerably from others. Our measurements were similar to those of Fogelberg et al. (1998) who found for carrots and four weed species at the two leaf stage, mean anchorage forces were less than 1 N. In our study, carrots and all weed species tested except mustard also had anchorage forces of <1 N at the 2-leaf stage or younger. Mustard had an average anchorage force of 2.3 N at 22 DAS, but it had 2-4 true leaves. Our anchorage force measurements were also similar to measurements by Tokura et al. (2006) at 10-11 DAS, but around 20 DAS ours were lower. Foxtail, common lambsquarters, and two other weed species tested did not have significantly different anchorage force values in their experiment, with mean uprooting force 0.23 N at 11 DAS, and 3.1 N at 21 DAS. At 10 DAS in our experiment, foxtail uprooting force was 0.25 N and common lambsquarters was 0.16 N. However, at day 20, foxtail was only 0.68 N and lambsquarters 0.47 N.

Differences in mean anchorage force measurements may have been due to several factors, related to either actual differences in root growth, or differences in methodology used to uproot and measure forces. One reason our measurements could have been lower than those of Tokura et al. (2006), is that they used iron blocks to stabilize the soil around the plant, to ensure that anchorage force was a measurement of the roots breaking, not the soil moving. We did not stabilize the soil, so our lower values might be partially explained by soil movement contributing to lower anchorage forces. Additionally, Tokura et al. (2006) used a balance method with weights to capture only the vertical uprooting force because they thought other methods which less precisely uproot may also capture torsion forces, which could underestimate anchorage force.

Variability in height and anchorage forces in previous studies was similar to that observed in our study. Tokura et al. (2006) reported lower variation in uprooting force than we observed at day 10, but higher variation in uprooting force than we observed at day 16 and 21.

Baseline Model Predictions: Species and Timing Effects on Selective Potential

Baseline model predictions of selective potential from uprooting and burial depend on weed species and plant age (Fig 3.5). For amaranth (Fig 3.5a) and lambsquarters (Fig 3.5b), potential efficacy is initially higher from uprooting than burial, but burial efficacy increases over time. After approximately 263 GDD (18 days at 20 C) for amaranth and 350 GDD (23 days at 20 C) for lambsquarters, burial is predicted to be more effective than hilling. In contrast, for both grass species, potential efficacy from burial is higher than from uprooting over the entire period (Fig 3.5d and 3.5e). Due to its more rapid establishment relative to carrots, the potential efficacy on mustard is zero from either tool, although after 306 GDD potential efficacy from burial increases.

Interestingly, the optimal timing of cultivation based on our model is later from broadleaf weeds than for grasses. For both large crabgrass and giant foxtail, the model predicts highest potential selectivity using tools that hill at approximately 200 GDD (13 days at 20 C) from planting. In contrast, the efficacy of hilling on broadleaf weeds increases up to our last modelled date (350 GDD).

In most cases, under our baseline assumptions, the model predicted greater selective potential from burial than that from uprooting. Interestingly, this effect appears to be due primarily to less variation in carrot shoot height compared to carrot anchorage force (Table 3.1; Fig 3.4). Lower variability in carrot height implies that higher levels of burial can be tolerated for the same level of carrot mortality (5% in our baseline model), and therefore greater weed mortality can be attained.

Effects of Stale Seedbed on Model Predictions

When growers use a stale seedbed, they often give carrots a 5-7 day advantage over the weeds. Not surprisingly, when a 100 GDD (7 days at 20C) delay is used to simulate stale seed practices in the model, overall potential efficacy increases for all species and both tools (Fig 3.6). Interestingly, it also changes the optimal tool for some species and timings. For example, for lambsquarters and red amaranth, the stale seedbed model predicts equivalent potential efficacy from burial compared to uprooting (Fig 3.6a-b). Moreover, with stale seedbedding, potential efficacy from burial is equivalent or greater than efficacy from uprooting for all species and timings.

The model predicts that the use of stale seedbedding is most pronounced for mustard. In the absence of a stale seedbed, mustard emerging simultaneously with the crop is predicted to be difficult to impossible to manage with either tool (Fig 3.7c). In contrast, with stale seedbedding, hilling at approximately 2 weeks from carrot planting (213 GDD) is predicted to result in potential selectivity of 90% (Fig 3.7c). Interestingly, delaying hilling in this case appears to reduce potential efficacy on mustard to 60% or less. Also notable is that for mustard, even when a stale seedbed is used, tools that uproot have very low potential efficacy.

Effects of 'Improved' Carrots on Model Predictions

When we vary model assumptions regarding the relative size of carrots, several interesting changes in predicted potential efficacy emerge. For example, at 263 GDD (18 days at 20 C), our model predicts improvements in potential efficacy of uprooting from better anchored carrots depending on weed species, and stale seedbed success (Fig 3.7). Compared to 'Bolero' the standard ‘baseline’ carrot cultivar used in the model, carrots with greater anchorage force at this timing could lead to higher selectivity with all weed species except mustard if the stale seedbed is missed (Fig 3.7a). For a burial tool, our model also predicts that greater height in carrots would likely help control all species of weeds when the stale seedbed is missed (Fig 3.8a). However, the extent of those benefits varies with weed species. For example, for mustard, our model predicts that even with a stale seedbed, and increases in carrot anchorage force of 50% above Bolero, potential selectivity would be low (<30%). However, a 50% increase in carrot height relative to ‘Bolero’ would increase potential mustard mortality from burial to 100% when the stale seedbed was successful (Fig 3.8b).

Our model also illustrates the hazards for mechanical weed management of using less vigorous carrot cultivars or seedlots. Previous studies with fresh market carrots have shown that Bolero is among the most vigorous (Colquhoun et al. 2017; Hitchcock-Tilton 2018). Our model predicts that potential efficacy for difficult to manage weeds like mustard and giant foxtail is considerably lower in fields with weaker cultivars. For example, in our best-case scenario for cultivation tool success—hilling following stale seedbedding (Fig 8b)—potential efficacy on mustard is predicted to drop from around 60% for Bolero to 10% or less for carrot cultivars like ‘Danvers’ or ‘Napoli’ which are often 30-50% smaller than Bolero at this stage (Hitchcock-Tilton 2018).

Our results also suggest that for a smaller cultivar than ‘Bolero’, breeding that targets increasing height of seedlings at early growth stages would likely be more beneficial for increasing selectivity than attempting to increase anchorage force. For growers, using taller cultivars and high quality seed that result in taller carrots is also clearly beneficial for improving the likelihood of early cultivation success. Our results also emphasize the importance of a stale seedbed even with a cultivar like ‘Bolero’ since it improves uprooting and burial selective potential.

Model Implications for Carrot Seed Size Effects

In our field experiments, we had a successful stale seedbed (or handweeding to match timing) and approximately 20% greater anchorage force and 12% greater height of carrots from large compared to small seed sizes (Table 2.7). This situation corresponds to model assumptions resulting in predicted potential efficacy shown in Figures 3.7b and 3.8b. The model predicts that with the 20% increase in carrot anchorage force associated with large seed carrots we would not see increased potential efficacy for red amaranth or most ambient weeds, and only modest improvements in potential efficacy for mustard by uprooting tools (Fig 3.7b). In contrast, with the 12% observed increase in height from larger seed sizes, our model predicts an improvement in potential efficacy of hilling on mustard from approximately 55% to 70%. However, increases in height would not be expected to improve potential efficacy of burial for other species.

Unfortunately, for various reasons, our study provides limited insights into observed impacts of tools on carrots and weeds in our field experiments (described in Chapter 2). First, it should be noted, our primary objective in those studies was to evaluate differences in carrot tolerance to tools, rather than impacts of carrot seed size on potential efficacy on weeds. Therefore, the tools were set at relatively aggressive settings, and the level of aggressiveness was the same for both large and small seed carrot treatments; unlike the model, we did not adjust tool aggressiveness to a tolerated level of carrot mortality and evaluate impacts on weeds at those varying levels. Nonetheless, we expected that the relative efficacy of finger weeders and hilling disks on weeds observed in our field study would be roughly consistent with model predictions. For example, our model predicts greater efficacy from hilling at early stages, and greater efficacy on red amaranth than mustard regardless of tool. Neither of these predictions were consistently observed in our field trial.

Deviations from potential efficacy, and actual efficacy observed in the field are not surprising, and likely derive from both uncertainty regarding model assumptions, and deviations of the idealized tool used in the model, from actual tools used in the field. For example, while it is generally assumed that finger weeders work primarily by uprooting weeds, they do not do so consistently. In contrast, hilling disks do bury weeds, but there is considerable variation in the depth to which they do so under field conditions (Mohler et al. 2016; Chapter 2).

Model Insights into Carrot Cultivar Effects

The model can be useful for generating hypotheses about ways to improve selectivity for a given crop and weed combination. Various cultural practices can be utilized to improve selectivity by increasing the relative strength of the crop relative to the weeds (Melander et al. 2005). For example, Champagne (2021) and Hitchcock-Tilton (2018) tested different carrot cultivars to determine if some cultivars had stronger anchorage forces or larger biomass that would make them more tolerant of cultivation. Using height and anchorage force data for different carrot cultivars, the model could predict which cultivars have the potential to improve selectivity.

In the future, other practices to improve crop strength relative to weeds could be tested. For example, Muhie et al. (2021) showed that different methods of carrot seed priming can increase carrot height under heat and drought stress. Using the predicted height increase from priming, the model could be used to predict if priming would be beneficial for weed management under those conditions.

Implications for Tool Use and Development

The model predicts uprooting selectivity for idealized tools that can either uproot or bury precisely at the level to maintain 5% carrot mortality with no variability. Obviously in reality, tools that uproot or bury are not close to achieving that ideal, and actual selectivity will be lower than potential selectivity. Finger weeders have been considered a tool to work primarily by uprooting weeds, however recent studies (Hitchcock-Tilton 2018; Pannacci et al. 2017) have shown that depending on settings and soil conditions it often buries weeds more than uprooting. Therefore, to take advantage of potential selectivity by uprooting, a different tool should be considered.

Our results suggest that for carrots, using tools that bury have greater potential success than those that uproot. If true, carrot growers would more likely benefit from tool innovations that improve the precision of burial so that actual selectivity approaches potential selectivity. Conversely, investing time and effort into tools that uproot is likely to have relatively small payoff since they have lower potential selectivity than burial tools.

Future Directions

The model could also incorporate soil conditions. Soil conditions can affect tool efficacy, but they can also change anchorage force of the crop and weed. For example, Ennos (2000) found that for plants with a single taproot, the way it dies when uprooted depends on the soil conditions. In soft, wet soils, the soil is easily moved and the roots push soil aside until the plant leans over permanently. In stronger or drier sol, the stem or tap root are more likely to fail. Therefore, to accurately predict uprooting efficacy, anchorage force should be measured in various soil conditions.

The model calculates selective potential of the crop and weeds, but in the future it could also incorporate the tool to make predictions about selective ability of various tools. Tools apply variable uprooting forces and burial depths depending on the location of the tool compared to the plant (Terpstra and Kouwenhoven 1981; Mohler et al. 2016) and soil conditions.

LITERATURE CITED

Baerveldt S, Ascard J (1999) Effect of soil cover on weeds. Biol Agric Hortic 17:101-111

Champagne R (2022) Evaluating Physical and Cultural Methods to Improve Weed Management in Organic Vegetables. PhD Dissertation. Orono, ME: University of Maine. 105 p

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

Ennos AR (1990) The anchorage of leek seedlings: the effect of root length and soil strength. Ann Bot 65(4):409-416

Ennos AR (2000) The mechanics of root anchorage. Advances in Botanical Research (33):134-157

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

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

Hithcock-Tilton S (2018) Improving Weed Management in Carrots With Stacked In-Row Weeding Tools and Cultivation-Tolerant Cultivars. MS Dissertation. East Lansing, MI: Michigan State University. 127 p

Kurstjens DAG, Kropff MJ (2000) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. Weed Res 41:211-228

Kurstjens DAG, Perdock UD (2000) The selective soil covering mechanism of weed harrows on sandy soil. Soil Tillage Res 55(3-4):193-206

Kurstjens DAG, Perdok UD, Goense D (2000) Selective uprooting by weed harrowing on sandy soils. Weed Res 40:431-447

Kurstjens DAG, Kropff MJ, Perdock UD (2004) Method for predicting selective uprooting by mechanical weeders from plant anchorage forces. Weed Sci 52:123-132

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

Merfield CN, Bennet JR, Berry NA, Bluton A, O’Connell DM, Hodge S (2020) The potential of mini-ridging for controlling intrarow weeds: estimating minimum lethal burial depth. Weed Res 60:353-362

Milliken GA, Johnson DE (2009) Analysis of Messy Data Vol 1: Designed Experiments. CRC Press

Mohler CL, Teasdale JR, DiTommaso A (2021). Manage weeds on your farm: a guide to ecological strategies. SARE

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

Muhie S, Memis N, Ozdamar C, Gokdas Z, Demir I (2021) Biostimulant priming for germination and seedling quality of carrot seeds under drought, salt and high temperature stress conditions. International Journal of Agriculture Environment and Food Sciences 5(3): 352-359

Pannacci E, Lattanzi B, Tei F (2017) Non-chemical weed management strategies in minor crops: a review. Crop Prot 96:44-58

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. Journal of Agricultural Engineering, 48(2):57-70

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

Rasmussen J (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. Weed Res 32:267-274

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

Tokura Y, Devee E, Hongo A (2006) Uprooting and shearing resistances in the seedlings of four weedy species. Weed Biol Manage 6:35-43

van der Schans D, Bleeker PO, Molendijk L, Plentinger M, van der Weide RY, Lotz B, Bauermeister R, Total R, Baumann DT (2006). In: D. van der Schans and P. Bleeker (Eds.), Practical weed control in arable farming and outdoor vegetable cultivation without chemicals. Applied plant research, Wageningen, UR

APPENDIX

Tables and Figures

Table 3.1. Height and anchorage force of carrot and weeds over time.

DAS[a]	6					10					13				
GDD[b]	113					164					213				
	Height		AF[c]		Leaf	Height		AF		Leaf	Height		AF		Leaf
Species	Mean	SD[d]	Mean	SD	Stage	Mean	SD	Mean	SD	Stage	Mean	SD	Mean	SD	Stage
	--------cm------		--------N------			------cm-----		--------N-------			------cm-----		--------N--------		
Carrot	0.28 d	0.13	NA[e]	NA		2.24 b	0.50	0.3 b	0.11	C[f]	2.86 b	0.52	0.5 b	0.15	C
Amaranth	1.27 b	0.36	0.2 b	0.12	C	1.79 c	0.46	0.18 d	0.07	C	2.36 c	0.54	0.30 d	0.10	C
CHEAL[g]	0.8 c	0.44	NA	NA		1.65 c	0.47	0.16 d	0.07		2.19 cd	0.53	0.20 e	0.07	C
DIGSA[h]	0.65 cd	0.22	NA	NA		0.92 d	0.36	0.15 d	0.07	1	1.32 e	0.73	0.2 e	0.09	1
Mustard	1.5 a	0.48	0.4 a	0.18	C	2.87 a	0.61	0.54 a	0.13	C	3.52 a	0.64	0.80 a	0.22	C-2
SETFA[i]	0.51 cd	0.22	NA	NA		1.51 c	0.58	0.25 c	0.08		2.05 d	0.47	0.4 c	0.08	1-2
	---p-value---														
ANOVA															
Species	**<0.001**		**<0.001**			**<0.001**		**<0.001**			**<0.001**		**<0.001**		

[a] Days after seeding (DAS) from November greenhouse trial. Data for corresponding growing degree days of October trial are also included except for last two measurement dates.

[b] Growing degree days

[c] Anchorage force

[d] SD= standard deviation

[e] Not applicable

[f] C=Cotyledon

g Common lambsquarters

h Large crabgrass

i Giant foxtail

Table 3.1 (cont'd)

DAS[a]	16					19					22				
GDD[b]	263					306					350				
	Height		AF		Leaf Stage	Height		AF		Leaf Stage	Height		AF		Leaf Stage
Species	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
	------cm------		---------N------			--------cm------		--------N--------			-------cm-----		---------N------		
Carrot	3.70 ab	0.62	0.57 b	0.20	C	4.23 a	0.82	0.65 b	0.22	C	5.26 a	0.82	0.97 b	0.3	C-1
Amaranth	3 c	0.67	0.37 d	0.10	C	3.10 dc	0.59	0.48 bc	0.16	C-1	3.77 b	0.49	0.75 bc	0.20	1-2
CHEAL	2.7 d	0.65	0.24 e	0.08	C	3.53 bc	0.54	0.34 c	0.11	C-2	3.67 b	0.52	0.47 d	0.2	2
DIGSA	1.9 d	0.83	0.27 e	0.09	1-2	2.53 dc	0.96	0.37 c	0.16	1-2	3.96 b	1.30	0.61 cd	0.3	1-2
Mustard	4.4 ab	0.90	1.23 a	0.40	2	4.21 ab	0.74	1.9 a	0.47	2-4	4.82 a	0.84	2.30 a	0.7	2-4
SETFA	3.3 bc	1.08	0.45 c	0.15	1-2	3.60 abc	1.26	0.48 c	0.15	2	5.19 a	1.27	0.68 cd	0.2	2-4
ANOVA	---p-value ---														
Species	**<0.001**		**<0.001**			**<0.001**		**<0.001**			**<0.001**		**<0.001**		

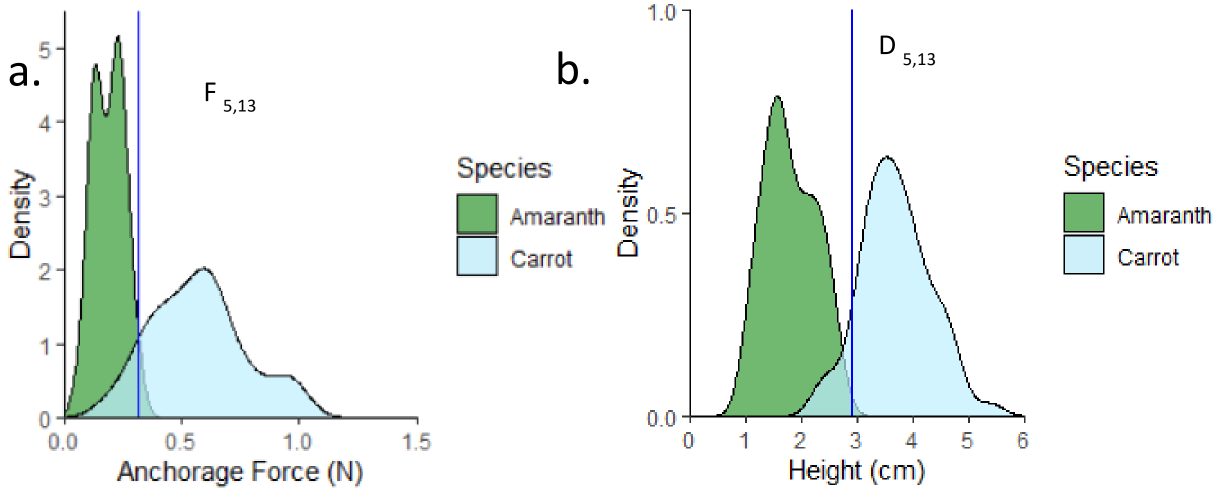

Figure 3.1. Probability density functions of (a) anchorage force of carrot and amaranth at 13 days after seeding (DAS) and (b) height of carrot and amaranth at 13 DAS. Vertical blue lines show the uprooting force ($F_{5,13}$) and the burial depth ($D_{5,13}$) corresponding to 5% carrot mortality from idealized cultivation tools that uproot or bury, respectively.

Figure 3.2. Tarp clip (Outus brand "crocodile mouth" tarp clip) used to connect plants to force gauge for anchorage force measurements.

Figure 3.3. Anchorage force gauge (Alluris FMI-S30) shown uprooting mustard seedling.

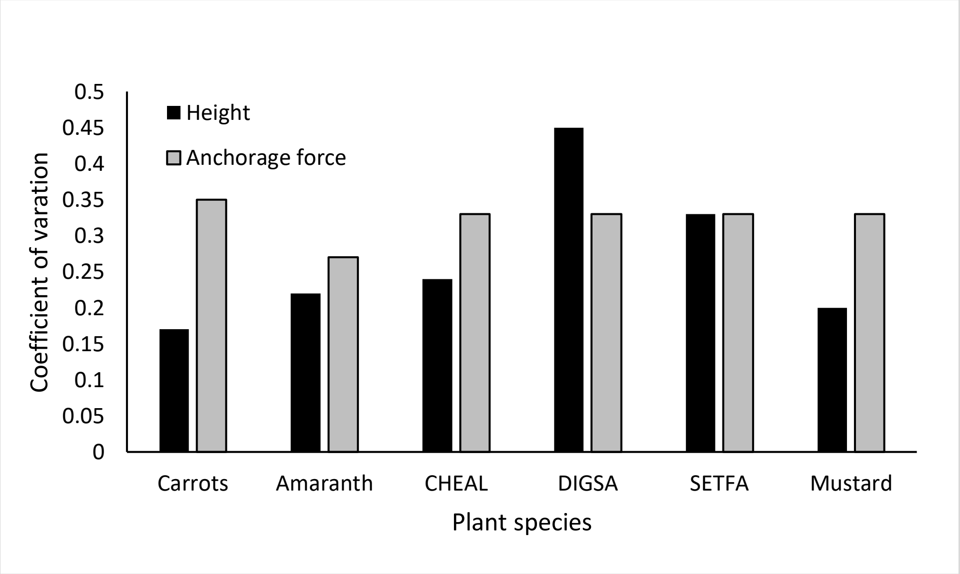

Figure 3.4. Coefficient of variation in height and anchorage force of crops and weeds at 263 growing degree days (GDD) (18 days at 20 C) after planting.

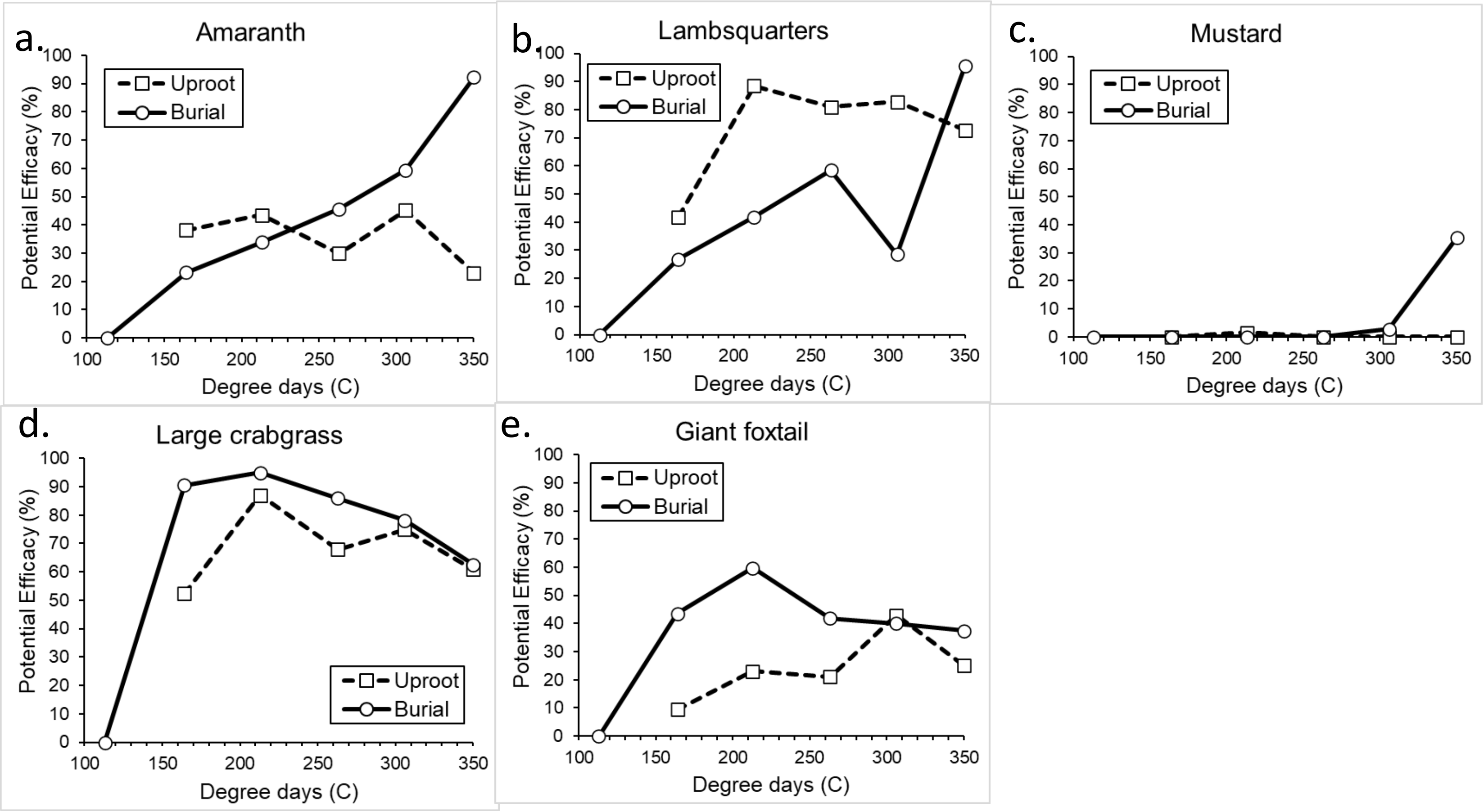

Figure 3.5. Baseline model predictions of potential efficacy of uprooting or burial,100 - 350 growing degree days (7–23 days at 20C) after planting) for (a) red amaranth, (b) common lambsquarters, (c) condiment mustard, (d) large crabgrass and (e) giant foxtail.

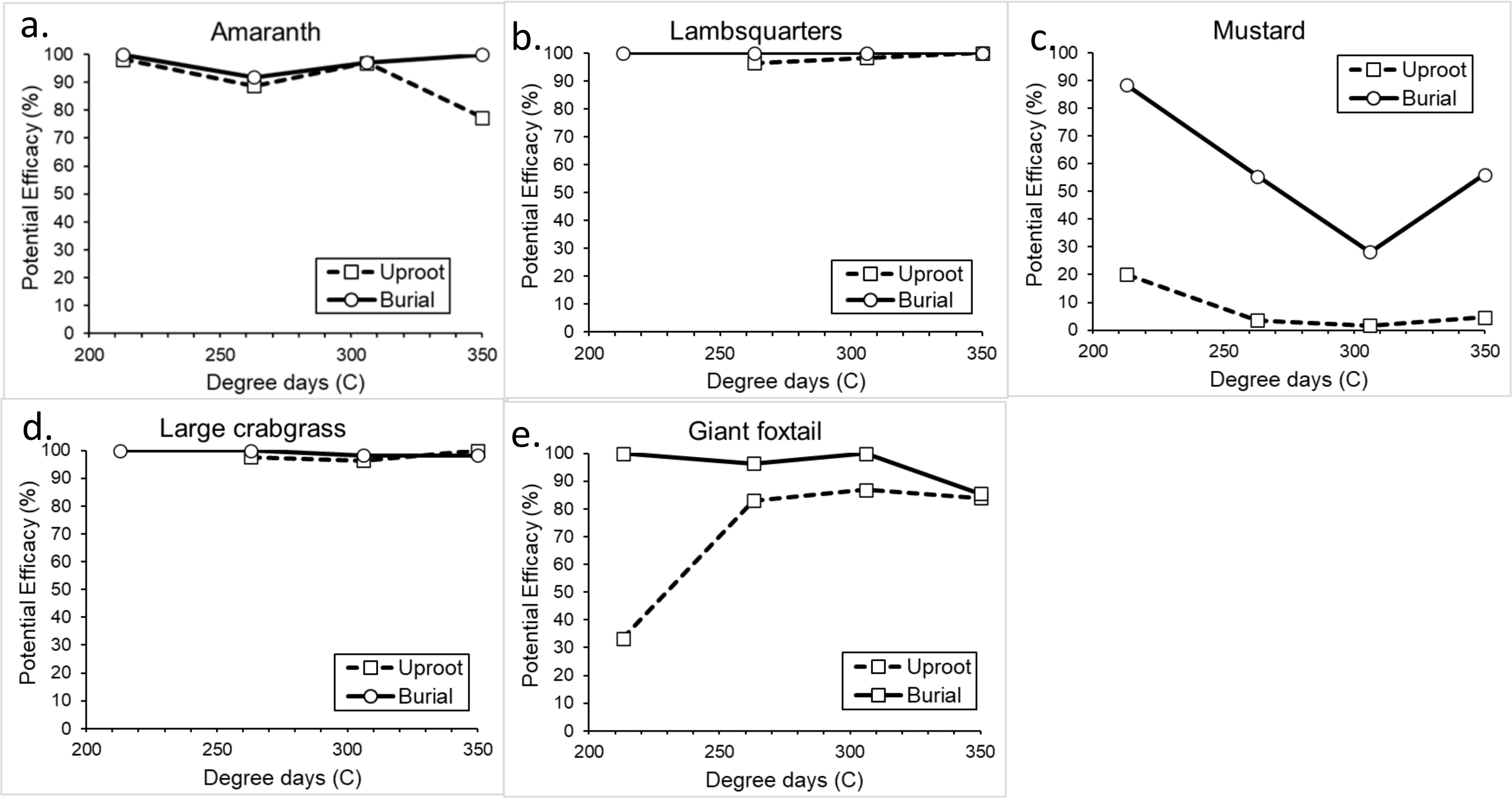

Figure 3.6. Model predictions with stale seed bed resulting in 100 growing degree days (GDD) delay in weed emergence relative to carrots. Potential efficacy of uprooting or burial, 100-350 GDD (7-23 days at 20C) after planting for (a) red amaranth, (b) common lambsquarters, (c) condiment mustard, (d) large crabgrass and (e) giant foxtail.

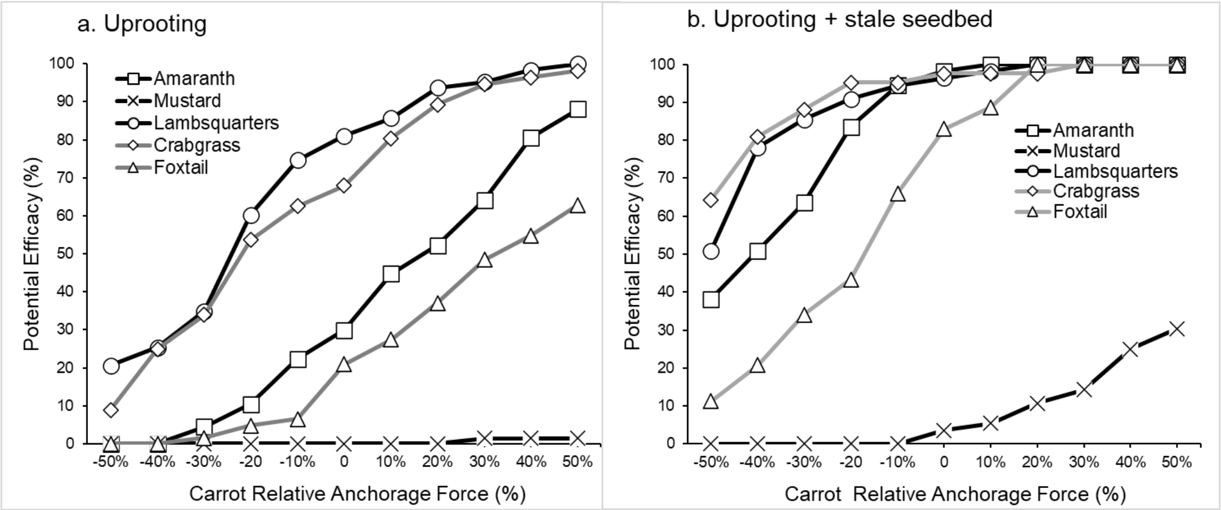

Figure 3.7. Effect of carrot anchorage force (relative to the cultivar 'Bolero') on potential efficacy of uprooting on 5 weed species at 263 growing degree days (GDD) (18 days at 20 C) after carrot planting assuming (a) simultaneous emergence of weeds and carrots or (b) stale seed bed resulting in 100 GDD (7 days at 20 C) delay of weed emergence relative to carrots.

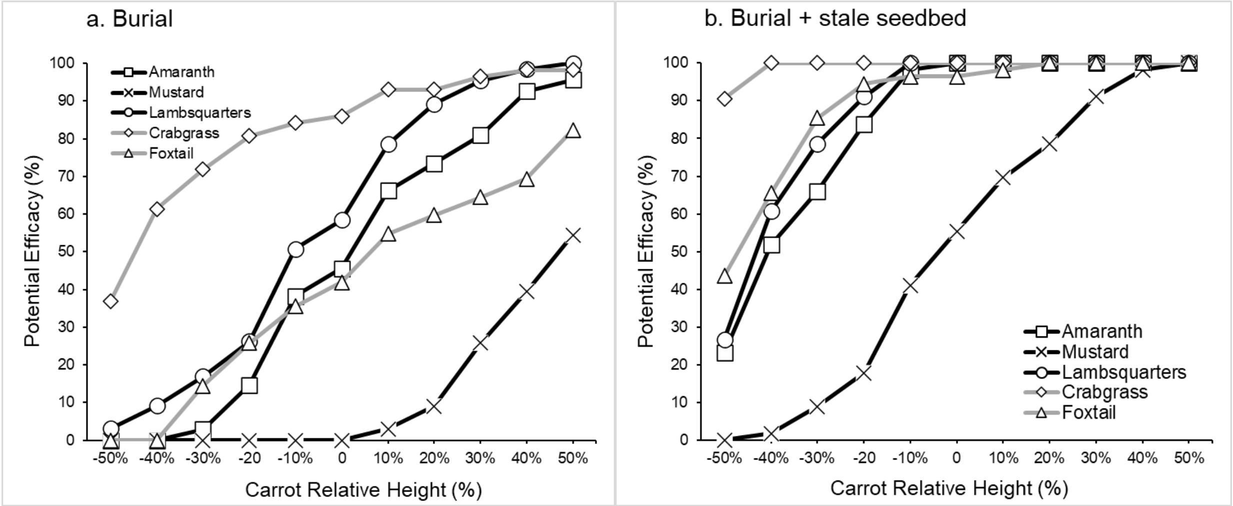

Figure 3.8. Effect of carrot height (relative to 'Bolero') on potential efficacy of burial on 5 weed species at 263 growing degree days (GDD) (18 days at 20 C) after carrot planting assuming (a) simultaneous emergence of weeds and carrots or (b) stale seed bed resulting in 100 GDD (7 days at 20 C) delay of weed emergence relative to carrots.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 - 1346 USA