SOIL SURFACE CHARACTERISTICS AND CULTIVAR CHOICE AFFECT MECHANICAL WEED CONTROL EFFICACY IN ORGANIC VEGETABLES

By

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ABSTRACT

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Seed bed preparation and soil management history are thought to have a large impact on the efficacy of mechanical cultivation, but limited information is available on the mechanisms of these effects. In field trials, we tested how pre-plant bed preparation, historic compost use, and molasses applications affected soil surface characteristics and the efficacy of flextine cultivation. Contrary to expectations, historic compost and molasses application had little or no effect on the efficacy of flextine cultivation, and rolling beds prior to planting reduced flextine efficacy. Rolling beds resulted in lower soil surface roughness, but also increased soil penetrometer resistance, which was associated with reduced efficacy of cultivation. These surprising results highlight the importance of characterization of soil conditions in cultivation research.

Table beets (*Beta vulgaris)* are among the most challenging crops to mechanically cultivate. Four beet cultivars were evaluated for their tolerance to deep planting and mechanical cultivation as well as their competitiveness with escaped weeds. Results suggest that 1) deep planting to delay emergence may improve success with stale seedbedding for some cultivars, but that results are inconsistent under field conditions; 2) adoption of cultivars with greater tolerance to mechanical cultivation and greater competitiveness with weeds can improve weed management success in table beets.

This thesis is dedicated to Janet Tarrant. She was a model of optimism during my program and shared with me her love of the natural world.

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CHAPTER ONE: Soil Surface Effects on Flextine Cultivation Efficacy in Vegetables

ABSTRACT

Seed bed preparation and soil management history are thought to have a large impact on the efficacy of mechanical cultivation, but limited information is available on of the mechanisms of these effects, and their implications for management. In a series of field trials on a loamy sand soil, we tested how pre-plant bed preparation (rolled vs not), historic compost use (12 previous years of annual applications vs none), and presence of soil crust (induced through application of molasses or not) influenced soil surface characteristics and the efficacy of flextine cultivation in bush beans (*Phaseolus vulgaris*) and sweet corn (*Zea mays* L.). Rolling beds prior to planting generally resulted in lower soil surface roughness, greater soil micro-penetrometer resistance, higher soil moisture content, and reduced efficacy of flextine cultivation compared to unrolled beds. Historic compost and molasses applications had few impacts on these soil characteristics and little or no effect on flextine efficacy. The results of this study challenge conventional cultivation wisdom that rolling seed beds improves cultivation efficacy by facilitating more uniform tine working depth. This potential benefit is offset by increasing soil hardness through compaction, which reduce the capacity of tines to disturb soil and uproot weeds. Our surprising results highlight the importance of characterization of soil conditions in cultivation research.

Keywords: flextine, rolling, soil surface roughness, soil crusting, efficacy, mechanical weed cultivation

Introduction

Growing demand for organic vegetables, coupled with the high cost of handweeding, has resulted in increased interest in mechanical cultivation tools (Bowman 1997; Gallandt et al. 2018). Conventional vegetable growers are increasingly integrating mechanical control as well since reliance on chemical herbicides has increased selection pressure for herbicide resistant weed populations (Norsworthy et al. 2012). Moreover, increased regulatory pressure and consumer preference for reduced pesticide use is leading more growers to rethink standard chemical weed control practices. Growing demand for mechanical weed control strategies necessitates more research to understand the mechanisms by which tools influence weed mortality and provide growers with information and confidence to use these tools optimally on their farms (Gallandt et al. 2018; Kurstjens 2007; van der Weide et al. 2008).

Mechanical weed cultivation tools are designed to control weeds after crop planting and have a shallow working depth, killing weeds at early growth stages (Mohler 2001). Cultivation equipment kills weeds by burial (Kurstjens and Perdok 2000), tearing and cutting (Toukura et al. 2006), uprooting (Fogelberg and Gustavsson 1998), or a combination of these. Weed control efficacy of these modes of action in weed control depends on weed physical properties and soil conditions. Early season management of soil conditions is an important consideration for growers integrating mechanical cultivation in their weed control system.

Pre-plant management decisions influencing soil surface roughness are thought to impact cultivation tool efficacy. The relative importance of level soils in cultivation efficacy is important for growers making early season management decisions. For example, level soils are thought to improve tool efficacy by facilitating more uniform working depth and uprooting forces (Bowman 1997; Mohler 2001). Evans el al. (2012) found that uneven soil surfaces were negatively corelated with cultivation efficacy. Level soils may also result in more consistent planting depth and uniform crop emergence which improve crop tolerance to cultivation. However, smooth bed preparation prior to planting requires deep soil disturbance and specialized equipment which are both expensive and potentially damaging to soil health.

Another factor that influences cultivation tool efficacy is soil moisture, which may influence efficacy through several mechanisms. Soil moisture may affect the movement of cultivation tools through the soil profile and hence their ability to disrupt weeds. For example, wet soils exert more torsion force on flextine cultivators, as increased soil cohesion increases the force necessary to move soil (Kurstjens and Perdok 2000; Mouazen et al. 2007). On the other hand, dry soils may result in crusted soils which inhibit tool movement or result in fractured soils that provide safe sites for weed seedlings (Mohler 2001). Soil moisture also influences the ability of weeds to re-root following soil disturbance. Weeds uprooted by cultivation equipment desiccate and die on the soil surface, but some can re-root and survive, especially if precipitation occurs before or after cultivation (Mohler et al. 1997; van der Weide et al. 2008). For example, flextine efficacy is often highest in dry conditions during and following cultivation (Cirujeda and Taberner 2004). In contrast, for weeds buried by cultivation, wet soils may reduce weed recovery by creating a more cohesive barrier to weed penetration. For example, Mohler et al. (2016) found that common lambsquarters (*Chenopodium album*) recovery following burial was lowest when soils were continuously wet following cultivation, relative to non-irrigated soils.

Soil texture is also thought to have a major influence on cultivation tool efficacy, often mediated by its interaction with soil moisture. For example, flextine efficacy has been shown to be higher in sandy soils compared to heavy, clay soils (van der Weide and Kurstjens 1996), perhaps due to the tendency of clay soils to retain moisture and promote recovery of uprooted weeds. In contrast, weed mortality following burial has sometimes been observed to be greater in soils with small compared to large diameter sand particles (Baerveldt and Ascard 1999), perhaps because smaller particles promote greater moisture retention and soil cohesion, inhibiting the recovery of buried weeds (Mohler 2016).

Soil organic matter and soil structure are also thought to influence cultivation efficacy (Bowman 1997; Mohler 2001). For soils with poor tilth, surface crusting following drying prevents cultivation equipment from appropriately working the soil, with the soil fracturing into clods that can both damage crop plants and provide safe sites for weeds, even with careful tool calibration (Bresson and Boiffin 1990); Mohler 2001). In soils that are prone to crusting, effective cultivation may require multiple passes or weeding may need to be delayed until soil moisture increases. Also, the re-rooting ability of weeds depends in part on how much soil clings to their roots after uprooting, which is influenced by soil tilth. Previous research suggests that weeds rooted in soil clods following soil disturbance more easily re-root as clods are reincorporated into the soil matrix (Mohler et al. 1997). However, it's also possible that soils higher in SOM may hold more water, which could reduce cultivation efficacy.

Flextine cultivators are among the most widely studied mechanical cultivation tools, including studies evaluating their efficacy, selectivity, and mechanism of action, primarily in agronomic crops such as wheat (Kursjens and Perdok 2000; Kursjens and Kropff 2001; Rasmussen 2004; Rasmussen et al. 2009). Flextine cultivators utilize multiple rows of flexible metal tines which are dragged at shallow depths through the soil, disrupting small weeds (Figure 1.1). They are most effective at controlling weeds at the white thread stage, before they visible emerge (Cloutier et al. 2007; van der Weide et al. 2008), but can also be effective on cotyledon or 1st true leaf weed stages (Rasmussen at al. 2009). Previous studies suggest that flextine cultivators kill weeds primarily through uprooting and burial (Kurstjens and Kropff 2001). Kurstjens and Perdok (2000) found that flextine selectivity in grain crops depended on soil moisture content, tine working depth, and working speed.

Although the mechanisms by which flextine cultivators selectively kill weeds are well documented in several cropping systems and soil types, information on the influence of soil surface characteristics on flextine performance is minimal. Soil organic matter, surface roughness, and soil surface resistance are likely important factors influencing flextine efficacy, but their relative importance has not been fully quantified. The primary objective of this study was to evaluate how pre-plant bed preparation (rolled vs not), historic compost use (12 previous years of annual applications vs none), and presence of soil crust (induced through application of molasses or not) influenced soil surface characteristics and the efficacy of flextine cultivation in bush beans (*Phaseolus vulgaris*) and sweet corn (*Zea mays* L.). We hypothesized that the efficacy and selectivity of flextine cultivation would be greatest in level soils with long-term organic matter additions and free of crusting.

Materials and Methods

Experimental setting

To test our hypotheses, 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 2020 growing season. The soil type was a 'Spinks Loamy Sand' with 74.8% sand, 17.8% silt, and 7.4% clay. This textural class is common for many Michigan vegetable growers. Two separate runs of the experiment were conducted in adjacent plots within a larger long-term experiment with multiple objectives. The first run was conducted from 18 June to 26 June in plots planted to sweet corn ('Sweetness F1 synergistic', Johnny's Selected Seeds, Winslow, ME).

The second run was conducted from 30 June to 17 July in plots planted with bush beans (Provider’, Johnny’s Selected Seeds).

Experimental design

To evaluate flextine cultivator efficacy under various soil conditions, the field experiment was set up in a split-split plot design with historic compost application (12 years of historic compost applications vs none) as the main plot factor; pre-plant bed preparation (rolled vs not rolled) as the sub plot factor; and induced crusting (application of molasses solution or not) as the sub-sub plot factor. All factor combinations were included for a total of eight treatments (Table 1.1), each replicated four times within each run of the experiment.

Compost treatments in main plots had received 12 consecutive years of spring applications of a dairy-manure based compost (‘Dairy Doo’ from Morgan’s Composting, Sears, MI) at 5.4 dry MT ha^{-1} yr^{-1}. Non-compost treatments had received no compost during the same period. Historic fertilizer applications in compost vs non compost treatments differed in some years based on soil nutrient testing, with additional NPK applications required in non-compost plots to meet recommendations for rotational crops. Otherwise, all management practices were the same in compost as non-compost treatments including rotational crops, cover crops, tillage, irrigation, and pest management. Estimates of differences in soil organic matter content in composted vs non composted plots prior to initiation of the experiment were taken from six composite soil samples per main plot sampled on 18 May 2019 at a depth of 15cm, and evaluated using loss on ignition.

Following primary tillage with a combination of rototilling and sub-soiling (Table 1.2), bed preparation sub-plots were established in adjacent beds, each measuring 1.5 by 24.5 meters.

Preceding cultivation rolled bed treatments were established using a 106 cm wide polyurethane lawn roller (Blue Hawk Tools, Mooresville, NC). (Figure 1.2)

Immediately following bed preparation, crops were planted in two rows spaced 76 cm apart per bed at 15.3 cm spacing (sweet corn) and 7.1 cm spacing (beans) using a MaterMacc precision vacuum seeder (MaterMacc, San Vito al Tagliamento PN, Italy). Following crop planting, four 0.25m^2 permanent quadrats were created in all sub plots, two to evaluate ambient weeds and two to evaluate surrogate weeds. Surrogate weeds included red amaranth (*Amaranthus cruentus* 'Red Spike'Johnny's Selected Seeds) and condiment mustard (*Brassica juncia*'Mighty Mustard Pacific Gold' Johnny's Selected Seeds) with 200 seeds of both species suspended in 250 ml sand sown with the goal of obtaining approximately 100 seedlings of both species at the time of cultivation.

Two days before anticipated flextine cultivation, soil crusting treatments were established in sub-sub plots by applying a solution of molasses (Sweet Select Unsulfured Molasses, Gordon Food Services, Wyoming, MI) and water through a $C0_2$ backpack sprayer at a rate of approximately 200 ml molasses m^{-2} within two 50 cm x 25 cm quadrats within each sub-plot (one for ambient and one for surrogate weeds). This rate was determined based on preliminary greenhouse testing at multiple rates with the same field soil. Molasses applications were made two days before flextine cultivation to provide sufficient time for crusting to occur. In run 2, weeds and beans had emerged at this stage, but no observed effects of the molasses on plant growth were observed by the time of cultivation.

Flextine cultivation was accomplished with an Einbock flextine cultivator (Einböck GmbH, Schatzdorf, Austria) at 7 DAP in run 1, and 14 DAP in run 2 (Table 1.2). These timings followed flextine recommendations for each crop given the crop stage and weather conditions.

Sweet corn (run 1) is more tolerant of flextine cultivation at an early stage, so cultivation occurred shortly after weed and crop emergence, with weeds at the cotyledon to one leaf stage, and corn at the V3 stage. In contrast, snap beans are susceptible to flextine damage at the hook stage, so cultivation was delayed until the 2-leaf stage. At that point, surrogate weeds had failed to germinate, but ambient weeds were at the cotyledon to two leaf stage. The flextine cultivator was 3-point rear-mounted to a John Deere 5054 tractor and run at approximately 9.7 $km \cdot h^{-1}$. Prior to cultivation, the flextine was calibrated in adjacent plots using a tine working depth of 2 cm, and a tine angle of approximately 90 degrees relative to the soil surface. Speed was the primary factor adjusted during calibration, with gradually increased speeds evaluated until complete horizontal disturbance of the soil surface was observed.

Soil surface characterization

Soil surface roughness was quantified using a A2 LIDAR laser scanner (SlamTec, Shanghai, China) mounted to the top of a dark box custom constructed from wood and black plastic measuring 61 by 122 by 122 cm (Figure 1.3). The LIDAR was mounted to the top of the box, approximately 59 cm from the soil surface, with scans occurring in the lengthwise direction. Output from scans produced datapoints showing distance and relative angle from the LIDAR to the soil surface. The LIDAR scanner was centered between crop rows, and scans extended the full width of the beds. Scans were taken immediately before and after flextine cultivation. Length and angle data from the LIDAR was transformed to obtain distances in the vertical and horizontal direction relative to the center of the between-row zone. Transformations were made by converting LIDAR angle data into radians, and multiplying the length data by the cosine or sine of the radian data for the vertical and horizontal distance, respectively. Surface roughness was calculated from the standard deviation of soil height (Cramers et al. 1996) using the LIDAR vertical distances data for all horizontal distances within 25 cm from the center of the row (to exclude soil surface roughness created by the planter in the in-row zone). The effects of flextine cultivation on surface roughness were assessed by scanning plots immediately prior to cultivation, and immediately afterward, and calculating the change in surface roughness.

Micropenetrometer resistance (‘hardness’) measurements were conducted at 10 random locations within plots with a Shimpo force gauge (Model #: FGV-100XY Shimpo, Kyoto, Japan) slowly pressed into the top 1 cm of soil. The maximum force recorded as the gauge broke through this top layer of soil was averaged across these 10 readings.

Soil gravimetric water content (GWC) was evaluated based on soil samples collected with a trowel to a depth of 2 cm from areas directly adjacent to all plots immediately prior to cultivation events. This soil was weighed, dried, and then weighed again to calculate GWC. The 2 cm depth was chosen to reflect moisture conditions most relevant to the functioning of the flextine cultivator on small weed seedlings present at the time of cultivation.

Weed mortality and flextine efficacy

Tool efficacy was determined from weed and crop density counts in each quadrat before and after cultivation. Weed counts in ambient and surrogate subplots were done immediately prior to cultivation. Post counts were taken 1 day following cultivation in corn and 3 days following cultivation in beans. Weed mortality was estimated based on the percent change in weed density for each species from the pre and post counts. Based on the size of the weeds at the time of the post count, we believe that no new weeds had germinated, and that this calculation therefore provides a reasonable estimate of mortality.

Statistical analysis

Analysis was conducted in SAS (Statistical Analysis Software 9.2 Cary, NC). Assumptions of normality and equal variance for all response variables were evaluated using PROC UNIVARIATE and Levene's test. Where needed, data was transformed using a Box Cox test to determine optimal transformation. The effects of compost addition, soil preparation, molasses addition and their interaction on weed density, weed survival, soil surface roughness, soil moisture and soil micro-penetrometer resistance were evaluated using PROC MIXED procedures in SAS, with each of the three soil factors treated as fixed effects, and compost nested within replicate treated as random effects. Tool selectivity was analyzed separately for each surrogate species and crop and combined for ambient weeds due to low ambient weed pressure. Where main or interactive effects were significant, mean separation was conducted using Tukey's HSD adjustment for multiple comparisons.

Regression analysis was conducted using PROC REG, with soil condition measurements regressed against weed mortality for each weed category. The model equation used was:

$$y = \beta_0 + \beta_1 * hardness + \beta_2 * moisture + \beta_3 * roughness$$

Where *y* is either non-transformed weed mortality (for mustard in run 1 and ambient weeds for run 2) or the square root of weed mortality (for red amaranth and ambient weeds in run 1). Square root transformation was used to normalize residuals to meet model assumptions.

<u>Results</u>

Soil surface and weed density responses to compost, rolling and molasses

Surface roughness. The surface roughness of soil just before flextine cultivation was influenced by rolling or compost additions but not by molasses (Table 1.3). As expected, rolling reduced surface roughness in both runs of the experiment. In run 1, there was an interaction between rolling and compost addition: Rolled soils which had received historic compost additions had 26.3% greater roughness than rolled soils which had not received compost (Figure 1.4). Surprisingly, the effect of rolling was greatest where no compost had been applied (Figure 1.4). In run 2, the same trend held, but surface roughness in rolled compost plots was not different than rolled plots without compost (Figure 1.4).

Soil micro-penetrometer resistance. Soil hardness was influenced by rolling, but not by compost application (Table 1.3). The effect of molasses application on hardness was only detected in run 2, and only in treatments that had not been rolled (Table 1.3; Figure 1.5). Rolled plots were 73% and 85% harder compared to unrolled plots, in run 1 and 2, respectively (Table 1.4). In run 2, molasses application increased hardness by 24% in unrolled treatments, but had no effect in treatments that had been rolled (Figure 1.5).

Soil moisture. Rolling, compost and molasses factors had no detectable effect on soil moisture prior to flextine cultivation with one notable exception (Table 1.4): In run 1, rolled soils were 26.3% wetter than unrolled soils prior to sweet corn cultivation (Table 1.4).

Weed emergence. In run 1, the density of ambient weed seedlings prior to cultivation was influenced by compost and rolling, but not by molasses (Table 1.5). However, in run 2, no effects of treatments on weed emergence were detected. In run 1, ambient weed density was 80% higher in plots with historic compost applications compared to plots without compost, and 83% higher in rolled soils compared to unrolled soils (Table 1.6). Ambient weeds in both runs included purslane (*Portulaca oleracea*), common lambsquarter, crabgrass (*Digitaria sanguinalis*) and pigweed (*Amaranthus powellii*) species. None were present at sufficient densities to evaluate efficacy alone, so ambient species were combined for analysis.

Flextine effects on weed mortality and crop mortality following compost, rolling and molasses

Flextine efficacy. In both runs of the experiment, ambient weed mortality following flextine cultivation was influenced by the main effect of rolling, but not by historic compost or molasses application (Table 1.5). Rolling reduced flextine efficacy on ambient weeds by 1.7% in run 1 and 2.6% in run 2 (Table 1.6). In run 1, red amaranth surrogate mortality was also higher in unrolled treatments, but no effect was detected for mustard surrogate weeds. In run 2, germination of both surrogate weeds was poor, so no surrogate mortality could be evaluated. As anticipated given our calibration process, crop mortality in both runs of the experiment was low, averaging approximately 8% for sweet corn and 5% for beans, with no obvious effects of compost, rolling or molasses (Table 1.6). (Table 1.6).

Flextine effects on surface roughness. Surface roughness following flextine cultivation was influenced by the main effect of rolling in run 2, but not in run 1 (Table 1.3). Rolled soils had 38.5% lower surface roughness than unrolled soils following flextine cultivation in beans (Table 1.4). However, following cultivation in corn, surface roughness was not different between rolled and unrolled soils (Table 1.4).

Relationship between mortality and soil surface characteristics

Results from our regression analysis show that among the variables we tested, weed mortality was negatively correlated with soil hardness for all species in both runs (Figure 1.6). We were not able to detect correlations between weed mortality and soil moisture or surface roughness. Regression coefficient suggest that each one newton increase in soil penetrometer resistance was associated with a reduction in flextine efficacy of approximately 1 to 2 percentage points.

Discussion

Contrary to expectations, we found that rolling a seedbed to create a level soil reduced efficacy of flextine cultivation in most cases. In both runs of the experiment, rolling resulted in reduced efficacy of flextine cultivation for control of ambient weeds (Table 1.6). Although efficacy was greater than 95% regardless of rolling, the greater density of escaped weeds in rolled plots is likely to represent a real potential cost to growers in the form of higher handweeding costs or reduced quality and yield. For example, in run 1 of this experiment, ambient weed density following flextine cultivation was 6-fold higher in rolled compared to unrolled treatments.

Our results also suggest several mechanisms that help explain this counterintuitive effect of rolling on flextine efficacy. As expected, rolling beds prior to planting produced a more level soil surface in most cases (Table 1.3; Figure 1.4), which —other things equal—would likely result in the more uniform working depth to improve efficacy. However, although rolling reduced surface roughness, we were not able to detect any correlation between surface roughness and flextine efficacy (Figure 1.6). Rolling also affected other soil conditions which may have had a negative effect on flextine efficacy. In particular, rolling soils increased soil micropenetrometer resistance (hardness) in both runs of the experiment, and increased soil surface moisture content in run 1 (Table 1.4). Our regression analysis shows that among these factors, soil hardness was most clearly associated with weed mortality (Figure 1.6). Regression coefficients estimates suggest that a 1 N increase in soil penetrometer resistance was associated with a reduction in efficacy of 1 to 2 percentage points. Lack of observed surface roughness effects on efficacy may have been due in part to the relatively small differences in the range of roughness evaluated in this trial; although differences existed across rolled and unrolled bedsi

(Table 1.4), the soil surface was probably sufficiently level to facilitate tine working depths that effectively killed weeds.

Rolling soils prior to planting represents a cost to growers in time, labor, and increased soil disturbance, and we found no benefit to this practice for flextine cultivation of large seeded vegetable crops on our loamy-sand soils. In fact, our results suggest that rolling can reduce flextine efficacy through its adverse effects on soil penetrometer resistance. However, these results may not be generalizable to other soil textures, crops, or cultivation tools. For example, soils with finer textures may be rougher following primary tillage and may benefit from leveling with a roller to improve cultivation equipment function and reduce potential safe-sites for weeds. Levelling may also provide benefits for smaller seeded crops such as carrots or beets by improving planting depth, stand establishment and tolerance to cultivation.

Our results also did not support our initial hypotheses that historic compost additions would improve cultivation efficacy (Table1.5). We anticipated that compost additions would improve efficacy by improving tool movement through the soil as previously asserted in several studies (Bowman 1997; Mohler 2001). However, these potential benefits on tool action may have been offset by several negative indirect effects. First, compost applications may have influenced flextine efficacy through effects on the density or growth of weeds and hence their ability to tolerate cultivation. For example, in run 1, historic compost addition was associated with higher densities of ambient weeds (Table 1.6). Although no clear differences in weed growth prior to cultivation were observed, it is also possible that weeds growing in composted soil had more vigorous root systems that improved their tolerance to cultivation. Second, it is interesting to note that compost itself in some cases contributed to greater surface roughness (Figure 1.4) which may have also offset any benefits of compost for flextine efficacy. We speculate that this effect may have been due to aggregates present in the compost applied in the spring just before initiation of the experiment. Such aggregates may have produced safe-sties for weeds that offset any longer term benefits for cultivation of compost addition on soil tilth.

The lack of compost effects on flextine efficacy may have also been due to the limited effects of that compost on soil tilth. Note that our study was conducted on a loamy-sand soil common in Midwest vegetable production. Potential changes in soil organic matter and structure in such soils is limited compared to more fine textured soils. In our case, soil organic matter (SOM) in treatments receiving annual compost for 12 years was 1.6%, compared to 1.3%, in soils receiving no compost. Moreover, both compost and non-compost treatments had identical cover crop and tillage management over this 12 year period, which may have overshadowed compost effects on SOM . It is possible that this difference in SOM between treatments was simply not sufficient to impact soil tilth and tool function. Indeed, we observed no impacts of compost on soil moisture or hardness (Table 1.4) that might have been expected in soils with significant changes in SOM. Cultivation tool function may be improved in soils with increased SOM and tilth, but we were not able to create sufficiently distinct soil conditions in this study to adequately test this hypothesis.

Artificial induction of soil crusting using molasses also did not have detectible effects on cultivation efficacy. Although we observed crusting due to molasses in these soils in greenhouse testing, molasses effects in the field appear to have been relatively small, with little or no detectable effect on soil penetrometer resistance (Table 1.4). However, we did observe that the soil surface with molasses appeared to create visible differences in soil crusting that were not adequately captured by resistance measured with our micropenetrometer. Again, the loamy sand soil where this trial was conducted has a lower propensity for crusting compared to finer textured soils, and our ability to produce a detectable soil crust with molasses was limited. Heavier soil types with poor soil structure are more likely to produce a crust that inhibits function of cultivation tools (Bresson and Boiffin 1990).

Our study demonstrates that soil conditions can play an important role in cultivation tool function. Characterization of soil conditions before and after cultivation events can provide insights into the mechanisms responsible for these effects. Observed discrepancies between tool function across years and sites may be attributable to differences in soil characteristics including roughness, moisture, and crusting. Unfortunately, soil conditions are often overlooked in cultivation studies, making inferences about the mechanisms of tool efficacy difficult or impossible. Ultimately, we'd like to be able to tell growers which tool will work best under which conditions, and give insights into management decisions. For instance, we saw in this study how soil compaction effects from rolling on efficacy might not be obvious when preparing level beds for cultivation. Including mechanistic information in cultivation studies is critical for providing growers with the information they need. Further research opportunities exist to more deeply explore how these characteristics impact cultivation efficacy and make management recommendations to growers.

APPENDIX

TABLES AND FIGURES

Table 1.1. List of treatments in flextine cultivation experiment

	Main Plot Factor	Sub Plot Factor	Sub-Sub Plot Factor
Treatment	Roughness	Compost	Crust
1	None	None	None
2	None	None	Molasses
3	Rolled	None	None
4	Rolled	None	Molasses
5	None	Compost	None
6	None	Compost	Molasses
7	Rolled	Compost	None
8	Rolled	Compost	Molasses

Table 1.2. Schedule of major field operations and data collection events

		Run 1 (Sweet Corn)		Run 2 (Bean)	
Trial	Event	Date	DAP	Date	DAP
	Mowed and rototilled cover crops	5-Jun	-13	5-Jun	-25
	Compost applied (main plots)	16-Jun	-2	8-Jun	-22
	Subsoiled	16-Jun	-2	16-Jun	-14
	Fertilized	16-Jun	-2	24-Jun	6
	Rototilled	16-Jun	-2	30-Jun	0
	Rolled (sub-plots)	18-Jun	0	30-Jun	0
	Planted	18-Jun	0	30-Jun	0
	Surrogate weeds sown	18-Jun	0	30-Jun	0
	Molasses applied (sub-sub plots)	23-Jun	5	12-Jul	12
	Scanned soil surface (pre)	24-Jun	6	13-Jul	13
	Weed density evaluated (pre)	25-Jun	7	13-Jul	13
	Soil resistance evaluated	25-Jun	7	14-Jul	14
	Flextine cultivated	25-Jun	7	14-Jul	14
	Scanned soil surface (post)	25-Jun	7	14-Jul	14
	Weed density evaluated (post)	26-Jun	8	17-Jul	17

Table 1.3. Significance (P values) of effects of compost, rolling, and molasses applications on soil random roughness, soil moisture (gravimetric moisture content) and soil hardness (micropenetrometer resistance).

Soil Treatments	Run 1 (Sweat Corn)				Run 2 (Bean)			
	Surface Roughness				Surface Roughness			
	Pre-Cult	Post-Cult	Soil Moisture	Soil Hardness	Pre-Cult	Post-Cult	Soil Moisture	Soil Hardness
	----------Significance (P-value)----------							
ANOVA								
Compost (C)	0.1082	0.5156	0.2236	0.9696	0.3330	0.8923	0.2205	0.3274
Rolling (R)	**0.0004**	0.7425	**0.0036**	**0.0001**	**0.0001**	**0.0001**	0.7786	**0.0001**
Molasses (M)	0.4208	0.5289	0.2617	**0.0045**	**0.0138**	0.6219	0.0732	0.2820
C X R	**0.0150**	0.2682	0.4873	0.8266	**0.0058**	0.1436	0.7996	0.5531
C X M	0.1451	0.8770	0.3851	0.2852	0.6011	0.1276	0.8101	0.8306
R X M	0.0894	0.3915	0.8199	**0.0279**	**0.0001**	0.1170	0.7152	0.4181
C X R X M	0.0764	0.3117	0.6589	0.4160	0.9213	0.4974	0.9869	0.8543

Bolded p values are statisticaly significance (p = 0.05)

Table 1.4. Mean surface random roughness, soil water content, and micropenetrometer resistance in response to main effects of historic compost, rolling and mollasses application in run 1 and run 2.

Soil Treatments	Run 1 (Sweet Corn) Surface Roughness Pre-Cult	Run 1 Surface Roughness Post-Cult	Run 1 Soil Moisture	Run 1 Soil Hardness	Run 2 (Bean) Surface Roughness Pre-Cult	Run 2 Surface Roughness Post-Cult	Run 2 Soil Moisture	Run 2 Soil Hardness
	----------- mm ----------		---%---	---N---	----------- mm ----------		---%---	---N---
Compost Main Effect								
Compost	6.4	10.0	6.9	10.0	5.1	7.7	5.7	7.5
None	5.6	9.6	5.8	9.8	5.0	8.0	5.1	8.2
Rolling Main effect								
Rough	7.4 a	10.0	5.6 b	6.3 b	6.5 a	9.8 a	5.4	5.5 b
Rolled	4.6 b	9.6	7.1 a	13.5 a	3.6 b	6.0 b	5.5	10.2 a
Molasses Main Effect								
Molasses Applied	5.7	9.6	6.6	10.6 a	4.8 b	8.0	5.6	8.1
None	6.3	10.0	6.0	9.1 b	5.3 a	7.7	5.2	7.5

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Table 1.5 Significance (P values) of effects of compost, rolling, and molasses applications on weed density and mortality of mustard, red amaranth, and ambient weeds following cultivation.

	Run 1 (Sweet Corn)				Run 2 (Bean)	
		Weed Mortality				Weed Mortality
Factors	Ambient [a] Weed Emergence	Mustard	Red Amaranth	Ambient Weeds	Ambient[a] Weed Emergence	Ambient Weeds
	---------------------------------------Significance (P-value)--------------------------------------					
ANOVA						
Compost (C)	**0.0085**	0.1350	0.3364	0.7186	0.7726	0.9011
Rolling (R)	**0.0001**	0.0877	**0.0447**	**0.0066**	0.2068	**0.0010**
Molasses (M)	0.0586	0.9915	0.9836	0.9708	0.5533	0.9194
C X R	0.2011	0.0860	0.9924	0.1682	0.5181	0.8651
C X M	0.1613	0.3760	0.6484	0.9601	0.3967	0.5404
R X M	0.0834	0.6805	0.6186	0.4664	0.6037	0.8551
C X R X M	0.7071	0.9393	0.6259	0.4164	0.8040	0.7853

Bolded p values are statistically significance (p = 0.05)

[a] Ambient weeds were purslane (*Portulaca oleracea*), lambsquarter (*Chenopodium album*), crabgrass (*Digitaria sanguinalis*) and pigweed (*Amaranthus powellii*) species

Table 1.6. Mean weed density and mortality following flextine cultivation in response to main effects of historic compost, rolling and molasses application in run 1 and run 2. There were no significant interactions (see Table 1.4).

Soil Treatments	Run 1 (Sweet Corn) Ambient[a] Weed Emergence		Mortality: Sweet[b] Corn	Mortality: Mustard	Mortality: Red Amaranth		Mortality: Ambient Weeds		Run 2 (Bean) Ambient[a] Weed Emergence	Mortality: Bean[b]	Mortality: Ambient Weeds	
	---# m^{-2}---		-- % --------------------------------------						---# m^{-2}---	----- % -----		
Compost Main Effect												
Compost	216.4	a	6.4	87.8	94.9		99.0		262.5	3.9	98.0	
None	121.5	b	9.7	95.0	97.1		98.6		287.0	5.7	98.1	
Rolling Main Effect												
Rough	119.3	b	9.4	94.2	98.2	b	99.6	b	249.8	3.7	99.3	b
Rolled	218.6	a	6.6	88.6	93.8	a	98.0	a	299.8	6.0	96.8	a
Molasses Main Effect												
Molasses Applied	186.7		7.5	91.0	95.8		99.0		283.2	5.6	98.0	
None	148.8		8.7	91.9	96.2		98.6		265.2	3.7	98.1	

Statistical significance ($p = 0.05$) is indicated by different letters within the same column.

[a] Ambient weeds were purslane (*Portulaca oleracea*), common lambsquarters (*Chenopodium album)*, large crabgrass (*Digitaria sanguinalis*) and Powell amaranth(*Amaranthus powellii*) species.

[b] No statistical means separations were performed on crop mortality due. Unable to normalize data through transformation.

Figure 1.1 Einböck flextine harrow.

Figure 1.2. Image of bed difference in surface roughness between rolled and unrolled beds at corn planting (run 1).

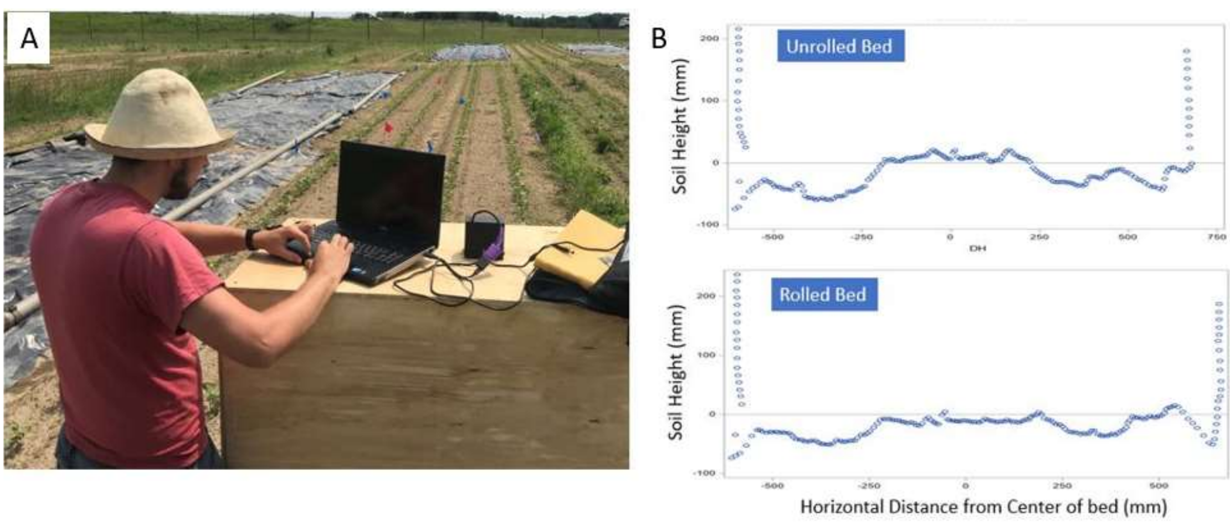

Figure 1.3. a) Image of the author taking LIDAR surface roughness scans in the field with a light exclusion box. b) Sample LIDAR scan outputs.

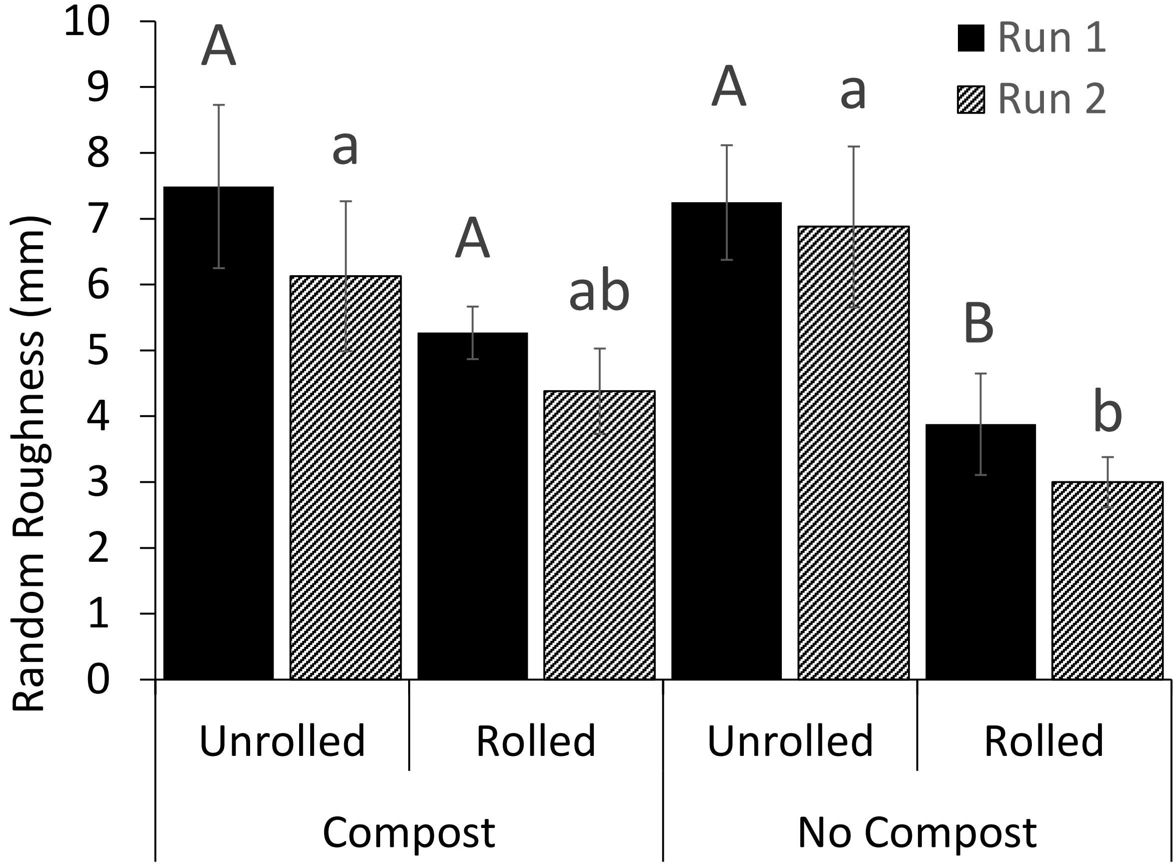

Figure 1.4. Mean random roughness of soil surface of plots in run 1 and run 2 in rolled and unrolled plots, with and without compost applications. Rolled plots without historic compost applications were less rough than all unrolled plots. However, rolled plots that had received historic compost applications were not different than unrolled plots, and were less rough than rolled soils with compost in run 1.

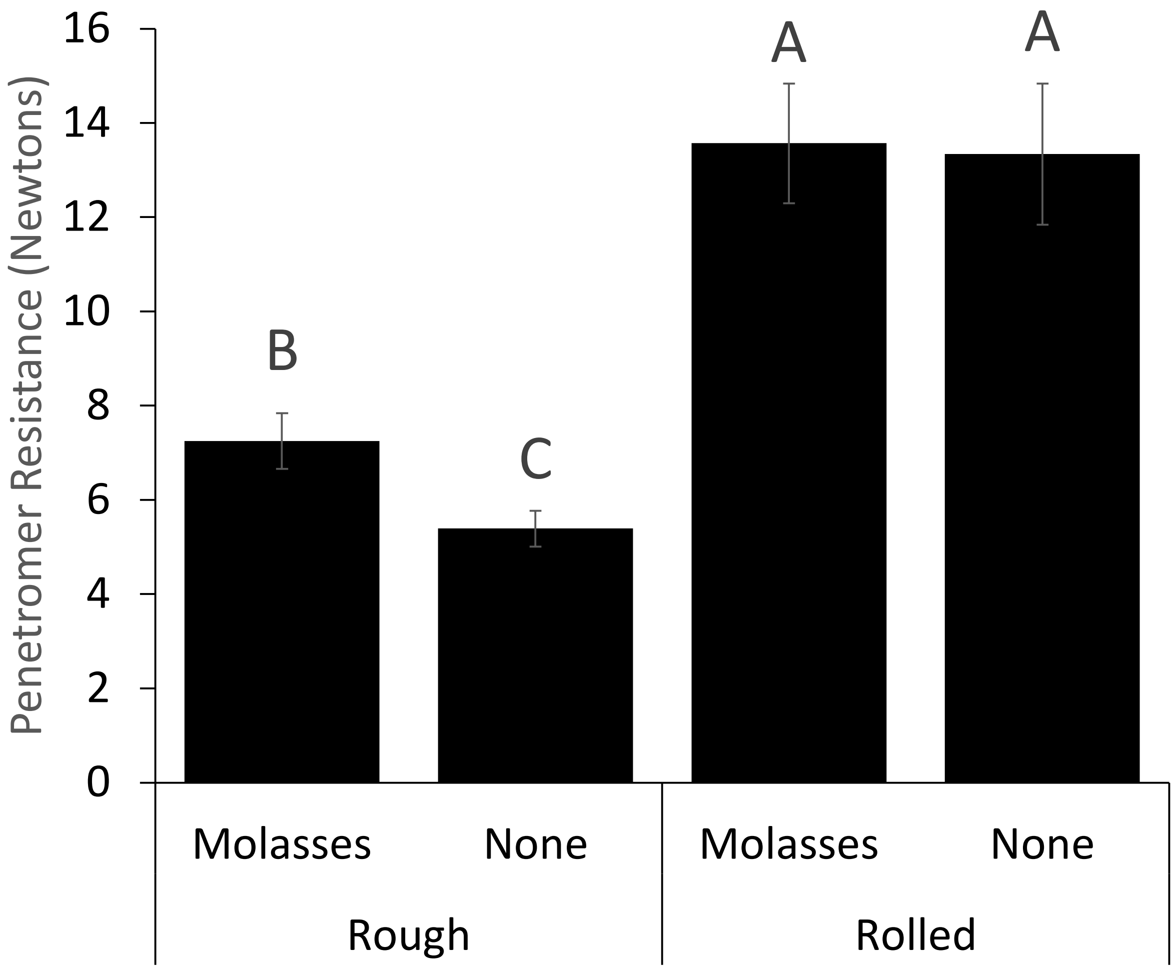

Figure 1.5. Run 1 Mean soil hardness in sub plots with and without soil crusting molasses applications in rolled and rough beds. Plots that had molasses applied were harder than those without molasses application in beds that were not rolled. However, rolled beds were harder than rough beds with and without molasses applications. Molasses application did not make soils harder in rolled plots.

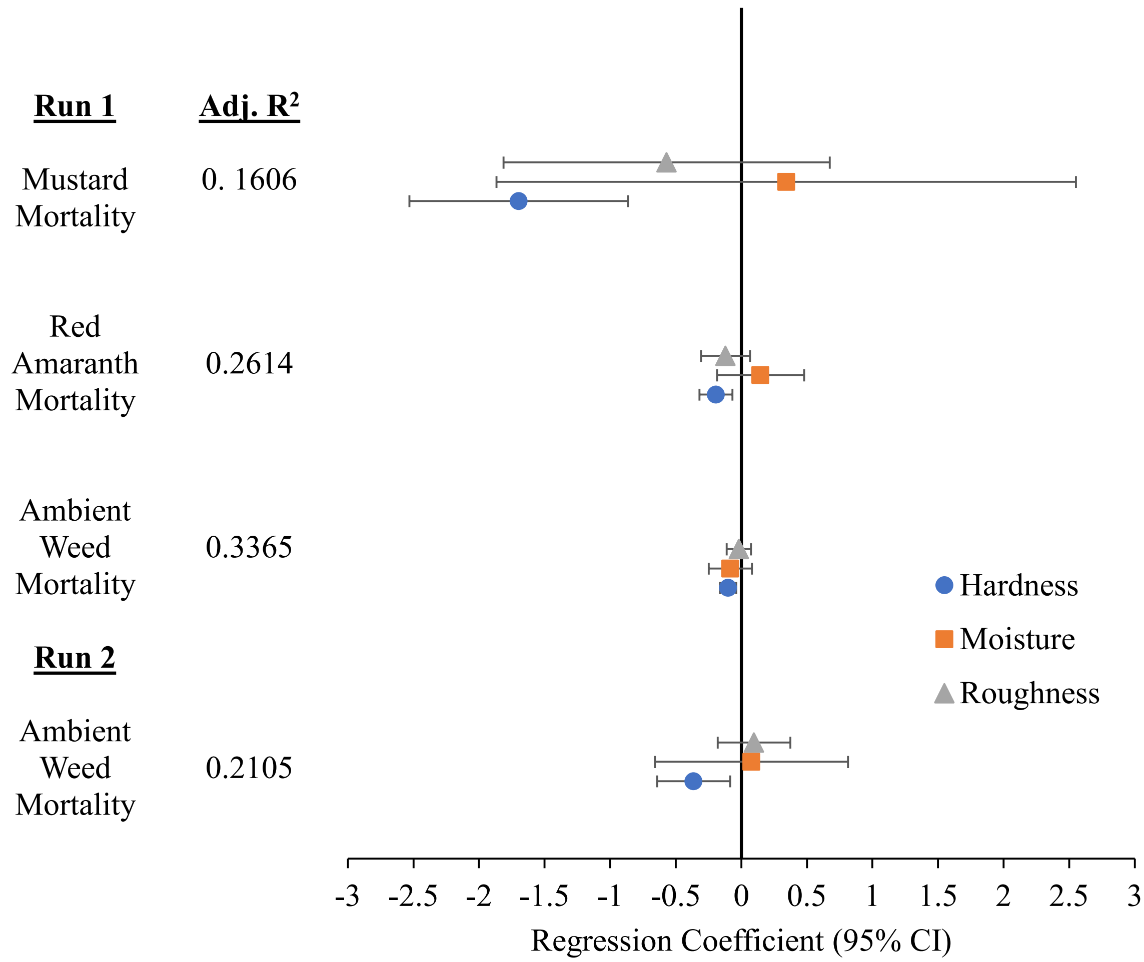

Figure 1.6. Regression coefficients for soil hardness, moisture, and surface roughness when modeled against mustard, red amaranth, and ambient weed mortality in run 1 and run 2. Variables where the 95% confidence interval does not overlap with 0 are significant (p = 0.05). Dependent variable of red amaranth and ambient weed mortality in run 1 were square root transformed.

LITERATURE CITED

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Bresson LM, Boiffin J (1990) Morphological characterization of soil crust development stages on an experimental field. Geoderma 47:301–325

Bowman G (1997) Steel in the field: A farmer's guide to weed management tools

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

Cloutier DC, van der Weide RY, Peruzzi A, Leblanc ML (2007) Mechanical Weed Management. Pages 111–134 *in* MK Upadhyaya, RE Blackshaw, eds. Non-chemical Weed Management: Principles, Concepts and Technology Edited. CAB

Cremers NHDT, Van Dijk PM, De Roo APJ, Verzandvoort MA (1996) Spatial and temporal variability of soil surface roughness and the application in hydrological and soil erosion modelling. Hydrol Process 10:1035–1047

Cirujeda, A and Taberner, A (2004) Defining optimal conditions for weed harrowing in winter cereals on *Papaver rhoeas* L. and other dicotyledoneous weeds. 6th EWRS Workshop on Physical and Cultural Weed Control. Lilliehammer, Norway, 8–10 March.

Evans GJ, Bellinder RR, Hahn RR (2012) An Evaluation of Two Novel Cultivation Tools. Weed Technol 26:316–325

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

Gallandt, E.R., D. Brainard, and B. Brown. (2018) Developments in physical weed control. In Zimdahl (ed) Integrated Weed Management for Sustainable Agriculture. Pages 261-283. ISBN: 978-1-78676-164-4

Havlin JL, Kissel DE, Maddux LD, Claassen MM, Long JH (1990) Crop Rotation and Tillage Effects on Soil Organic Carbon and Nitrogen. Soil Sci Soc Am J 54:448–452

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

Kurstjens DAG, Kropff MJ (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. Weed Res 41:211–228

Kurstjens DAG (2007) Precise tillage systems for enhanced non-chemical weed management. Soil Tillage Res 97:293–305

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

Mouazen AM, Duerinckx K, Ramon H, Anthonis J (2007) Soil Influences on the Mechanical Actions of a Flexible Spring Tine during Selective Weed Harrowing. Biosyst Eng 96:7–18

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations.

Rasmussen IA (2004) The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. Weed Res 44:12–20

Rasmussen J, Nielsen HH, Gundersen H (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. Weed Sci 57:338–345

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

van der Weide, RY and Kurstjens, DAG (1996), Plant morphology and selective harrowing, Physical Weed Control, 2nd EWRS Workshop.

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

CHAPTER TWO: Integrated Physical and Cultural Weed Management in Table Beets

ABSTRACT

Table beets (*Beta vulgaris)* are among the most challenging crops to mechanically cultivate, but improved understanding and exploitation of cultivar differences in emergence, growth and morphological characteristics may improve cultivation success. In a series of field and greenhouse trials, four beet cultivars—Boro (B), Chioggia Guardsmark (CG), Moneta (M), and Touchstone Gold (TG)— were evaluated for their tolerance to deep planting and mechanical cultivation as well as their competitiveness with escaped weeds. In one set of experiments, seeds of each cultivar were sown at 1, 2, 3 and 4 cm depth and monitored for emergence and early growth under both greenhouse and field conditions. In a separate field experiment, the effects of cultivar, cultivation tool (finger weeder vs hilling disk) and weed competition (none vs escaped weeds) on weed and beet survival, beet yield and final weed biomass were evaluated. We hypothesized that cultivars with greater root biomass and root anchorage force would be more tolerant to finger weeders, while those with greater shoot biomass and height would be more tolerant to hilling. In emergence studies, we found that under greenhouse conditions, B, CG and TG beet varieties could be planted at 3 or 4 cm depth to delay emergence by 1-2 days relative to shallower seeding depths, potentially allowing for a longer window to stale seedbed. However, under field conditions, emergence from greater depths sometimes resulted in either no apparent difference in emergence timing or reduced total emergence and hence may be an impractical strategy, depending on soil conditions. In field cultivation studies, we found that cultivars differed in their tolerance to cultivation, as well as competitiveness with weeds. B had both the highest yield and was the most weed competitive.

Introduction

Increasing demand for organic vegetables, coupled with the high cost of hand weeding, has resulted in renewed interest in mechanical cultivation tools. Among these, between-row cultivators are the most widely implemented due to their ease of use, but weeds within the crop row remain untouched (Van Der Weide et al. 2008). In-row cultivation tools target these problem weeds, but are more difficult to use effectively and are less studied. For in-row weeds, tools must be able to kill weeds while minimizing crop damage, a feature known as tool selectivity (Kurstjens et al. 2004; Rasmussen 1990).

The selectivity of mechanical cultivation tools depends on differences between crops and weeds in characteristics which confer tolerance to those tools such as height, stem strength, and root anchorage forces (Fogelberg and Dock Gustavsson 1998; Kurstjens et al. 2004). Kurstjens et al. (2004) defines tool selectivity in terms of both 'selective potential' and 'selective ability'. Selective potential is the maximum selectivity that can be achieved with an idealized tool under a given set of crop-weed conditions. Selective potential can be improved by creating a large crop to weed size difference, through a variety of approaches including transplanting, seed priming, targeted fertilization or intense early-season weed control (Gallandt et al. 2017). Selective potential may also be improved by reducing the variability of crop characteristics that confer tolerance to cultivation tools. For example, use of uniform vigorous seeds, planted at their optimal depth can help ensure uniform emergence and early crop growth to facilitate improved crop tolerance and selective potential (Gallandt et al. 2017). Selective ability is the actual ability for a tool to reach its selective potential, and is improved by carefully selecting and calibrating tools based on soil, weed and crop conditions.

Table beets (*Beta vulgaris* L.) are among the most challenging crops to cultivate for several reasons. Beet seed germination is not uniform and is sensitive to wet soil conditions, which limits oxygen availability (Taylor et al. 2002), often resulting in small and variable stands with limited ability to tolerate early cultivation. Many beet cultivars also contain multiple embryos per seed ball, resulting in weak secondary seedlings, and large variability in seedling size at the time of cultivation. In addition, beets are easily damaged by in-row cultivation or hilling until they are at the 4-leaf stage (Ascard and Bellinder 1996). Therefore, beet growers typically need to use pre-emergent herbicide or hand weeding at this early stage for the crop to develop a competitive advantage over emerging weeds. Early weed control is critical in the first eight weeks of growth, after which beets are better able to compete with weeds without influencing yield (Mansilla Martínez et al. 2015).

One approach to improve the selectivity of mechanical weeding is to implement a 'stale' or 'false' seedbed to give crops a size advantage relative to weeds (Mohler and Caldwell, 2001; Riemens et al. 2007). This approach involves preparing a seedbed several weeks before planting the crop, stimulating non-dormant weed seeds to germinate, then removing weeds with herbicides, flame weeding, or shallow cultivation. Stale seedbedding is commonly used for direct-seeded vegetable crops after planting to reduce weed pressure during the early growth stage of the crop and to facilitate a size advantage of crops relative to weeds. For example, Mohler and Caldwell (2001) found that stale seedbeding with a flame weeder or herbicide application prior to planting significantly reduced broadleaf weed biomass compared to treatments that were tilled immediately prior to planting.

Unfortunately, implementation of pre-emergent stale seedbed is challenging in table beets. Beets germinate quickly and concurrently with the first flush of weeds and beet seedlings are poor competitors. This contrasts sharply with slower emerging vegetables like carrots which generally emerge several days after weeds, allowing a 2-3 day window of opportunity to kill weeds prior to crop emergence. Therefore, for beets, strategies to delay emergence may be helpful for facilitating pre-emergence weed management and stale seedbed practices. If germination and emergence of beets can be delayed for only one to two days, a gap between weed and beet emergence can be exploited to kill weeds emerging from the germinal seedbank.

One possible way of delaying beet emergence to facilitate pre-emergence weed control is to plant seeds at greater depth. One study found that doubling sowing depth of beets in greenhouse trials delayed emergence without reducing final stand, however deeper sowing in field conditions reduced emergence without delaying emergence (Romaneckas at al. 2009).

Another approach to improving selectivity of tools is to identify cultivars with traits that confer tolerance to mechanical cultivation. Crop cultivar differences in weed-competitive ability (Liebman et al. 2001) or tolerance to mechanical cultivation (Hitchcock-Tilton 2018) may be helpful in designing weed management strategies. While most research related to cultivation-tolerance has been based on grain cultivars (Kursjens and Perdok 2000; Rassmusen et al. 2009), studies in carrots (Hitchcock-Tilton 2018) and winter squash (Benzle 2019) also found cultivar differences in tolerance to mechanical cultivation. Such differences in tolerance are thought to derive from observed differences in early growth rate and anchorage force at the time of cultivation (Benzle 2019; Hitchcock-Tilton 2018; Rasmussen at al. 2009). Studies evaluating the weed competitiveness of different cultivars have mostly targeted agronomic crops including wheat (Wicks et al. 1986), rice (Garrity et al. 1992) and potatoes (Colquhoun et al. 2009). To our knowledge, no previous studies have evaluated differences in beet cultivar tolerance to mechanical cultivation or competitiveness with weeds, both of which may be potentially be exploited to increase ease and efficacy of mechanical weed cultivation for growers.

Cultivation tools use a variety of mechanisms to control weeds including burying, uprooting, and cutting weeds alone or in combination. Hilling discs for example target in-row weeds by throwing soil into the crop row and burying weeds. Finger weeders on the other hand can be set to either hill soil to bury in-row weeds or flick soil out of the in-row zone uprooting weeds in the process. There may be an interaction between cultivar tolerance and tool type used. The relative size of weeds vs crops, and their relative tolerance to forces applied by tools play an important role in determining the potential for a given tool to selectively kill weeds (Kurstjens and Perdok 2000; Mohler 2001). Hilling discs may be better suited for beets that have greater shoot partitioning and are tall enough to withstand burial. Conversely, finger weeders may be more selective in beet cultivars with greater anchorage force to resist being uprooted. In other words, optimal tool selection is likely to depend on growth habits of a particular cultivar.

Given the lack of early stage weed control options in beets, cultivar selection for tolerance to cultivation forces and delayed emergence could potentially offer growers greater control options. The objectives of these studies were: 1) evaluate whether deep-sowing of seeds of different cultivars could delay emergence; and 2) evaluate differences in beet cultivar competitive ability and tolerance to mechanical cultivation with finger weeders and hilling disks. We hypothesized that cultivars with greater root biomass and root anchorage force would be more tolerant to finger weeders, while those with greater shoot biomass and height would be more tolerant to hilling. In addition, we hypothesized that deep sowing would facilitate stale seed bedding by delaying the time of beet emergence relative to weeds.

Materials and Methods

Cultivar x Depth Studies

To test our hypotheses, separate experiments were conducted to evaluate 1) the impact of beet cultivar and sowing depth on emergence and early growth, and 2) the impact of cultivar and mechanical cultivation tool on weed control efficacy, selectivity, crop competitiveness and yield.

Greenhouse evaluations. In 2019, a greenhouse experiment was set up in a Randomized Complete Black Design (RCBD) with 14 replicates in the Plant Science Greenhouse facility at Michigan State University, East Lansing, MI. Experimental factors were cultivar and depth (Table 2.1). Two separate runs of the experiment were conducted between June 31 and August 18 (run 1) and November 8 and November 27 (run 2). For each experimental run, four table beet cultivars were evaluated: Boro, a red beet; Chioggia Guardsmark, a bicolored beet; Moneta, a monogerm red beet; and Touchstone Gold, a yellow beet. Beet seeds were sourced from Johnny's Selected Seeds (Winslow, ME). These cultivars represent the broad categories of fresh market beets available to growers.

Beet seeds were planted in 4 cm diameter and 21 cm deep black germination tubes at four depths (1, 2, 3, and 4 cm) using tweezers to ensure precise planting depth. A single beet seed was planted in each tube. Growing media was a 40:40:20 mixture of Suremix Perlite (peat, perlite, lime) (Michigan Grower Products Inc, Galesburg, MI), sand, and organic compost (Dairy Doo compost, Morgan's Composting, Sears, MI). Cotton balls were placed in the bottom of germination tubes before growth media to avoid loss of soil through drain hole in tubes.

Beet tubes were watered as needed to maintain uniform moisture and counted daily for emerging seedlings. Time to emergence and total seedlings produced per seed were recorded for the first 16 days after planting (DAP) in the first run and the first 19 DAP in the 2^{nd} run. In run 1, after all seedlings had emerged, beets were thinned to the single largest seedling per tube. These seedlings were grown until 24 DAP, then removed with roots intact and gently washed to remove soil adhering to roots, and roots and shoot lengths were measured.

Field evaluations. In August 2019, a field trial was set up in a Split Plot Design with four replicates at Green Wagon Farm in Ada, MI (42.874881, -85.446880). Experimental factors were cultivar (B, M and TG) and depth (1, 2, 3 and 4 cm) (Table 2.1). Soil type in the field was "Parkhill Loam". Seed beds were prepared by rototiller and then formed into 1.5m beds. Two rows of beets were planted in each bed with 0.76m between rows. B, M, and TG table beet cultivars were selected for their potential differences in early growth and depth response based on observations from greenhouse trails. Seeds were planted individually with tweezers at 1, 2, 3, and 4 cm depth in 3m row plots with 20 evenly spaced seeds per plot.

Beet plots were overhead irrigated as needed and weeded by hand to minimize competition. Daily stand counts were taken of emerging seedlings until emergence slowed at 8 DAS . Seedling clusters were then thinned to the largest seedling, which grew until 20 DAP. At 20 DAP, the anchorage force of five beets of each cultivar in each replicate seeded at 2cm depth was evaluated using a Shimpo force gauge (Model #: FGV-100XY, Shimpo, Kyoto, Japan); beets were clamped at the base of the stem and slowly and steadily pulled upward until uprooting occurred. The anchorage force was defined as the maximum force recorded on the force gauge during uprooting. In cases where five beets had not germinated, beets sown at 3cm depth were uprooted and evaluated for anchorage force. Uprooted beets were then separated into roots and shoots and dried at 100° C for 7 days and weighed.

Statistical analysis. For both greenhouse and field emergence studies, the fixed effects of cultivar and planting depth on beet emergence were evaluated using PROC MIXED procedures in SAS

(Statistical Analysis Software 9.2 Cary, NC). PROC UNIVARIATE and Levene's test were used to evaluate assumptions of normality and equal variance. Replicate was treated as a random effect. Mean separation for significant main effects and interactions was conducted using Tukey's HSD adjustment for multiple comparisons. Significant interactions between fixed effects of cultivar and depth were sliced by cultivar.

Cultivar x Tool Field Cultivation Study

Experimental design. In the 2020 field season, we evaluated the effects of cultivar (B, CG, M, and TG) and tool (Finger Weeder or Hilling Disk) on beet and weed survival and harvest yield. Plots were arranged in a split plot design with tool as the main plot factor, and cultivar as the sub-plot factor (Table 2.3). Main plots consisted of the center row of a 12.2 m long bed with subplots consisting of 6.1m row length. Beds contained 3 rows of beets spaced at 38 cm between rows, with the outer rows planted to the 'Boro' cultivar.

Beet cultivar sub-plots were sown in the center row at 3cm spacing and 2cm depth with a one-row Jang Speed Seeder (Jang Automation Co., LTD, Cheongju-city, South Korea), belly-mounted to a 520 Series Cultivating Tractor (Tilmor, Dalton, OH). The hopper was exchanged with different cultivars to establish subplots. Out-row 'Boro" beets were sown with a MaterMacc precision vacuum seeder (MaterMacc, San Vito al Tagliamento PN, Italy).

Field operations. The entire experimental area was tilled with a subsoiler, amended with compost, rototilled, and then tarped to flush weeds seeds from the surface soil layer approximately 2 months before planning (Table 2.3). Two weeks before planting, tarps were removed, fertilizer applied (430.56 kg ha^{-1} of 10-2-8 + 22.34 kg ha^{-1} boron) in accordance with soil tests, and beds rototilled to incorporate fertilizer and form beds. Final bed preparation occurred 6 days before planting beets, and flame weeding occurring at 3 DAP to kill emerged weed seedlings just before beet emergence. Flame weeding was accomplished with a hand-held flame weeder targeting the in-row (7-10 cm) zone. Between-row weeds were managed with a basket weeder at 9 and 13 DAP (Tilmor) with baskets set with a 13 cm gap to avoid disturbance of the in-row zone (Table 2.3). Following flame weeding, two adjacent 1.25m sections of the center row in each subplot were flagged to create permanent sampling quadrats, spanning 7cm over the center the crop row, representing the in-row zone for evaluation of the effects finger weeder and hilling disks on weeds and beets. One quadrat served as an area to sow surrogate weeds; the other quadrat used to count ambient species. Stand counts of emerging beets were conducted in all quadrats at 5, 6, and 8 DAP. At 15 DAP, all quadrats were handweeded and beets were thinned to approximately 5cm spacing. We then spread approximately 200 seeds of both "Red Spike" red amaranth (*Amaranthus cruentus*) and "Mighty Mustard Pacific Gold" condiment mustard (*Brassica juncia*) (both from Johnny's Selected Seeds) suspended in 250 ml of sand evenly over the in-row plots and covered lightly with loose soil. Cutaway disks set to a DUO parallel linkage (Kult-Kress, Germany) were used at 18 DAP to remove weeds near row leaving approximately 10 cm of undisturbed soil centered on the crop row (Table 2.3).

Crop and weed evaluation before in-row cultivation. Two days before in-row cultivation (22 DAP), height measurements were taken from 10 random beets in each plot, adjacent to the quadrat area. One day before in-row cultivation (23 DAP), the anchorage force of five beets were estimated as described above for the greenhouse study. At 24 DAP, emerging surrogate and ambient weeds were counted in plot quadrats. At this stage, carpetweed (*Mollugo verticillata*) was the only ambient weed species sufficiently abundant to evaluate tool efficacy. Surrogate red amaranth germination was also low, leaving mustard as our only surrogate weed to evaluate.

Beets were at the four to six leaf stage, while surrogate and ambient weeds were at cotyledon stage.

Mechanical cultivation treatments. At 24 DAP, after all weed and crop evaluations, plots were cultivated with either a DUO cutaway disks (Kult-Kress) set to hill or with finger weeders mounted on a floating arm (Tilmor). Both tools were belly mounted on a Tilmor cultivating tractor (Figure 2.1). Hilling disks were calibrated to throw soil into the crop row to a height of approximately 3.5 cm. This height was chosen to bury the tallest weeds (mustard) while minimizing burial of any beet leaves. This was accomplished by setting the front edge of the disks 18cm apart and the rear edge 10cm apart; gauge wheels adjusted to cut soil at 2cm working depth; and speed adjusted upward until the desired 3.5 cm was accomplished, with occurred at 4 km h^{-1}. Closer spacing of the disks would have clipped beet leaves. Wider spacing would have required greater speed to accomplish the same result which was deemed too risky for retaining precise steering. Fingers were calibrated to 'scrub' soil and weeds out of the crop row, rather than hill soil. This was accomplished by setting the toolbar height so that the floating arm sloped upward slightly from the toolbar to the finger mount, resulting in an angle of the vertical shanks to which fingers were mounted of 85 degrees relative to the soil in front of the fingers (Figure 2.1). Tips of fingers were set 1 cm apart to minimize disturbance of beet stems. Calibration was then accomplished by increasing the speed until beet damage occurred, and then reducing the speed so no noticeable beet damage was observed. This occurred at approximately 9.5 km h^{-1}. Post-cultivation weed counts were conducted within each quadrat 2 days after cultivation. At the time of the post count, some new ambient weeds were emerging, but were excluded from counts based on size. Weed and beet mortality were estimated based on percent change in density from pre and post-cultivation counts.

Weed-crop competition. At 42 DAP, ambient quadrats were handweeded to serve as a control for evaluation of the effect of escaped surrogate weeds on beet growth. Surrogate weeds that survived cultivation were left to grow in surrogate quadrats until beet harvest. In effect, the experimental design for end of season crop and weed evaluations was a split-split plot, with late-season weed competition (none or escaped surrogates) as the sub-sub plot factor. Harvest occurred at 69 DAP. Beets were separated into roots and shoots. Shoots and weeds growing in the surrogate plot were dried in a 100° C oven for 6 days and weighed for biomass. Roots were categorized into "marketable" and "unmarketable" categories based on a 2cm diameter cutoff. Marketable and unmarketable beets were weighed fresh and total beet diameter was taken for all plot quadrats.

Statistical analysis. The fixed effects of experimental factors on all responses were evaluated using the PROC MIXED procedures in SAS, with replication treated as a random effect. For emergence and early beet data, the fixed effect of cultivar was evaluated. For weed and crop survival data following cultivation, the fixed effects of cultivar and tool were evaluated. Finally, for final weed and beet biomass data, the fixed effects of cultivar, tool, and weed competition were evaluated. All responses were evaluated for normality and equal variance using PROC UNIVARIATE and Levene's test and transformed as necessary to meet model assumptions. Where fixed effects or interactions were significant, mean separation was conducted using Tukey's HSD.

Results

Cultivar x depth studies

Greenhouse

Total number of emerged seedlings. The final number of seedlings seed^{-1} to emerge was influenced by the main effect of cultivar but not by depth of planting (Table 2.5). B and TG varieties had the greatest total seedling emergence, and M had the least (Table 2.5). Final emergence of CG was higher than M in run 1, but lower than B and TG in run 2 (Table 2.5).

Percent emergence days 4-8. The percentage of final seedlings that had emerged at 4-8 days appears to have been influenced by both cultivar and depth (Figures 2.2 and 2.3). In run 1, B and CG planted at 4 cm appear to have emergence delayed by 1 day, relative to other depths, without a noticeable reduction in yield (Figure 2.2a and 2.2b). TG and M in run 1 seem to have reduced germination at 4 cm depth (Figure 2.2c and 2.2d). In run 2, delay in B and CG emergence based on depth was not noticeable, but TG planted at 4 cm is much lower than other depths at day 7, before catching up with other depths at day 8 (Figure 2.3).

Field trail

Final emergence was influenced by the main effects of cultivar and planting depth, however no interactions between cultivar and depth were detected (Table 2.5). Beets planted at 4cm had lower final emergence compared to beets planted at 1 and 2cm. B germinated with more seedlings seed^{-1} than M and TG varieties.

Shoot biomass was influenced by the main effect of cultivar, while root biomass and the root-shoot ratio (RSR) were influenced by cultivar and depth main effects (Table 2.6). Both root and shoot biomass were greater for B than M and TG. TG had particularly small roots, with biomass representing only 24% that of B and 42% that of M. Lower root biomass of TG was due to both smaller overall plant growth, and lower partitioning to root tissue relative to shoot tissue (lower RSR).

The effects of planting depth on root biomass and RSR—but not shoot biomass—differed for B and M (Table 2.6). For B, the root biomass and RSR were lower when planted at 1 cm compared to 2 cm. RSR in Moneta was also lower when planted at 1cm compared to 2cm.

Cultivar x tool field cultivation study

At the time of cultivation, beet varieties differed in their height, anchorage force, root biomass and shoot biomass, but not in their RSR (Table 2.7). The root and shoot dry weights and anchorage forces of B and M were greater than those of TG. B also had greater shoot length than CG and TG (Table 2.7). No differences in dry weights, anchorage forces or heights were detected between the CG and TG cultivars, nor between TG and M cultivars.

Beet survival following cultivation was influenced by beet cultivar but not by tool type or tool by cultivar interactions (Table 2.8). CG beet survival following cultivation was significantly greater than TG variety, where 17.1% of beets did not survive cultivation (Table 2.8). However, no differences in survival were detected between B, M, and the other cultivars.

Cultivation efficacy on the surrogate mustard weed was greater for finger weeders than hilling disks (Table 2.8). Compared to density prior to cultivation, mustard density three days after cultivation was 65% lower following finger weeding, but 17% greater following hilling compared to pre-cultivation density, suggesting some mustard seeds did not germinate until after cultivation (Table 2.8). However, carpetweed control was not influenced by tool, and neither weed species' survival was influenced by beet cultivar.

The biomass of surrogate mustard weeds was affected by both cultivar and tool, but not their interaction (Table 2.8). Mustard biomass was the lowest in B plots, while weed dry weights from CG, M, and TG plots were not different (Table 2.8). Final mustard biomass was lower in plots that had been cultivated with the finger weeder compared to the hilling disks (Table 2.8). However, yield loss due to surrogate mustard was affected neither by beet cultivar nor cultivation tool (Table 2.8).

Yield was affected by cultivar but not by tool or tool x cultivar interaction (Table 2.9). B was the highest yielding variety among the four cultivars tested, both in marketable and total beet yield (Table 2.9). CG and M had significantly higher yield than TG, which was the lowest yielding cultivar (Table 2.9).

Discussion

As hypothesized, we found that planting beets deeper than the typical recommended 2cm depth may delay germination by a day or two, allowing for more flexibility in implementing a stale seedbed. However, this result was not consistent across cultivars or trials (Figure 2.2, 2.3, and 2.4). Under field conditions, deep planting of beets did not obviously delay emergence, and final emergence was reduced at depths greater than 3 cm (Table 2.4). For polyembryonic beet cultivars, a slight reduction in stand may reduce the need for thinning of beets but greater stand losses could be costly for growers. Our results are similar to those obtained by Romaneckas et al. (2009), who also found that deep planting delayed sugar beet emergence in the greenhouse, but reduced emergence under field conditions. Such discrepancies between greenhouse and field studies likely reflect more uniform and optimal growing conditions in the greenhouse. For example, differences by depth in soil moisture, temperature or soil resistance are much more common in the field, and undoubtedly influence relationships between seed depth and seedling emergence in some cases. Tradeoffs associated with different planting depths must be considered based on specific field conditions. Our results suggest that although planting beets deeper may not be practical in all soil conditions, it has the potential to give growers more flexibility in implementing a pre-emergent stale seedbed.

A second central hypothesis of our study was that cultivars differ in their tolerance to in-row cultivation, and that this difference might be exploited to improve tool selectivity and lower weed management costs. Our results were consistent with this hypothesis (Table 2.7), although the magnitude of differences in cultivar tolerance were relatively small. Our primary finding was that TG tolerance to both finger weeding and hilling was lower than that of the CG variety. Poor relative tolerance of TG to cultivation is not surprising given that it was consistently among the cultivars with the shortest height and lowest anchorage force (Table 2.6). The CG cultivar appears to both establish more slowly, and partition fewer resources to early root development than other beet cultivars (Table 2.5), and hence—other things equal—is not a good choice for improving weed management in beets.

We anticipated that such differences in beet cultivar partitioning to root vs shoot tissue might confer preferential tolerance to tools that killed weeds either by uprooting (fingers) versus burial (hilling disk). However, we were unable to identify specific plant traits related to cultivation tolerance because beet mortality was too low and beet characteristics too similar. B was our most vigorous cultivar, with the greatest root and shoot biomass, and anchorage force. However, B survival was not different than CG and M cultivars. Nor did we detect any differences in beet tolerance based on tools differing in their mode of action.

We were surprised to find that our estimate of mustard "survival" following cultivation with the hilling disk was greater than 100% (Table 2.7). The tool hilled soil nicely in the crop row, covering mustard and ambient weed seedlings but not beets. However, buried mustards were able to recover, and some mustard seeds that had been on the soil surface prior to cultivation may have been induced to germinate by hilling, resulting in greater post-cultivation counts.

Our study also provided insight into the relative competitive ability of beet cultivars with weeds. In particular, surrogate mustard biomass was lowest in plots with the B cultivar (Table 2.7). This apparent weed-suppressive ability of the B cultivar was presumably due to the fact that it was among the cultivars with the highest shoot biomass and height (Table 2.6), traits shown in studies in other crops to improve weed competitive ability through shading (Colquhoun et al. 2009; Garrity et al. 1992). Though B survival following cultivation was not different than other cultivars, its weed competitive ability makes it a good cultivar choice for suppressing weeds.

Cultivar choice may be an important consideration for growers managing weeds through physical and cultural approaches. Differences in both cultivation tolerance and weed competitiveness among cultivars of the same species can be important factors in determining weed management success in certain crops (Colquhoun et al. 2009; Garrity et al. 1992; Wick et al. 1986). However, within the conditions of our study, cultivation tolerance appears to have been less important than weed competitive ability in determining agronomic success. It can be difficult to draw broad conclusions from weed competition in one study because weed impact is dependent on weed populations, crop conditions, soil type, and a host of other factors. Nevertheless, future research should consider both cultivation tolerance and weed competitive ability as potentially important characteristics for reducing weed management costs in vegetable crops including table beets. Identification of specific traits associated with these characteristics may be also be helpful for plant breeders wishing to select useful cultivars for improving weed management However, our results suggest that straightforward selection criteria to improve weed management success are unclear. For example, given the greater efficacy of uprooting (finger weeding) relative to burial (hilling disk) in controlling weeds in our study, selection of cultivars which partition more early season resources to roots relative to shoots might be desirable; however, partitioning resources to roots at the expense of shoots might reduce the capacity of that cultivar to suppress weeds through shading. Early season partitioning to shoots may be a desirable trait for weed competitiveness, along with improved cultivation tolerance to burial with hilling disk. Beet breeders could also select for cultivars with delayed emergence from shallow planting to facilitate a longer stale seedbed window, further improving weed competitiveness of a shoot-partitioning cultivar.

APPENDIX

TABLES AND FIGURES

Table 2.1. List of treatments for cultivar*depth studies.

	Cultivar	Depth	GH1	GH2	Field
1	Boro	1	X	X	X
2	Boro	2	X	X	X
3	Boro	3	X	X	X
4	Boro	4	X	X	X
5	Chioggia Guardsmark	1	X	X	N/A
6	Chioggia Guardsmark	2	X	X	N/A
7	Chioggia Guardsmark	3	X	X	N/A
8	Chioggia Guardsmark	4	X	X	N/A
9	Moneta	1	X	X	X
10	Moneta	2	X	X	X
11	Moneta	3	X	X	X
12	Moneta	4	X	X	X
13	Touchstone Gold	1	X	X	X
14	Touchstone Gold	2	X	X	X
15	Touchstone Gold	3	X	X	X
16	Touchstone Gold	4	X	X	X

Table 2.2. Treatment list of cultivar*cultivation tool field trial.

	Tool	Cultivar
1	Finger Weeder	Boro
2	Finger Weeder	Chioggia Guardsmark
3	Finger Weeder	Moneta
4	Finger Weeder	Touchstone Gold
5	Hilling Disk	Boro
6	Hilling Disk	Chioggia Guardsmark
7	Hilling Disk	Moneta
8	Hilling Disk	Touchstone Gold

Table 2.3. Schedule of relevant events in cultivation study.

Trial	Event	Date	DAP
	Subsoiled with Unverferth	26-May	-64
	Added compost	27-May	-63
	Rototilled all plots, incorporated compost	27-May	-63
	Applied tarps	1-Jun	-58
	Removed tarps	14-Jul	-15
	Fertilizer applied	23-Jul	-6
	Rototilled all plots	23-Jul	-6
	Rolled beds with water roller	23-Jul	-6
	Irrigated to germinate weeds	24-Jul	-5
	Planted crop	29-Jul	0
	In row flame weeding	1-Aug	3
	Cultivar emergence count	3-Aug	5
	Cultivar emergence count	4-Aug	6
	Cultivar emergence count	6-Aug	8
	Basket weeded between-row	7-Aug	9
	Basket weeded between-row	13-Aug	15
	Thinned beets	13-Aug	15
	Sowed surrogate seeds	13-Aug	15
	Duo cutaway disk near-row cultivation	16-Aug	18
	Beet height measure	20-Aug	22
	Uprooting force measurements	21-Aug	23
	Crop and weed density evaluation (pre)	22-Aug	24
	In-row cultivation	22-Aug	24
	Crop and weed density evaluation (post)	24-Aug	26
	Handweeded ambient weed quadrat	9-Sep	43
	Beet Harvest	6-Oct	70

Table 2.4. Mean final emergence of seedlings per seed in response to cultivar and planting depth.

Treatment	Final emergence: GH Run 1		GH Run 2		Field	
	---seedlings seed^{-1}---					
Cultivar Main Effect						
Boro	1.27	a	1.53	a	1.30	a
Chiogga Guardsmark	1.42	a	1.19	ab	N/A	
Moneta	0.71	b	0.88	b	0.70	b
Touchstone Gold	1.57	a	1.29	a	0.82	b
Depth Main Effect						
1 cm	1.29		1.22		1.04	a
2 cm	1.45		1.30		1.03	a
3 cm	1.18		1.20		0.88	ab
4 cm	1.05		1.21		0.80	b
ANOVA	------------------Significance (P-value) ------------------					
Cultivar	**0.0001**		**0.0003**		**0.0001**	
Depth	0.2073		0.8580		**0.0078**	
Cultivar x Depth	0.8655		0.8796		0.2316	

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Table 2.5. Mean root and shoot biomass and root/shoot ratio in response to cultivar and planting depth in field trial. Cultivar*depth interactions are sliced by cultivar, so mean separations represent differences in depth within each cultivar.

Treatment	Field					
	Root Biomass		Shoot Biomass		Root/Shoot Raito	
	------g------				--%--	
Cultivar Main Effect						
Boro	1.47	a	8.05	a	0.18	a
Moneta	0.84	b	5.26	b	0.16	a
Touchstone Gold	0.35	c	4.39	b	0.08	b
Depth Main Effect						
1 cm	0.71	b	5.60		0.12	b
2 cm	1.09	a	6.56		0.15	a
3 cm	0.86	ab	5.98		0.14	ab
4 cm	0.88	ab	5.47		0.14	ab
Cultivar*Depth						
Boro						
1 cm	1.08	b	6.83		0.15	b
2 cm	2.01	a	9.51		0.21	a
3 cm	1.34	ab	8.04		0.16	ab
4 cm	1.46	ab	7.84		0.19	ab
Moneta						
1 cm	0.67		4.97		0.13	b
2 cm	0.95		5.27		0.18	a
3 cm	0.81		4.96		0.16	ab
4 cm	0.96		5.83		0.16	ab
Touchstone Gold						
1 cm	0.38		4.99		0.07	
2 cm	0.33		4.89		0.07	
3 cm	0.44		4.94		0.09	
4 cm	0.23		2.74		0.08	
	--------------- Significance (P-value) ------------					
ANOVA						
Cultivar	**0.0001**		**0.0001**		**0.0001**	
Depth	**0.0212**		0.1885		**0.0182**	
Cultivar x Depth	**0.0374**		0.0644		**0.0484**	

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Table 2.6. Mean beet height, anchorage force, root and shoot biomass and root/shoot ratio for each cultivar immediately before in-row cultivation with finger weeders and hilling disks in cultivation field trial.

Soil Treatments	Beet Height		Anchorage Force		Root Biomass		Shoot Biomass		Root/Shoot Ratio
	----cm----		----N----		----------g----------				----%----
Cultivar Main Effect									
Boro	9.74	a	3.55	a	0.29	a	1.28	a	0.22
Chioggia Guardsmark	8.23	bc	3.08	ab	0.21	ab	0.76	ab	0.28
Touchstone Gold	7.97	c	2.44	b	0.16	b	0.86	b	0.23
Moneta	9.16	ab	2.91	ab	0.21	ab	0.92	ab	0.19
	---------------------------- Significance (P-value) ----------------------------								
ANOVA									
Cultivar	**0.0009**		**0.0175**		**0.0292**		**0.0012**		0.1018

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Table 2.7. Mean beet and weed density following cultivation and surrogate weed biomass at harvest in response to cultivar and tool used. Interaction between cultivar and tool was not significant.

Factors	Beet Survival		Change in Weed Density: Mustard		Change in Weed Density: Carpetweed	Final Mustard Biomass		Yield Loss
	-----------------%--------------------					----g m^{-2}---		---%---
Cultivar Main Effect								
Boro	93.73	ab	54.24		38.89	48.88	a	-0.07
Chioggia Guardsmark	98.18	a	105.95		66.67	155.76	b	0.00
Moneta	94.18	ab	68.05		43.85	141.12	b	-0.14
Touchstone Gold	82.90	b	76.64		37.32	133.40	b	-0.68
Tool Main Effect								
Finger	90.96		35.31	b	54.42	79.24	a	-0.23
Hilling Disk	93.54		117.13	a	39.17	170.24	b	-0.21
	------------------------- Significance (P-value) -----------------------------------							
ANOVA								
Cultivar	**0.0249**		0.3398		0.4249	**0.0046**		0.0670
Tool	0.5858		**0.0001**		0.3815	**0.0001**		0.9044
Cultivar*Tool	0.8081		0.8442		0.5412	0.8613		0.5228

Statistical significance (p = 0.05) is indicated by different letters within the same column.

[a] Percent change in weed population density following cultivation

[b] BRAJU = condiment mustard (*Brassica juncea)*

[c] MOLVE = carpetweed (*Mollugo verticillata)*

Table 2.8. Mean marketable and total yield weights, counts, and sizes of beets at harvest in response to cultivar and tool. Total yield, counts, and average diameter includes all marketable and unmarketable beets.

	Yield					Final Root Number				Diameter	
Factors	Total		Marketable		% Mkt	Total		Marketable		Total Avg	Mkt Avg Diameter
	-----g m^{-1}----				--%--	-----# m^{-1}----				-----cm ----	
Cultivar Main Effect											
Boro	804	a	778	a	96.7	14.7	a	12.0	a	4.4	4.8
Chioggia Guardsmark	497	b	480	b	96.6	9.6	b	7.9	b	4.3	4.8
Moneta	484	b	467	b	96.2	9.8	b	7.9	b	4.1	4.6
Touchstone Gold	280	c	266	c	94.5	6.6	c	5.2	c	3.9	4.3
Tool Main Effect											
Finger	502		483		95.6	10.0		8.1		4.1	4.5
Hilling Disk	531		512		96.4	10.3		8.4		4.2	4.6
ANOVA	----------------------Significance (P-value)----------------------										
Cultivar	**0.0001**		**0.0001**		0.4355	**0.0001**		**0.0001**		0.7760	0.0778
Tool	0.3332		0.3422		0.4534	0.6306		0.5565		0.0545	0.4634
Cultivar*Tool	0.2484		0.2414		0.5336	0.5746		0.7957		0.1508	0.4711

Statistical significance (p = 0.05) is indicated by different letters within the same column.

Figure 2.1 Tilmor cultivating tractor with finger-weeders belly mounted.

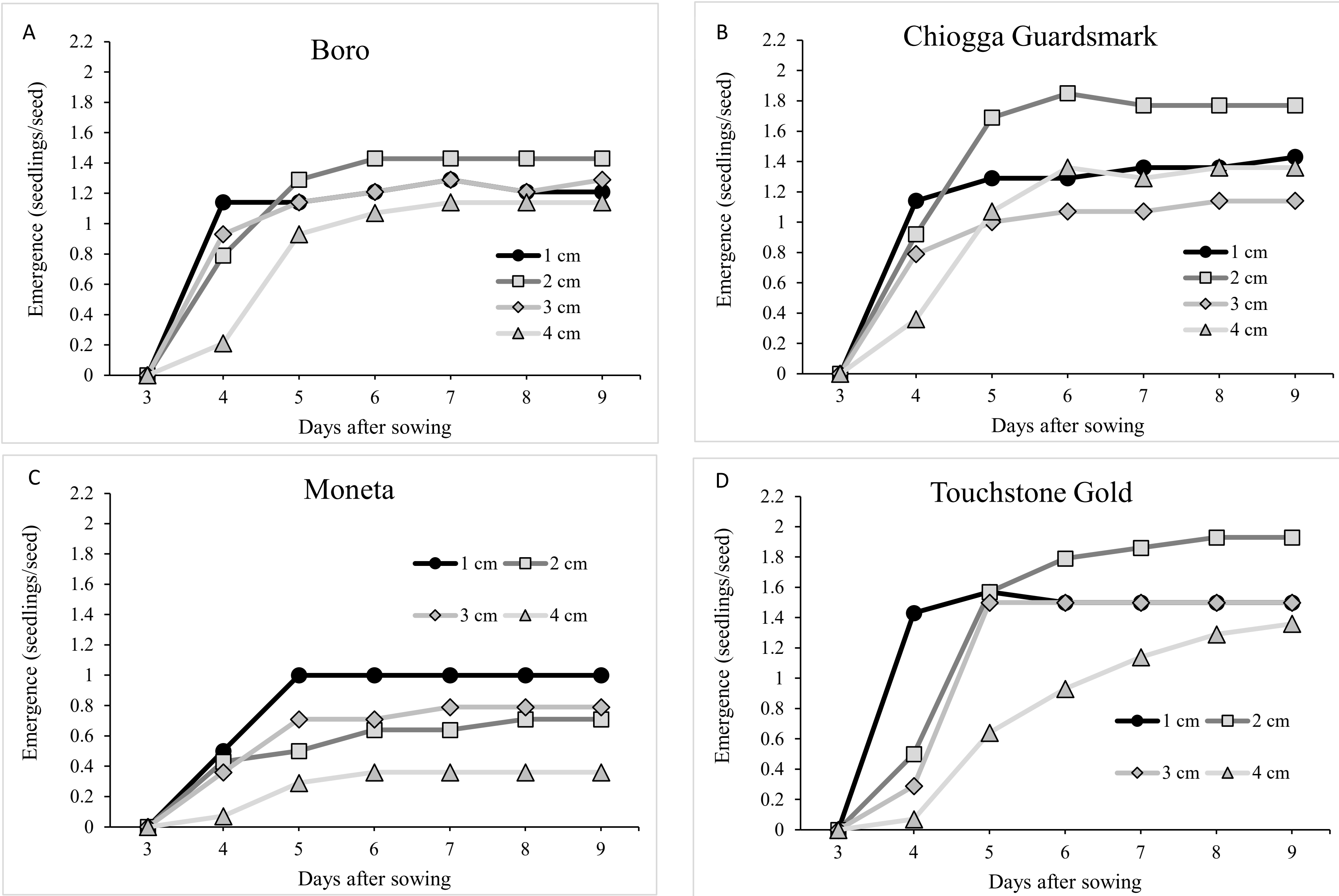

Figure 2.2. Mean seedling emergence per seed planted for greenhouse trial, run 1.

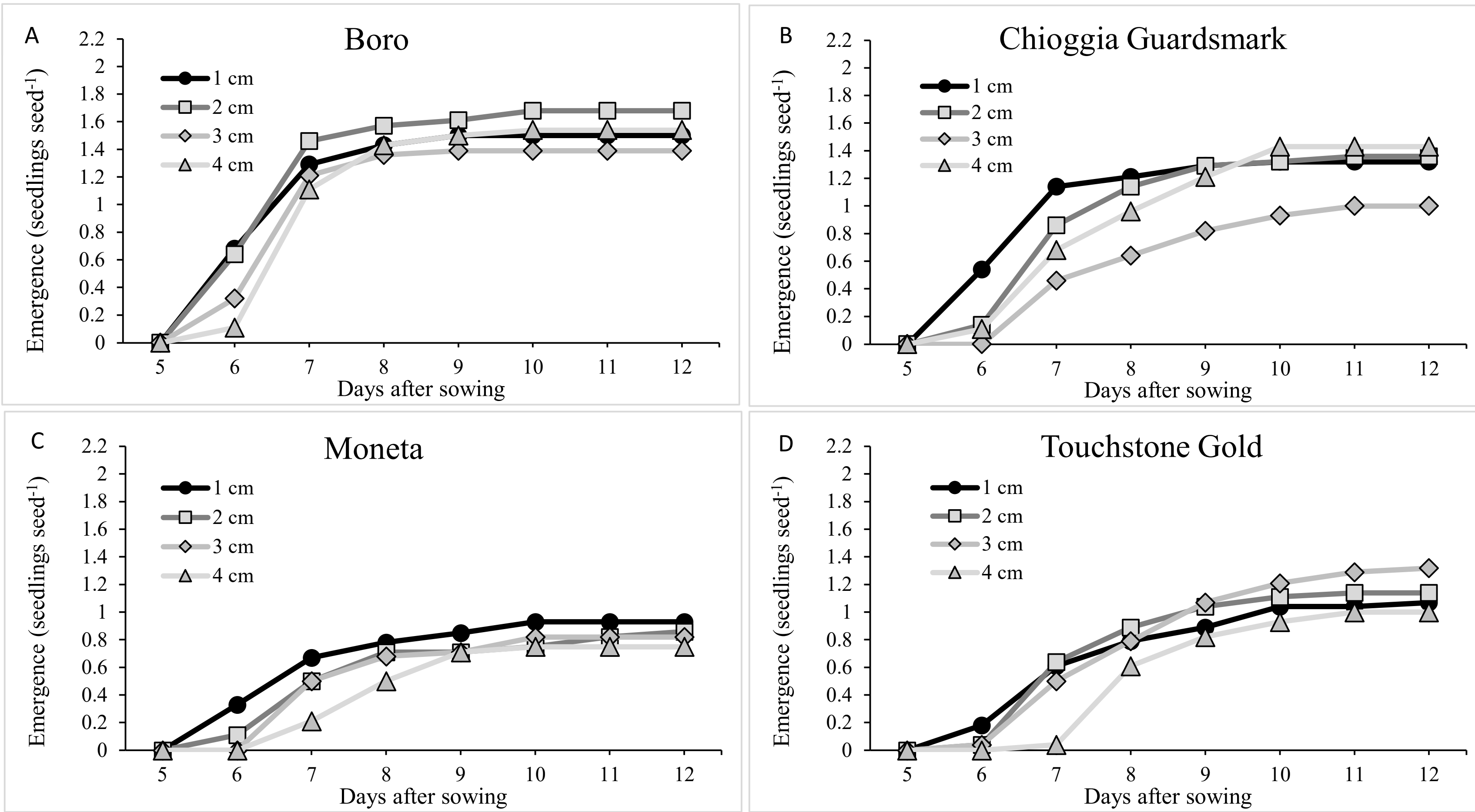

Figure 2.3. Mean seedling emergence per seed planted for greenhouse trial, run 2.

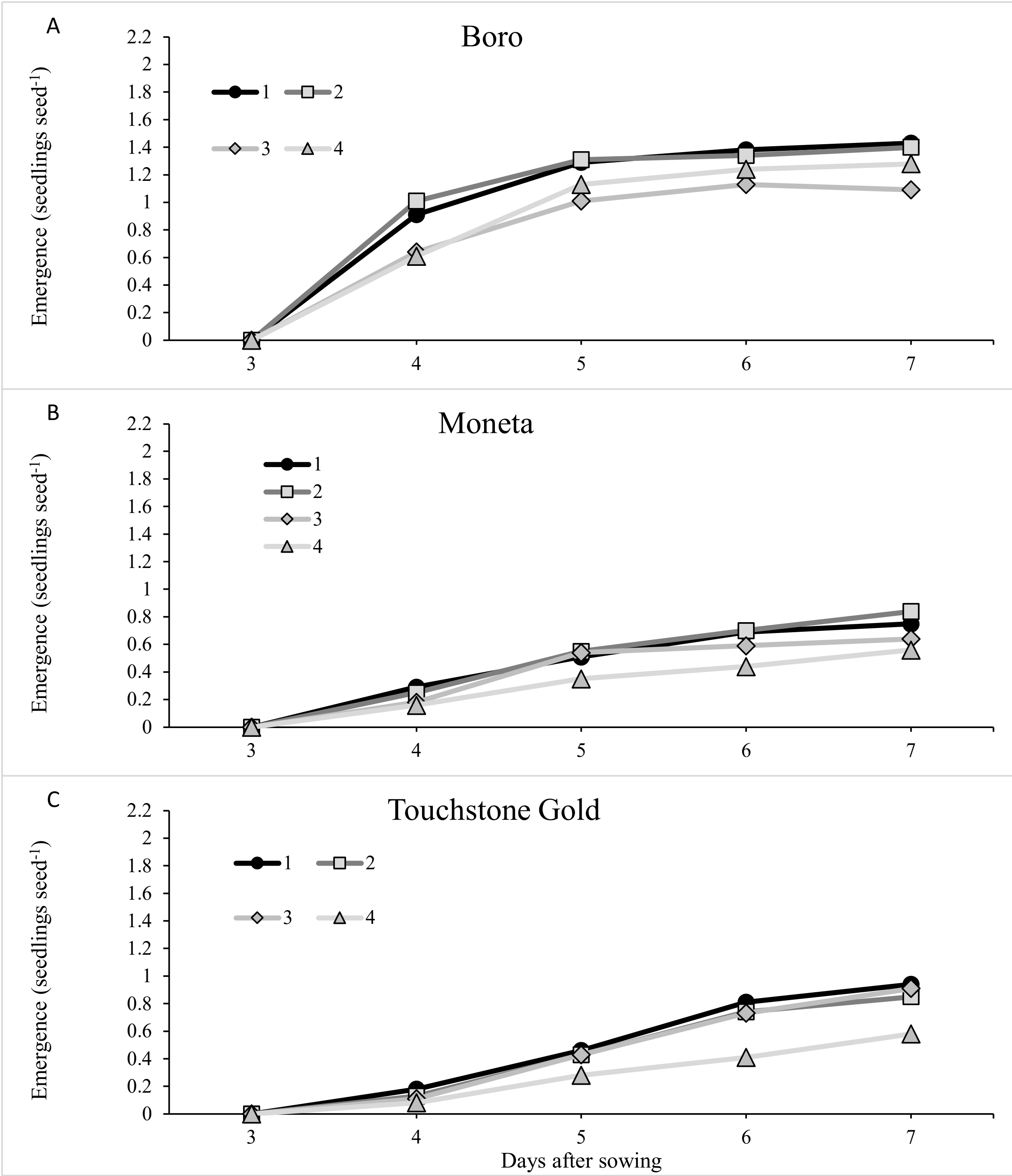

Figure 2.4. Mean seedling emergence per seed planted for field trial at Greenwagon Farm.

LITERATURE CITED

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Benzle MM (2019) Integrated Cultural And Mechanical Weed Management For Organic Winter Squash Systems. Michigan State University

Caldwell B, Mohler CL (2001) Stale seedbed practices for vegetable production. HortScience 36:703–705

Colquhoun JB, Konieczka CM, Rittmeyer RA (2009) Ability of Potato Cultivars to Tolerate and Suppress Weeds. Weed Technol 23:287–291

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

Gallandt, E.R., D. Brainard, and B. Brown. (2018) Developments in physical weed control. In Zimdahl (ed) Integrated Weed Management for Sustainable Agriculture. Pages 261-283. ISBN: 978-1-78676-164-4

Garrity DP, Movillon M, Moody K (1992) Differential Weed Suppression Ability in Upland Rice Cultivars. Agron J 84:586–591

Hitchcock-Tilton S (2018) Improving weed management in carrots with stacked in-row weeding tools and cultivation-tolerant varieties. Michigan State University

Kurstjens, D. A. G., Kropff, M. J. and Perdok, U. D. (2004), ‘Method for predicting selective uprooting by mechanical weeders from plant anchorage forces’, Weed Science, 52(1): 123–32.

Kurstjens DAG (2007) Precise tillage systems for enhanced non-chemical weed management. Soil Tillage Res 97:293–305

Mansilla Martínez J, De Juan Valero JA, Padilla AD, Buendía MRP (2015) Competition and critical periods in spring sugar beet cultivation. J Plant Prot Res 55:336–342

Rasmussen, J. (1990), ‘Selectivity-an important parameter on establishing the optimum harrowing technique for weed control in growing cereals’, Proceedings of an EWRS symposium, Helsinki, Finland, 4–6 June 1990, pp. 197–204, European Weed Research Society.

Rasmussen J, Nielsen HH, Gundersen H (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. Weed Sci 57:338–345

Riemens MM, Van Der Weide RY, Bleeker PO, Lotz LAP (2007) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. Weed Res 47:149–156

Romaneckas K, Pilipavicius V, Sarauskis E, Sakalauskas A (2009) Effect of sowing depth on emergence and crop establishment of sugar beet (Beta vulgaris L.). J Food, Agric Environ 7:571–575

Taylor AG, Goffinet MC, Pikuz SA, Shelkovenko TA, Mitchell MD, Chandler KM, Hammer DA (2003) Physico-chemical Factors Influence Beet ((Beta vulgaris L.) Seed Germination. Page The Biology of Seeds: Recent Research Advances. 433–440

Wicks GA, Ramsel RE, Nordquist PT, Schmidt JW (1986) Impact of wheat cultivars on establishment and suppression of summer annual weeds. Agron J 62:59–62