IMPROVING WEED MANAGEMENT IN CARROTS WITH STACKED IN-ROW WEEDING TOOLS AND CULTIVATION-TOLERANT CULTIVARS

By

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ABSTRACT

IMPROVING WEED MANAGEMENT IN CARROTS WITH STACKED IN-ROW WEEDING TOOLS AND CULTIVATION-TOLERANT CULTIVARS

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Finger weeders (F), torsion weeders (T), flextine harrows (X), and hilling discs (HD) were applied to carrots (*Daucus carrota*) and weeds individually and in combination (tool 'stacking') when the carrots had 1 true leaf, 25 days after planting. Tools combinations gave greater weed control and selectivity than single tools. The F+HD combination resulted in the greatest selectivity and reduction in subsequent hand weeding. The finger weeder controlled more weeds as soil moisture increased, or when more soil was moved into the carrot row. Whereas the torsion weeder did not appear to kill weeds through hilling and its efficacy was greater under relatively dry soil conditions.

One approach to improving the selectivity of mechanical cultivation tools identifying crop varieties tolerant to those tools. Field trials compared carrot response of eight carrot cultivars to four types of in-row weeding tools. Differences in survival rate of carrot cultivars were observed for the torsion weeder at all three sites and for the flextine harrow in one site. At the time of cultivation, carrot cultivars varied in their root size at all three sites, but varied in shoot size at only 1 of 3 sites. There was a positive relationship between carrot shoot size and tolerance to the finger weeder, and between carrot root size and tolerance to the torsion weeder (p=0.095; p=0.061). These results demonstrate that commercially available carrot cultivars vary in their tolerance to cultivation tools. Screening of carrot cultivars or seed-lots for large seed size may be a useful strategy for improving carrot tolerance to cultivation tools.

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Nola Hitchcock Cross and Steve Tilton, who inspired me with curiosity and confidence,
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CHAPTER ONE: In-row Mechanical Weed Control: A Literature Review

Introduction

There are several reviews of mechanical weeding tools and techniques. Tom Bowman's book *Steel in the Field* (1997) is widely cited for its descriptions of tools and their use, though because it is twenty years old and describes mostly American tools *Steel in the Field* is not exhaustive. Bond and Turner (2007) and Kurstjens (2007) offer a more academic perspective as well as helpful citations in their reviews. There is also the comprehensive manual on weed control for farmers edited by van der Schans and Bleeker (2006) that was the culmination of nearly a decade of Swiss and Dutch research into mechanical cultivation. These resources describe the common in-row weeding tools along with their working speeds and modes of action. They also describe the many factors that influence the efficacy of mechanical cultivation, such as soil moisture, soil particle size, soil texture, weather following cultivation, and weed morphology and growth stage. Depending on the mode of action of a particular tool, the authors agree that the best time for effective physical weed control is either when the weed is in the white-thread or cotyledon stage: when the plant has exhausted the energy stored in its seed but does not yet have true-leaves to begin drawing energy from the sun.

Weed control research generally draws a distinction between direct physical control of weeds growing with the crop and cultural controls (also called preventative controls). Whereas direct physical control is primarily to reduce weed competition with the crop at a single point in time, cultural controls aim primarily to decrease total weed seeds in the soil in order to reduce future weeds. Many authors describe cultural methods that can reduce overall weeds. Melander (2000) describes a multi-year cropping system in which soil is not inverted so as to discourage bringing more weed seeds to the surface. Merfield (2015) and Caldwell and Mohler (2001) describe the stale-seedbed technique whereby weeds are encouraged to germinate and then shallowly tilled just prior to planting. In two papers Bleeker and van der Weide (2000; 2002) describe how preventing exposure of weed seeds to light can further reduce weed germination. This is achieved by either tilling in the dark or excluding light from the machine's working area with shrouds. Melander (1998) also describes success with cultivation in the dark. Hatcher and Melander (2003) offer a helpful summary of physical, cultural, and biological weed control methods and how to integrate them. As many horticultural weeds germinate and grow faster than crop plants, these preventative practices are crucial so that the crop develops faster than the weeds.

Once the crop has germinated and is visible, precision becomes the watchword of cultivation. At this point all authors suggest cultivating frequently, every 7 to 10 days has been recommended for young crops (Ascard & Fogelberg 2008). Here a distinction is made between between-row cultivation (also called inter-row) and in-row cultivation (also called intra-row). Because there are no crops growing in the between-row area, cultivation there need not be selective and as such greater control is possible. In contrast, direct physical control in the in-row area must kill the weeds while preserving the crop. This need for selectivity in the row makes effective weed control much more difficult than in the between-row area.

For ten years, beginning in the late 1990's and led by the Dutch at Wageningen University, research on in-row tools and techniques proliferated. It is from this period that many resources are to be found on in-row tools. There are many papers referenced in the literature in Dutch or

German, and it would be a boon to further understanding of in-row tool research in America for the most important of these to be translated into English.

Most research has focused on four in-row tools – brush weeders (or brush hoe), flextine harrows (also called spring-tined harrows), finger weeders, and torsion weeders. The consensus is that at the low end, it is common for in-row tools to halve the required hand-weeding. These in-row tools can only reduce hand labor to the degree that they are effectively used. What are the best ways to use them? Below I cite research in order to describe the important properties of each tool and their effective use.

Brush weeder

Kouwenhoven (1997) gives a detailed explanation of the types and modes of action of the brush weeder as well as the possible adjustments. The axis of brush rotation is either perpendicular or parallel to the ground and in both cases the rotating brushes either uproot small weeds or throw soil to bury them. He describes the findings of earlier research by Van Duijin and De Haar (1991) that the first brush cultivation should move soil into the crop row to bury in-row weeds; in this way in-row weeds can be killed while keeping the brushes from coming into contact with the tender young crop. For the second cultivation, when the crop is bigger, brushes could work the in-row area, moving soil outward. Maximum working speed is given as 2.9 km/h. One must remember that working speed and efficacy differ greatly by type of crop and crop growth stage. Working depth was between 2 and 3 cm. Fogelberg and Gustavsson (1999) concluded that the major mode of action of the brush weeder is uprooting.

Melander (1998) used the opposite strategy for brush weeding; during the first cultivation he worried that throwing soil into the row could bury the crop, and so he pulled soil from the row and then in the second cultivation threw soil into the row the bury weeds. This difference in approach is likely explained by differences in crop and development – whereas Van Duijin and De Haar were cultivating sugar beet and maize at canopy closure, Melander was cultivating onion 38 days after planting. The difference in crop size likely also explains Melander's lower working speed of 1.5 km/h and shallower working depth of 1.5 cm.

Cirujeda et al. (2007) used a brush weeder on processing tomatoes and found it gave effective control when used at 1.5 km/h.

Flextine harrow

This tool consists of many spring-steel wire tines that are able to flex somewhat with changing topography and vibrate as they are pulled through the soil. Kouwenhoven (1997) provides summaries of several investigations into harrows and agrees with van der Schans and Bleeker (2006) that better results are generally obtained when tines are pointed forward. Van der Schans and Bleeker (2006) also conclude that greater tractor speed confers greater aggressiveness and state that some crop loss (2-5%) is unavoidable. They also write that overall effectiveness is increased if harrowing is combined with inter-row hoeing in the same pass. Van der Weide (2008) suggests that harrow efficacy increases if crops are sown in a deeper soil layer than that from which most weeds are emerging, because the crop will then be better rooted than the weeds. He also states that harrows can be used before or after crop emergence and concluded that, "only small weeds that are not yet past the first true-leaf stages can be effectively controlled by harrowing".

Fogelberg (2007) gives the maximum working speed of the flextine harrow at 10 km/hr. Rasmussen (1992), who has published extensively on harrows, used speeds between 5 and 8 km/h. Others (Vanhala et al. 2004) vary the flextine harrow's intensity by driving between 2 km/h and 12 km/h. Rasmussen et al. (2008) found indications that high driving speeds reduced selectivity but increased effectiveness, and that repeated passes at lower speeds produced better results. Duerinckx et al. (2005) corroborated Rasmussen's connection between speed and selectivity, concluding that selectivity increased with lower speed and constant depth, and was facilitated by a thinner tine and a vertical or trailing tine orientation. They also found that effective weed uprooting increased with higher driving speed and deeper penetration, facilitated by a thicker tine and leading tine angle. These studies show that the settings required for selectivity can be in opposition to those required for efficacy, and so the intended effects must be kept in mind when calibrating the tines.

Kurstjens et al. (2000; 2001) cite early research showing that harrows kill weeds mainly by burying them, but conclude that uprooting plays a significant role both in directly killing weeds and in making them vulnerable to burial. Vanhala et al. (2004) opine that a high negative angle decreases intensity whereas a more positive angle gives more aggressive treatment, this is in accordance with the findings of others (Duerinckx et al. 2005).

However, these harrow adjustments may all be mere details, as the godfather of harrow research, Rasmussen, found that neither type of harrow, seedbed quality, nor number of passes influence selectivity. Rather, he concluded that differences in the height and canopy structure between the crop and weeds are the most important factors effecting selectivity, suggesting that no amount of harrow adjustments can make up for poor crop establishment (Rasmussen 1990).

Finger weeder

The Finger weeder consists of two wheels with rubber fingers rotating on either side of the crop row. There are metal drive-pins underneath the flexible rubber or plastic fingers. The drive-pins engage the ground and turn at ground speed. Because the drive-pins are a smaller diameter than the flexible fingers, the fingers rotate faster than ground speed. Though developed as a single row tool by the Buddingh Company in Michigan, USA in the mid-twentieth century, in the late 1990's finger weeders were redesigned in Europe by the Kress Company and the Steketee Company. Their simpler design allows finger weeders to be spaced closer together and set-up on cultivator frames in gangs, like shovels, hilling discs, and other cultivation implements. Because of these two different tool designs, a distinction must be made between those studies using the Buddingh tool (often before 1999) and those using the European tool.

Finger weeders are generally more successful in transplanted crops because of the bigger size difference between crop and weed. In transplanted leek and lettuce Bleeker et al. (2002) observed that the European finger weeder killed up to 95% of weeds. They concluded that like most weeding tools, the efficacy of the finger weeder is greatly reduced when used in soil which has a crusted surface. Also, similar to other tools, the finger weeder works better in lighter sandy soils than heavier clay. Between 36% and 71% weed control, and between 5.9% and 15% crop plant reduction has been achieved in 2-leaf drilled onion (Bleeker et al. 2002).

Van der Schans and Bleeker (2006) recommend that a direct-seeded crop be at the 2-leaf stage to tolerate the finger weeder, while the ideal weed stage is from cotyledon to 2-leaf. They found the appropriate speed was 4-12 km/h. Like many other in-row weeding tools (including the flextine harrow), efficacy was improved when finger weeders were coupled with between-row knives run simultaneously and working as close to the row as possible in front of the finger weeders.

There is general agreement between researchers and farmers that finger weeders are more effective at higher speeds. For example Kouwenhoven (1998) found greater efficacy with the Buddingh finger weeder when used at speeds greater than 10 km/h. Ascard and Bellinder (1996) also found that greater driving speeds seemed to confer greater weed control with the finger weeder.

In one of the few published studies of European finger weeders in the US, in one trial the fingers did not reduce in-row weeds in transplanted lettuce compared to a between-row cultivator (set to hill soil into the in-row area); but in most trials, the fingers removed up to 88% of weeds, whereas between-row cultivation only removed 28% (Smith & Silva 2008).

Finger weeders negatively affected yield in some of Smith and Silva's trials. In general, efficacy was best when weeds were cotyledon to one-leaf stage; once weeds had two leaves, weed removal without crop damage was much more difficult. Different sized fingers and levels of firmness both caused some variation in weed control and crop damage. Van Der Weide (2008) found that when used in the right manner finger weeders are gentler on the crop than torsion weeders and do not require such precise steering.

Torsion weeder

Torsion weeders are lengths of spring-steel varying in diameter from approximately 0.7 cm to 1 cm. They are bent into a loop that allows the metal tine to flex or vibrate under tension. Pairs are set-up on either side of the crop so that their tips cross, or nearly cross, making a ‘V’ shape. According to manufacturers, as they are pulled through the soil they vibrate, uprooting small weeds (Hitchcock Tilton 2017). Similar to the finger weeder, torsion weeders were invented in the USA by the Bezzerides Company, and later redesigned in Europe by the Frato and HAK Companies. Torsion weeders vary in the diameter of the steel tine and in the direction and size in which they are coiled. Researchers have used both the older Bezzerides and newer European models.

Torsion weeders can be highly effective. Two passes with the torsion weeder gave good overall results in direct-sown onions, halving the time required for subsequent hand-weeding with no significant yield reduction compared to inter-row weed control alone (Ascard & Bellinder 1996). In later experiments, two in-row cultivations gave 51-57% in-row weed control and 48-64% reduction in subsequent hand-weeding, compared with between-row cultivation alone. Others have found that torsion weeders reduce hand-weeding by two-thirds compared to flame weeding coupled with subsequent between-row cultivation (Ascard & Fogerlberg 2008).

Several researchers have concluded that the torsion weeder requires more precise steering than the finger weeder (Ascard & Belinder 1996; Bleeker et al. 2004). “When the tines of the torsion weeder were not centered exactly to the middle of the crop row, the crop loss rose from 10 to 30 %” (Bleeker et al. 2004). This would imply that a lower working speed is necessary in comparison to the finger weeder. Ascard and Fogelberg (2008) used a speed of 1.5 to 5.4 km/h. Bleeker et al. (2004) suggest 4-12 km/h. Like the other in-row tools, it is thought that higher driving speeds confer greater efficacy. “Higher driving speed of the torsion weeder showed a tendency for better weed control, with no yield reduction compared with a lower driving speed (Ascard & Bellinder 1996). Again we see a trade-off, while higher driving speed can give great efficacy it can also increase crop damage, because steering is less precise.

In comparing tools, Bleeker et al. (2004) concluded that increased working depth and overlap of the finger weeder increased both crop loss and weed control, but to a lesser degree than the torsion weeder. They also found that the torsion weeder gave slightly greater reduction in labor but also higher plant losses than the finger weeder. Smith and Silva (2008) also found that the torsion weeder caused greater yield reduction in transplanted lettuce and brassicas than the finger weeder. However in an earlier study in onions, torsion weeding at the one-leaf stage caused considerable stand reduction, but still gave good weed control and yield, as following cultivation the remaining onion plants enlarged in size due to the increased space created by the decreased stand (Ascard & Bellinder 1996). In another study on direct-sown onions, torsion weeding beginning at the one-leaf stage, sixteen-nineteen days after emergence, did not significantly reduce onion numbers on average over the three years (Ascard & Fogelberg 2008).

Van der Schans (2003) and Bleeker et al. (2004) investigated the proper calibration of the torsion weeder and found that a greater overlap between the tines (in the range of -1 to 1 cm) and a greater working depth (between 1-3 cm) generally caused greater crop loss but only slightly better weed control. Both researchers and manufacturers have stated that angling the tips downwards into the soil increases effectiveness (Bleeker et al. 2004; Hitchcock Tilton 2017). The optimal setting in young onions was found to be 1 cm between tines and 3 cm working depth. One of the weaknesses of the torsion weeder is its difficulty penetrating dense or crusted soil (Smith & Silva 2008).

Hoe-ridger

Many cultivation tools work primarily or secondarily by burying weeds. Hoe-ridgers look like very small V-plows that fit on the shank (or steel) of a hoe-blade (or sweep) and are a simple and quick way to achieve the small amount of hilling tolerated by tender young crops. In contrast to the hilling discs and shovels widely used in the United States, hoe-ridgers are attached to and run behind flat sweeps. More popular in Western Europe, hoe-ridgers work simply by moving soil into the crop row to bury weeds and can be adjusted to move more or less soil. There is scant research on hoe-ridgers. Terpsatra and Kouwenhoven (1981) offer a descriptive and thorough discussion of how soil moves in response to the width and speed of the hoe-ridger. They found that when the hoe-ridger was run at 7.2 km/h, 2.5 cm was a satisfactory working depth for the hoe to which the ridger was attached and that increasing the depth to 4 cm gave only a small increase in the weeds killed. They also speculated that increasing the speed would increase the depth of soil deposited in-row.

Experimental methods

In evaluating these in-row tools what data is important to collect? What is the best way to share findings? How should we judge and compare these in-row weeding tools? In 2004 at the European Weed Research Society workshop on cultural and physical weed control, several scientists with a great deal of experience in cultivation research presented a paper entitled "Guidelines for physical weed control research" (Vanhala et al. 2004). In it they distill their recommendations for cultivation research. Their paper is the most complete I have found on methods for in-row cultivation research.

Their first recommendation of course is defining one's objective(s) and proceeding accordingly. For most experiments Vanhala et al. recommend a randomized complete block design with a minimum of 3 replicates and note that multi-site trials are helpful to demonstrate the robustness of effects. In counting weeds and crop the authors emphasize the importance of sufficient numbers to insure both accuracy and the ability to detect small changes in efficacy. By using statistical modeling, they recommend that counting at least 100 weeds and 180 crop plants per plot will give adequate accuracy. Some have found the use of surrogate weeds helpful to guarantee adequate numbers of weeds (Brown 2017).

For evaluating in-row tools, Vanhala et al. (2004) recommend that the size of the quadrat in which weeds are counted should correspond to the area not cultivated by the between-row tools. In calibrating tools for experimental purposes they suggest that crop damage up to 10% can be acceptable, because plants will fill-in so that generally the crop death will not be reflected in yield, as has been seen in the literature (Ascard & Bellinder 1996). Vanhala et al. (2004) also advice maintaining a hand-weeded quadrat in each plot, so that after applying the tools it can be ascertained how many weeds germinated immediately after cultivation.

The authors suggest recording the following environmental data – temperature (including min/max), quantity of water applied, weather at time of cultivation or immediately after (i.e. dew on leaves, or precipitation following cultivation), soil type, fertilization, soil moisture at time of cultivation, weed species (if a species is present at a density greater than 100 plants of each variety per plot) and weed and crop morphology (leaf number and height).

It can be very difficult to take meaningful measurements of the calibration of weeding tools. Vanhala et al. (2004) believe that, "technical descriptions may be of secondary importance to the [tool's] impacts on crops and weeds." Because of "significant and complex interactions between implement adjustments," and crop/weed response, they conclude that it is more important to record the crop/weed/soil response than particular tool adjustments, especially because some tools have myriad possible adjustments. For example, rather than including all tool calibrations, the most meaningful measurements might be driving speed, tool working depth, operative time, angle of tool to ground, soil movement in-row (hilling or de-ridging), tool distance from toolbar, and basic tool-specific settings, such as amount of overlap.

Vanhala et al. (2004) also advise that in order to compare tools it is not enough to describe the level of crop damage or weed control alone. Instead, they recommend selectivity as the basis for evaluation. They favor a slight reworking of Rasmussen's (1990) definition of selectivity, so that the selectivity of a tool is the ratio of weed death to crop death. In addition, they suggest that the amount of hand-weeding required to remove escaped weeds in each treatment can be helpful for calculating the economic impact of the tools. In order to make a fair comparison of selectivity, they recommend that each tool be calibrated to inflict an equal amount of crop damage and provide a protocol by which to calibrate each tool in the field based on balancing crop damage and weeding efficacy.

According to Vanhala et al. (2004), weed and crop counts should be done prior to cultivation, immediately afterwards, and a week later. It has also been suggested that any large weeds be removed before the application of tools, as, "the presence of weeds in an advanced stage of development noticeably reduced the effectiveness of the operation" (Peruzzi et al. 2007). Because cultivation is most effective on young weeds, Vanhala et al. (2004) recommend that surrogate weeds be cultivated when monocots have less than one leaf and dicots have less than two.

Selectivity

In-row weeding tools cannot be judged by the weeds they kill alone (efficacy), because doing so ignores the crop damage inflicted by the tool. Selectivity has arisen as a crucial way to understand the full effect of in-row tools on both weed and crop. As described by Kurstjens (2002), Meyler and Rühling (1966) were the first to introduce the concept of selectivity as describing the relationship between crop loss and weed control in mechanical cultivation. Rasmussen later expanded upon the concept, positing that, "a high selectivity indicates a high degree of weed control without associated crop damage" (Rasmussen et al. 1995). Rasmussen defined selectivity specifically for harrows as the percent weed mortality divided by the percent reduction of crop covered by soil.

Kurstjens et al. (2001) broadened this definition to be applicable to other tools and modes of action, defining selectivity as percent weed mortality divided by percent crop mortality. They contributed to the theoretical understanding of selectivity by distinguishing a tool's selective potential from its selective ability. Kurstjens et al. (2002; 2004) also introduced mathematical models exploring the effects on selectivity of the variability of relevant attributes within crop/weed populations (such as anchorage force) and the variability of the force applied by a tool. Observing the selectivity of a tool is crucial for understanding its effect on weed and crop, and becomes only more important with tender crops at early growth stages, such as carrots, where unacceptable levels of crop damage are more likely.

Even selectivity as introduced by Rasmussen and adapted by others is not a perfect measurement of tool effect (Kurstjens 2002; 2004; Gallandt et al. 2017; Brown 2017). For example, using the definition of selectivity suggested by Vanhala et al. (2004) and others (weed mortality % / crop mortality %) as crop mortality approaches zero, a tool's selectivity quickly increases, even if there was also low crop death. In effect low crop death could mask low weed death.

For our work we defined selectivity as the percent crop survival divided by the percent weed survival. By this definition, as weed survival approaches zero selectivity will greatly increase. Because high crop mortality appears less desirable than a low weed mortality in commercial applications of weeding tools, it was thought that a definition of selectivity which is more stable as crop mortality approaches zero would be preferred to a definition that is more stable as weed mortality approaches 100%. It would helpful to further investigate the selectivity of in-row tools and the most useful was to calculate it for meaningful comparisons of tools.

Modes of action

In seeking to improve the selectivity and efficacy of in-row tools, many researchers have found it helpful to investigate the precise method by which a tool kills weeds. The literature has identified three modes of action by which weeds are killed mechanically: uprooting, cutting, and burial (Mohler 2001). Most research has focused on uprooting and burial, with the work of Toukura et al. (2006) on shearing a notable exception.

What are the factors that make uprooting effective? What are the factors that make burial effective? Are crops better suited than weeds to survive these modes of action, and at what growth stage, and which crops? Greater understanding of these questions can help us optimize the use of our tools.

Fogelberg and Gustavsson (1998) give a detailed discussion of the issues involved in uprooting, including summarizing previous research and presenting their findings on the force required various plants (anchorage force). They found that soil type significantly affected the anchorage force of carrots and weeds but that the angle of pull did not. They made comparisons at three developmental stages: when all plants were at the 2-leaf stage there was little difference in anchorage force between carrot and any of 5 weed species (including *C. album*). But, at the 4-6 leaf stage carrot anchorage forces were 3.5 N greater than the closest weed at the same stage. At the 6-8 leaf stage carrots required 4.5 N more uprooting force than the closest weed at the same stage. The authors speculated that carrots have greater anchorage force compared to the studied weeds because biennial species such as carrots prioritize below-ground storage more than annual weeds. For example, a carrot seedling can invest almost half of its total dry mass in its root, whereas the root dry-mass of many annual weeds is often below 20% or even 12% of total dry-mass. The authors also cite earlier research confirming that soil type can influence root architecture and hence rooting strength, and that plant density changes the growth habit of many species. A series of papers by Ennos (1990) provides a detailed discussion of the mechanics, forces, and plant architectures that effect anchorage force.

In their work on selective uprooting, Kustjens et al. (2004) report that sugar beets in the 2-4 leaf stage have a variable anchorage force ranging from 0.09 N to 0.39 N. However, when compared to Fogelberg and Gustavsson's findings, this range is well within the difference in anchorage force observed between carrots and weeds (3.5 N) – so that even when accounting for interspecies variation in crop uprooting force, there should still be a significant difference in the force necessary to uproot beet versus weed; a difference that a tool could exploit.

Burial is the second mode of action by which cultivators kill weeds. Kurstjens et al. (2000) describes the three sequential processes that determine successful weed burial: the tool bending the plant stem down into the soil, then securing the prostrate stem in position by depositing soil on top of the leaves, and finally raising the soil surface enough to cover plants that are not bent. The ultimate success of the burying tool is determined by the degree to which it accomplishes these three processes. Mohler et al. (2016) give a vivid description of the burial process, "when soil is thrown into the crop row . . . the impact of the leading edge of the wave bends the weed seedlings over and they are buried under the crest of the wave." Kurstjens et al. (2000) point out the importance of cultivator speed, because faster moving soil has more force with which to bend plant stems upon impact.

Baerveldt and Ascard (1999) investigated how much soil cover is necessary to kill weeds. They cite earlier work showing that a burial depth of 1-1.5 cm is needed to kill 90% of weeds at the 1-2 leaf stage. They found that weeds had to be totally buried in order to be significantly controlled and confirmed the findings of Kurstjens et al. that burial is more effective if plants are bent prior to burial. Terpstra and Kouwenhoven (1981) ran hoe-ridgers in laboratory soil and similarly found that a soil cover of 1.5 cm was lethal to 2.5-3 cm tall seedlings of garden cress (*Lepidium sativum* L.) and a cover of 2 cm was lethal for seedlings of the same species when 7-9 cm tall. Authors agree that the best time for burial is at the cotyledon stage, when the seed's reserves have been depleted; weeds at the white thread may continue growing through soil after burial.

Baerveldt and Ascard (1999) also investigated the effect of soil particle size, and found that smaller soil particles increased weed death. For example, with *C. album*, when the plant was bent and covered with smaller soil particles (0.1 mm) 1 cm of soil cover provided effective control, whereas with larger particles (0.95 mm) 1.5 cm of soil cover was required for effective control. This confirms the common observation that soil type and seedbed preparation play a large role in cultivator efficacy. The authors comment that, "weed plants should be totally covered with a soil of fine tilth to be affectively controlled." An ideal cultivator would, as part of its action, crumble the soil as it is moved into the crop row.

Mohler et al. (2016) provide more details on weed-burial in their paper. They confirmed that burial can be an effective mode of action: when weeds were bent before burial and covered under 2 cm of soil, recovery above 5% was rare. This was true for *C. album*, S*etaria faberi*, and A*maranthus powellii*. However, they stress that it is imperative to achieve complete burial of some weed species. For example, when a single leaf of *C. album* was left exposed after burial, recovery improved up to 67%. Investigating farmer experience, Mohler et al. also report findings that the precipitation pattern after cultivation may affect weed recovery, though not to significant levels.

Carrots

Most in-row cultivation research has focused on transplanted crops or larger-seeded vegetables, for which successful cultivation is easier compared to carrots. Carrots are one of the least weed-competitive crops (Van Heemst 1985). The critical weed free period for carrots has been estimated to include the time of emergence until 4 weeks later (Shadbolt & Holm 1956; Bevan et al. 1993). Swanton et al. (2010) noted that the critical weed free period is approximately halved if the carrots are planted in late April versus mid-May, reflecting the experience of growers.

Because carrots are so poorly competitive with weeds they offer the ultimate test for mechanical weed control. In two experiments spanning six years Peruzzi et al. (2007) used stale-seedbedding, pre-emergence flextine harrowing, and a precision hoe with torsion weeders post-emergence. They included two treatments, their "best guess" innovative treatment consisting of several different tools used sequentially and the conventional practice. They found that their innovative method including in-row cultivation reduced in-row weeds by 55-97%, which resulted in a reduction in hand-weeding time. They also found that in-row cultivation did not lower yields in any years, and that in three years in-row cultivation resulted in higher final carrot density and yield than the hand-weeded control, which they attributed to relatively high crop mortality and low selectivity of the hand-weeding operation. This finding may also support farmer observation that cultivation can increase the rate of crop growth, by oxygenating the soil and increasing nitrogen mineralization.

Radics et al. (2002) examined the effects on carrots of 15 treatments consisting of combinations of herbicide, between-row hoeing, and a brush weeder over two years. Although the data they took did not follow suggested protocol (see above), they found that the action of the between-row hoes in moving soil into the crop from the rows resulted in increased crop biomass.

Fogelberg and Gustavsson (1999) performed experiments to learn about the mechanical damage to carrots from brush weeding. They concluded that for brush weeding the dominant cause of carrot death was by soil covering, as opposed to uprooting. They also found that when brush weeding, all 5 weeds studied (including *Chenopodium album* L.) were more sensitive to soil cover than carrots.

The work of Fogelberg and Gustavsson (1998) showed there are clear physiological differences between carrot and weed that can be exploited by a cultivator, and should result in a high selectivity. However, in the field carrots grow more slowly than weeds do, and so the chief challenge lies in the initial development of the carrot stand – once carrots are on equal developmental footing with weeds they can (out)compete.

LITERATURE CITED

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CHAPTER TWO: Stacked in-row cultivation tools improve weed management and selectivity in carrots

Abstract

In a series of field experiments we evaluated the impact of four in-row mechanical weeding tools on carrots (*Daucus carrota*) and two surrogate weed species: yellow mustard (*Sinapis alba*), and German millet (*Setaria italic*). Finger weeders (F), torsion weeders (T), flextine harrows (X), and Duo hilling discs (HD) were applied to carrots and weeds individually and in combination (tool 'stacking') when the carrots had 1 true leaf, approximately 25 days after planting. Tool combinations gave greater weed control and selectivity than single tools. The F+HD combination particularly resulted in the greatest selectivity and reduction in the time required for subsequent hand weeding. No tool effects were detected on carrot quality or yield. However, across all tools, lower final carrot densities were associated with lower yields. The finger weeder controlled more weeds as soil moisture increased or when more soil was moved into the carrot row. Whereas the torsion weeder did not appear to kill weeds through hilling and its efficacy was greater under drier soil conditions. In many cases, yellow mustard was more susceptible to death by burial than German millet.

Keywords: in-row, selectivity, stacking, cultivation, finger weeder, torsion weeder, flextine harrow, hilling, mechanical weed control

Introduction

In-row weed control

Weed management research draws a distinction between the curative control of weeds growing with the crop and preventative controls. Whereas curative controls—including mechanical cultivation and herbicides—are used primarily to reduce weed competition with the crop at a single point in time, preventive approaches aim primarily to decrease total weed seeds in the soil in order to reduce future weeds (Melander 2000; Merfield 2015; Caldwell & Mohler 2001; Bleeker & van der Weide 2000).

A further distinction is made between inter-row weed control (also called between-row) and in-row weed control (also called intra-row). Because there are no crops growing in the between-row area, weed control there need not be selective and as such greater levels of control are possible. In contrast, direct physical control in the in-row area must selectively kill the weeds while preserving the crop. This need for selectivity makes in-row weed control much more difficult than between-row control.

In-row Tools

It can be difficult to gain a holistic understanding of the effect of each in-row weeding tool from the literature; due to constraints, oftentimes the tool effects on both weed and crop survival and crop yield are not reported. Similarly, the way in which the tool was calibrated and the growth-stage and size of weed and crop may not be included. In addition, articles rarely document soil movement and how this differs by tool and relates to efficacy, or how soil moisture may affect the efficacy of each tool.

In the past two decades in-row weeding research has focused on three tools: the flextine harrow, finger weeder, and torsion weeder. The flextine harrow, also called the spring-tine harrow, consists of a series of spring-steel wire tines that vibrate as they are dragged through the soil. The main adjustments are tine angle and tension, and driving speed (van der Schans & Bleeker 2006; Kouwenhoven 1997; Rasmussen 1992; Rasmussen et al. 2008; Vanhala et al. 2004; Fogelberg 2007; Ascard & Bellinder 1996; Duerinckx et al. 2005). Generally, "only small weeds that are not yet past the first true-leaf stages can be effectively controlled by [flextined] harrowing" (Van der Weide et al. 2008). Differences in the height and canopy structure between the crop and weeds may be the most important factors affecting selectivity (Rasmussen 1990). Though commonly used on American vegetable farms for transplanted vegetables and vigorous direct-seeded vegetables such as sweet-corn and beans, little research is available on the use of the flextine harrow when combined with other tools, its effects in direct-seeded vegetables, or its effects on yield in root crops.

The Finger weeder consists of two wheels with rubber or plastic fingers rotating on either side of the crop row. Metal drive-pins underneath the flexible fingers engage the soil and turn at ground speed. Because the drive-pins are a smaller diameter than the plastic fingers, the fingers rotate faster than ground speed. Though developed as a single row tool in Michigan, USA in the mid-twentieth century, in the late 1990's finger weeders were redesigned in Europe.

One study suggested that finger weeders may negatively affect yield in transplanted lettuce (Smith & Silva 2008), though others have found no evidence of yield loss using finger weeders in direct seeded onions (Bleeker et al. 2004). Bleeker et al. (2002) found that European finger weeders, used in transplanted leek and lettuce and direct-seeded beet and onion, were more selective than flextine harrows. Although finger weeders have performed well in transplanted crops, less is known about their effects on direct-seeded crops or their effect on the yield of root crops. There is also a paucity of research on their precise mode of action: Do finger weeders uproot weeds, bury them, or both?

Torsion weeders are lengths of round spring-steel varying in diameter from approximately 0.7cm to 1 cm. They are bent into a loop that allows the metal tine to flex and vibrate under tension. Pairs are set-up on either side of the crop so that their tips cross, or nearly cross, making a 'V' shape. According to manufacturers, as torsion weeders are pulled through the soil they vibrate, uprooting small weeds (Hitchcock Tilton 2017). Similar to the finger weeder, torsion weeders were invented in the US and later redesigned in Europe. Torsion weeders vary in the diameter of steel used and in the direction and size of their coils.

Two passes with the American Bezzerides-brand torsion weeder in direct-sown onions reduced weed density and the time required for subsequent hand weeding by approximately 50% with no significant yield reduction (Ascard & Bellinder 1996). European torsion weeders reduced hand-weeding by two-thirds compared to flame weeding coupled with between-row cultivation (Ascard & Fogelberg 2008).

Torsion weeders have shown mixed effects on yield compared to finger weeders. Torsion weeders reduced yield in transplanted lettuce and plant density in direct-seeded onions (Bleeker et al. 2004; Smith & Silva 2008). However, in direct-seeded onions at 1-leaf, the torsion weeder did not reduce onion density (Ascard & Fogelberg 2008). Though a promising tool, there is a paucity of research on the efficacy of torsion weeders on smaller direct-seeded crops, its effect on the yield of root crops, or the mode of action by which it kills weeds.

Selectivity

In-row weeding tools cannot be judged by the weeds they kill alone (efficacy), because doing so ignores the crop damage inflicted by the tool. *Selectivity indices* provide a useful way to understand the full effect of in-row tools that encompass tool effects on both weed and crop (Meyler & Rühling 1966, as quoted in Kurtsjens 2002). Knowledge of an in-row tool's selectivity is crucial for understanding its full effect on weed *and* crop, and becomes only more important with tender crops at early growth stages, such as carrots, where unacceptable levels of crop damage are more likely. While the difference in plant size between crop and weed (either root or shoot, depending on the tool's mode of action) is usually the focus in understanding the selective potential of a tool, the variability of plant size (and subsequent anchorage force) as well as the variability of the force applied by the tool have also been shown to play an important role in a tool's theoretical selectivity (Kurstjens 2000; Kurstjens et al. 2004).

Selectivity indices as they have been previously defined (Kurstjens 2002, 2004; Rasmussen 1990, 1992; Rasmussen et al. 1995; Brown 2017) are not a perfect measurement of tool effect. For example, Rasmussen (1990) defined selectivity as the ratio of weed injury compared to crop injury. Using this definition, as crop death approaches zero, a tool's selectivity quickly increases. This definition of selectivity would result in a very good (high) selectivity index even if a tool killed few weeds, as long as there was also low crop death. In effect, low crop death could mask low weed death.

Modes of action

In seeking to improve the selectivity and efficacy of in-row tools, it is helpful to investigate the precise mode of action by which each tool kills weeds. The literature has identified three modes of action by which weeds are killed by mechanical weeding tools: uprooting, sheering (cutting), and burial (Mohler 2001).

In only a few instances has the mode of action of these in-row tools been directly investigated (Kurstjens 1998; Kurstjens et al. 2000) (Habel 1954; Kees 1962; Koch 1964, as discussed in Kurstjens 2002). Often the supposed mode of action by which in-row tools kill weeds has been based more on visual observation or instinct than statistical analysis (Kurtjens et al. 2000; Hitchcock Tilton 2017). A deeper understanding of specifically how in-row tools kill weeds could aid in their further optimization.

In-row tool combinations, tool stacking

Recently interest has grown in combining in-row tools and applying them in the same operation, also known as tool *stacking*. Farmers, researchers, and weeding tool manufacturers have been combining in-row weeding tools on single implements so that multiple in-row tools are applied in one pass (the HAK Company, the KULT-Kress Company, the Steketee Company). In some of the scant research on stacking, Bleeker et al. (2002) combined the torsion weeder and the finger weeder in both sugar beets and onions. This combination was applied in sugar beets from the 4 to 6-leaf stage onwards. After an unspecified number of applications, crop plant reduction was about 5%, with weed reductions of 41%, 38%, and 88%. Dividing the percent crop survival by percent weed survival for each trial, their data suggest that the torsion and finger weeder combination achieved selectivity indices ranging from 1.5 to 8. No significant differences were found in yield between the torsion and finger weed when combined versus when both were applied alone.

Based upon the stacked in-row tools produced by European manufacturers, Brown (2017) and Gallandt et al. (2017) hypothesized that combining in-row tools of different modes of action would lead to greater selectivity. They used a torsion weeder followed by finger weeder followed by flextine harrow in 2 to 3-leaf maize with weeds at cotyledon stage. This stacked tool combination resulted in approximately 16% crop mortality and 71% weed mortality. Dividing the percent crop survival by percent weed survival yields a selectivity of 2.8. In comparing single tools versus stacked tools, Brown and Gallandt (2017) observed evidence that the efficacy of stacked tools was greater than would be expected by the mere additive effects of the component in-row tools. Although the authors demonstrated synergies in efficacy there was significant crop death even when using an established and competitive crop. There is extremely little information on stacked in-row tools, their selectivity, or their calibration.

Carrots

Most in-row tool research has focused on transplanted crops or larger-seeded vegetables in which successful cultivation is easier due to a larger crop/weed size differential. Less work has been done on direct-seeded, slow growing crops like carrots. Previous research has demonstrated that carrots are one of the least weed-competitive crops, in contrast to crops like potato, maize, or beans, which have shorter critical weed free periods (Van Heemst 1985).

In two experiments Peruzzi et al. (2007) used a precision hoe with torsion weeders on carrots. Unfortunately the growth stage at which tools were applied to carrots was not noted. They found that in-row cultivation did not lower yields in any years, but in two of four years carrots receiving in-row cultivation had a higher density of carrot plants and a higher root yield compared to the hand-weeded control.

Though a greater percentage of carrots are grown organically in the US than any other crop, and though they are one of the most difficult crops to grow without herbicides, there exists little research investigating the effects of in-row weeding tools in carrot production (USDA ERS 2016). In addition, an informal poll of Midwestern vegetable growers using in-row tools (i.e. finger weeders) showed that only one had attempted to use finger-weeders on carrots, and had found moderate success.

We undertook this study to evaluate the new in-row weeding tools recently available in the US and to address the scarcity of research on modern in-row tools in direct-seeded crops generally and specifically in carrots. We also hoped to improve understanding of the mode of action of in-row weeding tools to aid in their optimization and to add to the knowledge of stacked in-row tools.

Objectives and Hypotheses

The primary objectives of our research were to evaluate the impact of in-row weeding tools used alone and in combination on weed and carrot seedling mortality, labor savings, carrot quality, and carrot yield. Based on the literature and the experience of farmers and tool manufacturers, we hypothesized that 1) Tools used alone would vary in their selectivity for grass versus broadleaf weeds and for weeds versus carrots; 2) Combinations of two or three tools would improve efficacy and selectivity; 3) Individual tools and tool combinations would vary in their impact on carrot quality and yield at harvest; 4) Carrot seedling mortality of less than 10% would not have a clear correlation with final yield; 5) Labor costs for hand-weeding would vary based on tool, and would be correlated with tool efficacy; 6) Tool combinations which pull away soil and then subsequently hill the soil will be the most effective and selective: the finger weeder angled slightly backward (i.e. less than 90 degrees) should pull soil away from the row, and if followed by hilling discs, the desired de-ridging/ridging would be achieved.

Materials and Methods

Experimental site

Field trials were conducted in 2017 at the Michigan State University Horticulture Teaching and Research Center in East Lansing, Michigan (42.6734° N, 84.4870° W, elevation of 264 m). The site chosen was a flat field of Marlette Silt Loam with 74.8% sand, 17.8% silt, and 7.4% clay, containing few rocks (mesic Oxyaquic Glossudalfs). The site had winter wheat planted the previous fall, and in the spring of 2017 the young winter wheat was tilled and the land prepared for research.

Tool descriptions Table 2.1

In-row tools and combinations were chosen based on efficacy, availability, and to represent several modes of action. Treatments of in-row weeding tools consisted of 1) Control, where the only in-row weed control was hand-weeding performed after treatments were applied; 2) Torsion weeder (T) treatment consisting of 7 mm diameter torsion weeders from the Frato Company (Frato, Postbox 240 Nl-6500AE Nijmegen, Holland); 3) Lely flextine harrow (X) (Lely Turf Products, P.O. Box 437 Pella, IA 50219); 4) Finger weeder (F) 29 cm in diameter with yellow fingers from the KULT-Kress Company (KK) (KULT-Kress LLC, 3817C Ridge Road, Gordonville PA 17529); 5) Hilling disc (HD) treatment consisting of a KK Duo-parallelogram with 15 cm diameter discs angled to throw soil into the row; 6) Finger weeder followed by hilling discs (F+HD); 7) Finger weeder followed by flextine harrow (F+X); 8) Torsion weeder followed by finger weeders, followed by flextine harrow (T+F+X).

Table 2.1: List of in-row tool treatments and their method of mounting to steerable toolbar, with reference to illustrating figures.

	Treatment	Mounting system	Figure
1	None		
2	Frato Torsion weeder (T)	Hak floating linkage	Fig. 2.1 & 2.2
3	Lely Flextine harrow (X)	Custom on Kult Kress floating arm	Fig. 2.3, 2.4, 2.5
4	Kult-Kress Finger weeder (F)	Kult-Kress floating arm	Fig. 2.6 & 2.7
5	Kult-Kress Hilling disc (HD)	Kult-Kress floating arm, parallel linkage	Fig. 2.8 & 2.9
6	Finger weeder + Hilling disc (F+HD)	Kult-Kress floating arm, parallel linkage	Fig. 2.10 & 2.11
7	Finger weeder + Flextine harrow (F+X)	Kult-Kress floating arm	Fig. 2.4
8	Torsion weeder + Finger weeder + Flextine harrow (T+F+X)	HAK floating linkage, Kult-Kress floating arm, Custom on Kult-Kress floating arm	Fig. 2.12 & 2.4

Tool mountings Figures 2.3-2.18

All cultivation tools were rear mounted on a HAK steerable toolbar (S-series) with rack and pinion steering, which had two bars (HAK Schoffeltechniek, Spectrumlaan 11 2665 NM Bleiswijk, Holland). The HAK toolbar was mounted to a 4-wheel drive tractor by means of three-point linkage with a hydraulic top link for ease of adjustment (Figure 2.13).

All tool treatments in trials A and B included between-row knives running in front of the in-row tool(s) (HAK mono blade, working width 16 cm). These knives had a rake angle of zero (i.e. they were parallel to the ground) and generally moved no soil into the crop row (Welsh 2002). In trial C, the soil was so loose from previous between-row weeding tools that no between-row knives were applied with the in-row tools, because doing so moved soil into the row.

The torsion weeder was mounted with one unit on each side of the crop row connected to HAK floating linkages that were mounted to the front bar of the HAK toolbar (Figure 2.18).

The finger weeder, flextine harrow, and hilling discs were all mounted to a KK floating arm attached to the rear bar of the HAK steerable toolbar (Figure 2.18). For these tools, the spring tension of the KK floating arm was set as loose as possible to avoid excessive down pressure on our sandy soil (Figure 2.4).

The flextine harrow consisted of 10 Lely tines mounted on a custom-built mini-frame measuring 74 cm by 50 cm, to achieve a working distance of 3.8 cm between each tine (the same spacing as used by the manufacturer) and a working width of 34 cm. This frame was suspended from the KK floating arm by a pivoting bracket in front and a chain in the rear. The length of the rear chain could be changed by means of an adjustable screw-type turnbuckle connecting the chain to the floating arm. By changing the length of the rear chain, then flextine unit could be made parallel with the ground. The flextine unit weighed approximately 20 kg, which provided sufficient down pressure to work the soil to desired depth (Figures 2.3 & 2.5).

The finger weeder and hilling discs were mounted as recommended by KK to the KK floating arm. The HD was mounted to two gauge wheels straddling the crop row and connected by parallel-linkage (as assembled by manufacturer) to the KK floating arm (Figure 2.18). The finger weeders were mounted to the floating arm by means of a KK mounting bracket (part number FH121) (Figure 2.18).

For the F+HD combination, tools were mounted as described above, with the finger weeders approximately 50 cm in front of the hilling discs on the same KK floating arm (Figure 2.11).

For the F+X combination, tools were mounted as described above, with the finger weeders mounted approximately 30cm in front of the flextine on the same KK floating arm. (Figure 2.4)

Finally, for the T+F+X combination, tools were mounted as described above, with the torsion in front, the fingers mounted approximately 45 cm behind the torsion, and the flextine mounted approximately 30 cm behind the fingers (Figure 2.4).

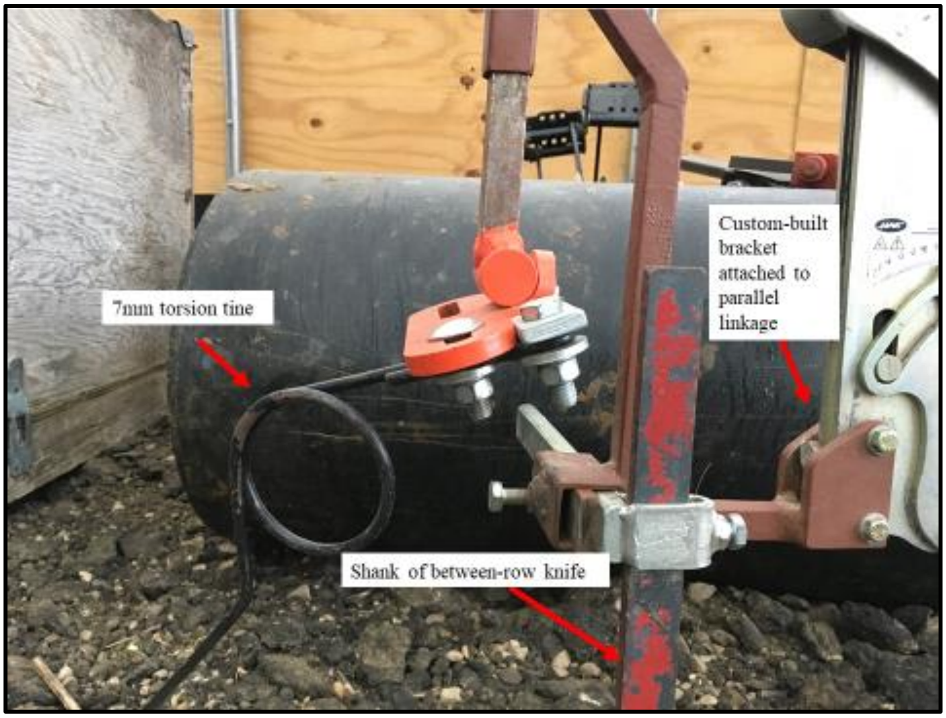

Figure 2.1: Frato Torsion weeder, 7mm tine, mounted on HAK parallel linkage by means of a custom-built bracket. Between-row sweeps are also mounted on custom-built bracket. Direction of travel is towards the right.

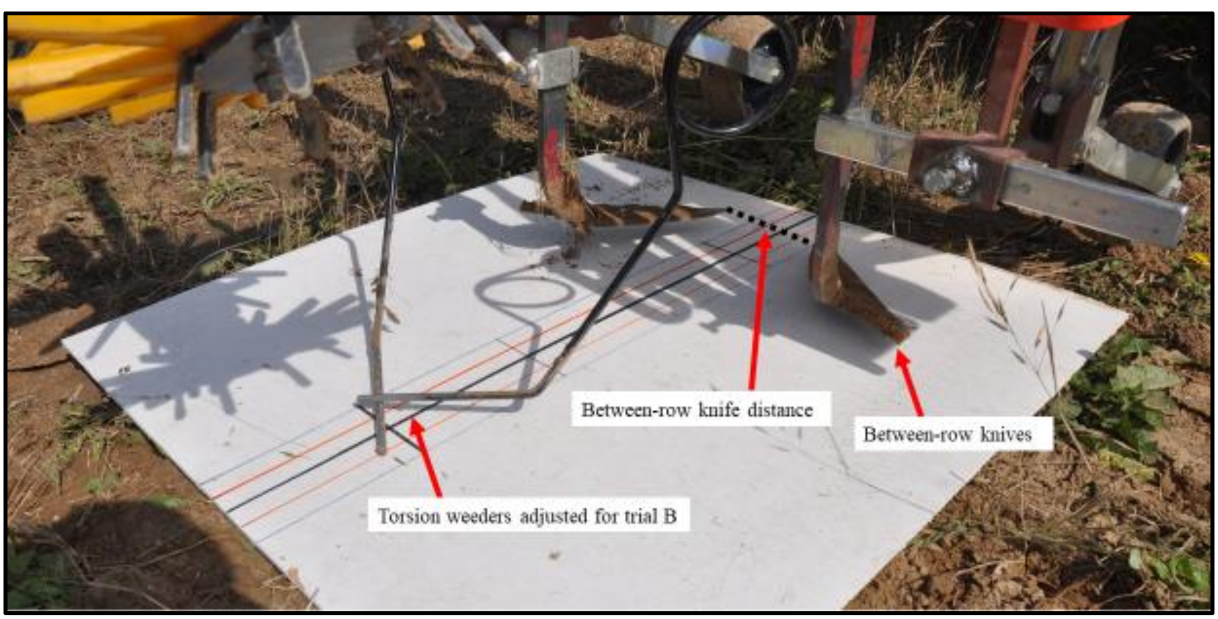

Figure 2.2: Frato 7 mm torsion weeder against calibration board with between-row knives in front, illustrating between-row knife distance. Direction of travel is towards the right.

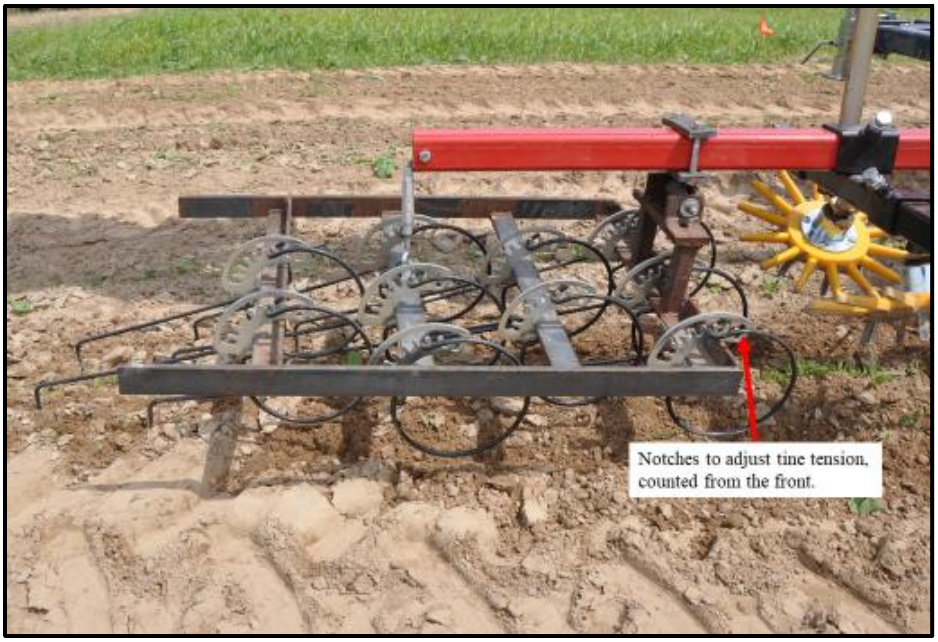

Figure 2.3: Lely flextines mounted on custom-built frame, mounted on floating arm, showing notches used to adjust tine tension. Direction of travel is towards the right.

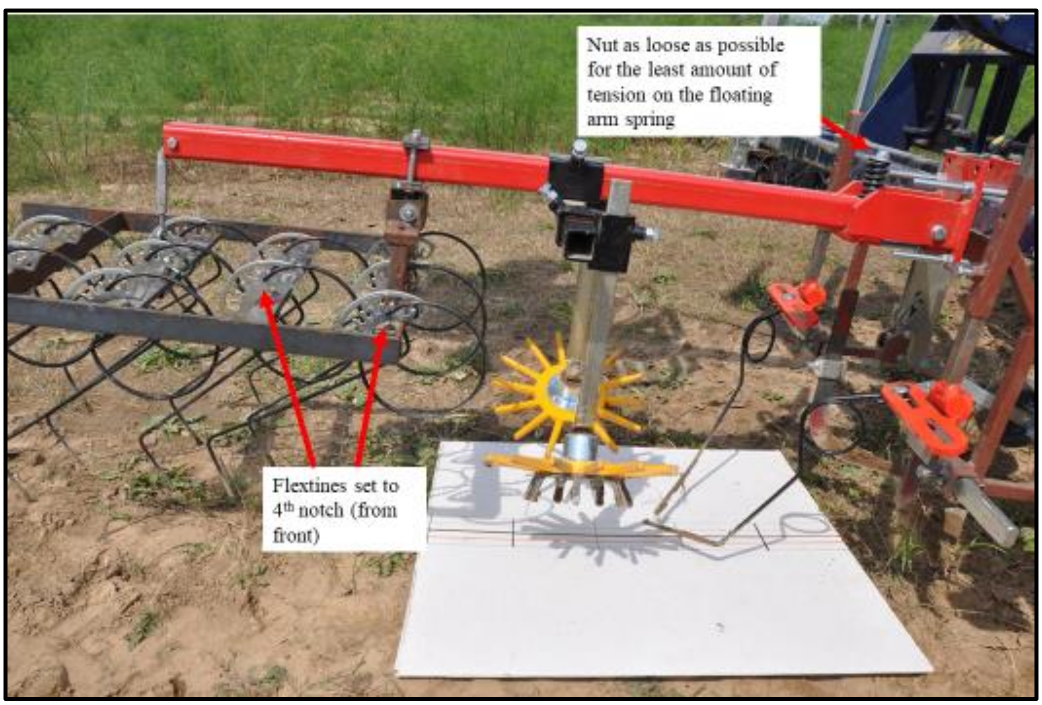

Figure 2.4: Full view of Lely flextines mounted on custom-built frame, mounted on floating arm. Showing notches used to adjust flextine tension and nut on floating arm used to adjust down pressure. Finger weeders in front of flextines, torsion weeders in front of fingers, between-row knives in front of torsion weeder. Direction of travel is towards the right.

Figure 2.5: Flextine harrow being applied to carrots. Note flextines working in the crop row.

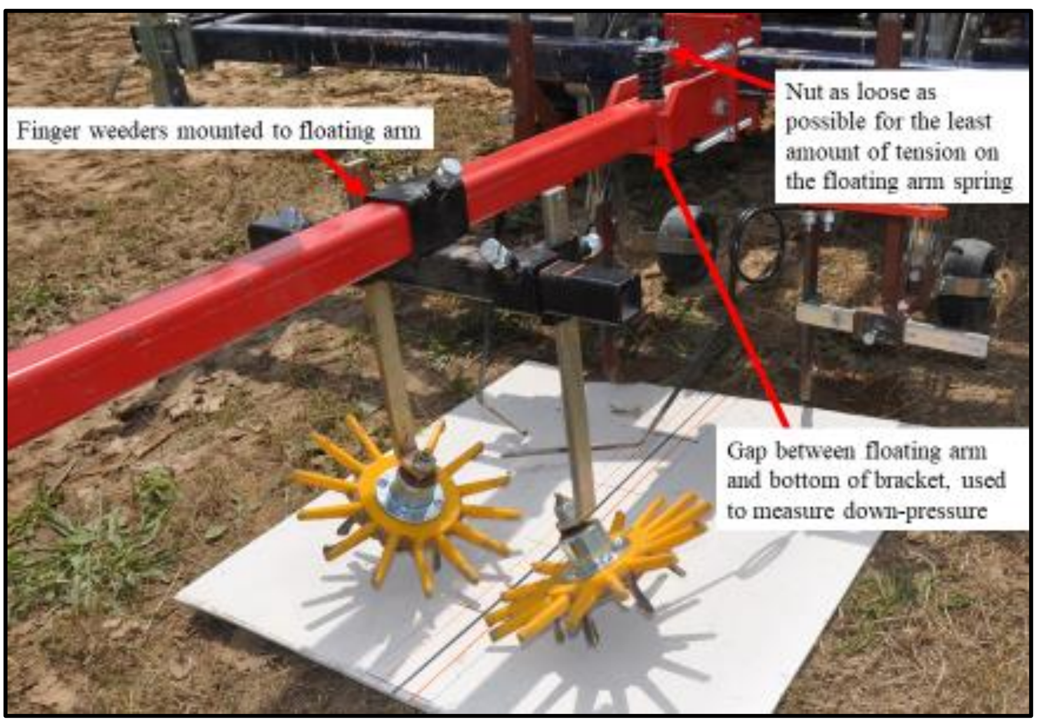

Figure 2.6: Finger weeders, against calibration board, mounted on floating arm. Showing the gap between the floating arm and baseplate that was measured to record down pressure. Direction of travel is towards the upper right-hand corner.

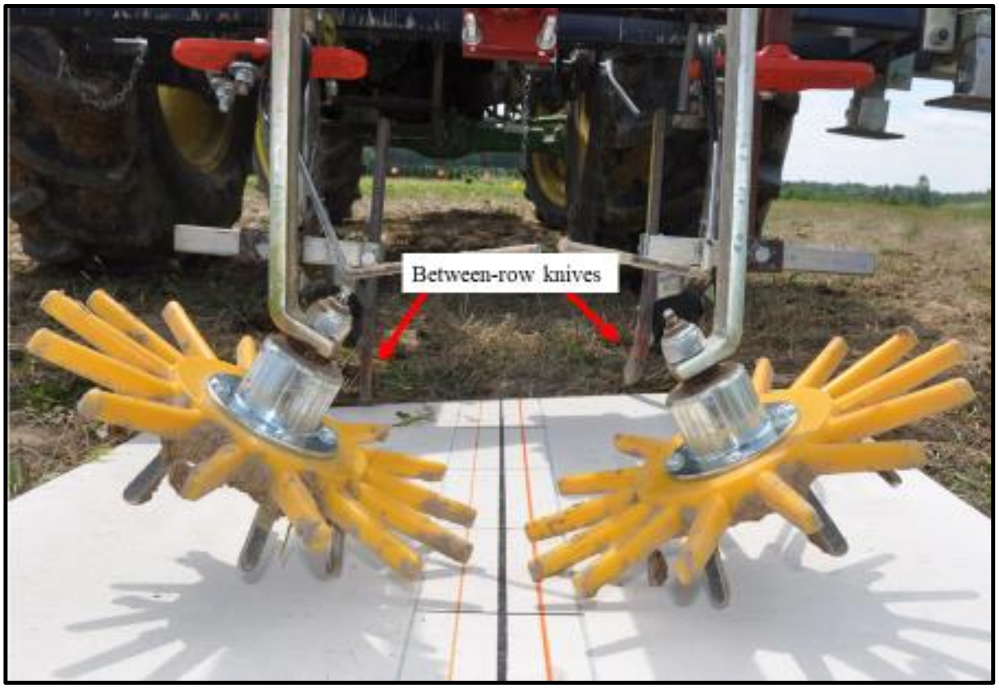

Figure 2.7: Finger weeders against calibration board, adjusted for trial B, with between-row knives ahead. Looking towards the direction of travel.

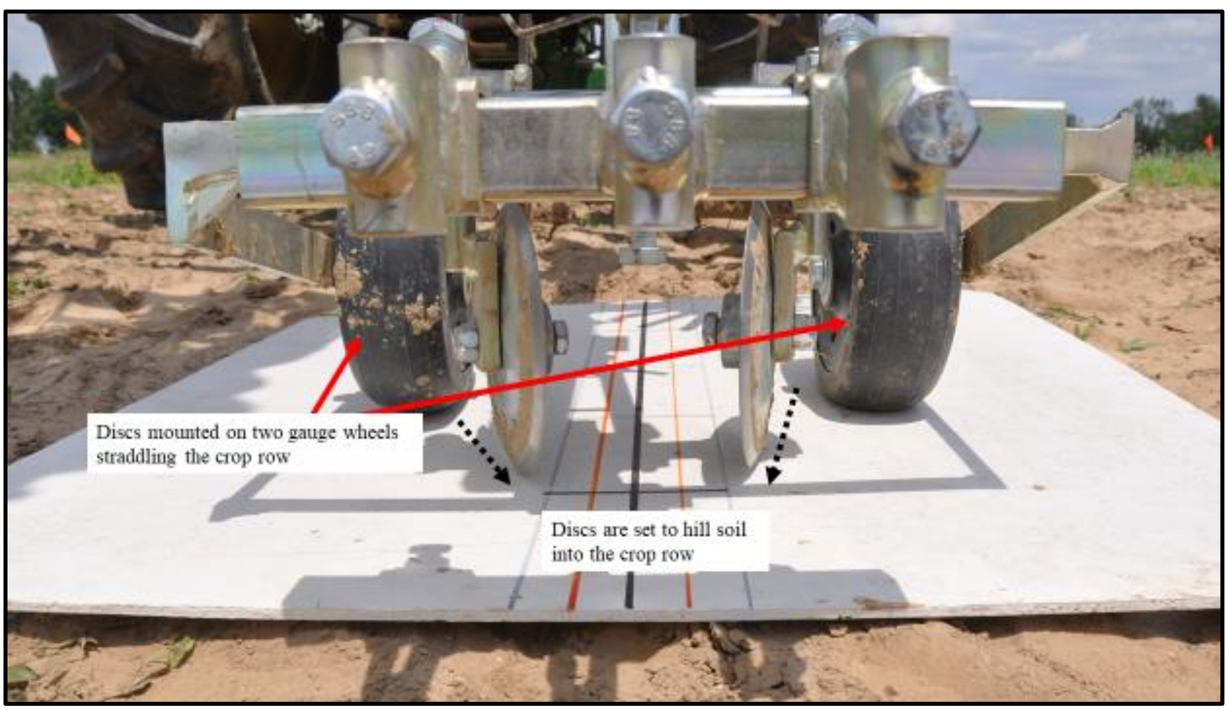

Figure 2.8: Hilling discs on calibration board, showing inclination of discs and location of gauge wheels. Looking towards the direction of travel.

Figure 2.9: Hilling discs hilling soil into the carrot row, looking towards the direction of travel.

Figure 2.10: Finger weeder + Hilling discs **(**F+HD) on calibration board, looking towards the direction of travel.

Figure 2.11: Finger weeder + Hilling discs **(**F+HD) being applied to carrots, looking away from the direction of travel.

Figure 2.12: Torsion weeder + Finger weeder + Flextine harrow **(**T+F+X) against calibration board, looking away from the direction of travel.

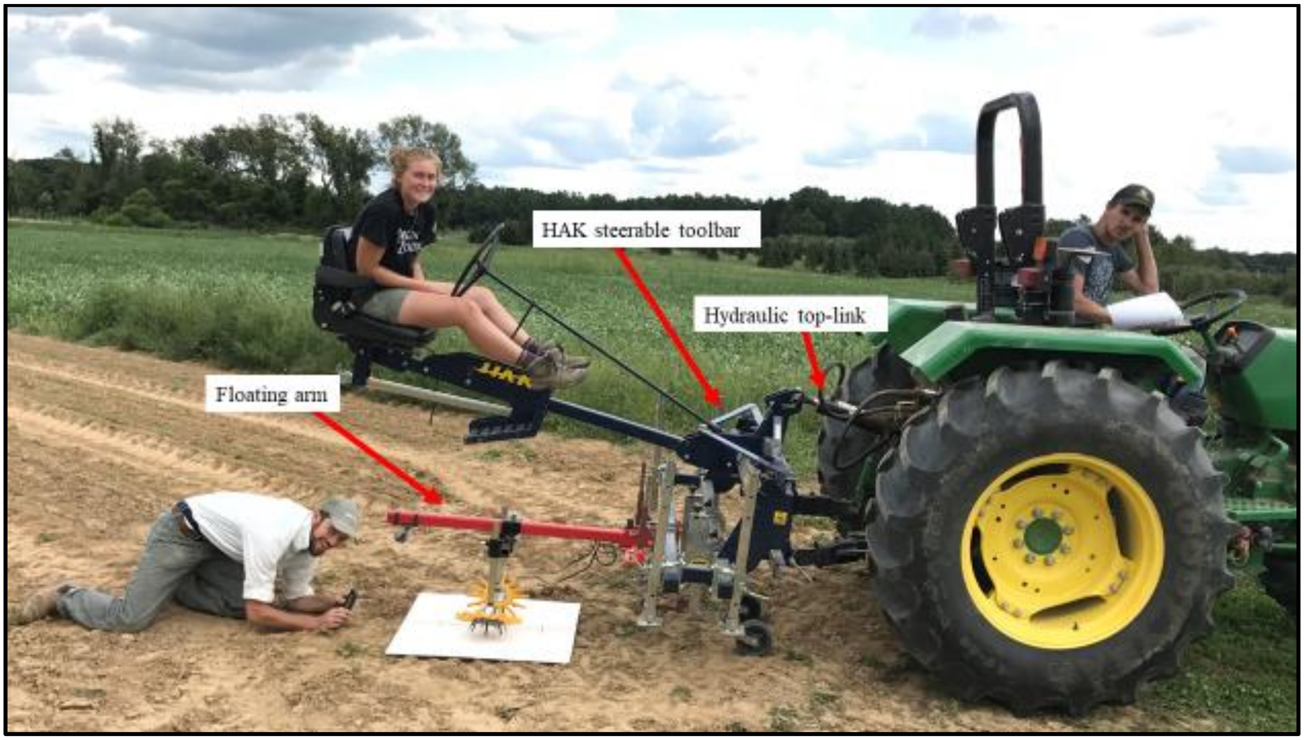

Figure 2.13: Full view of tractor, HAK steerable toolbar, floating arm, torsion weeder, finger weeder, and researcher.

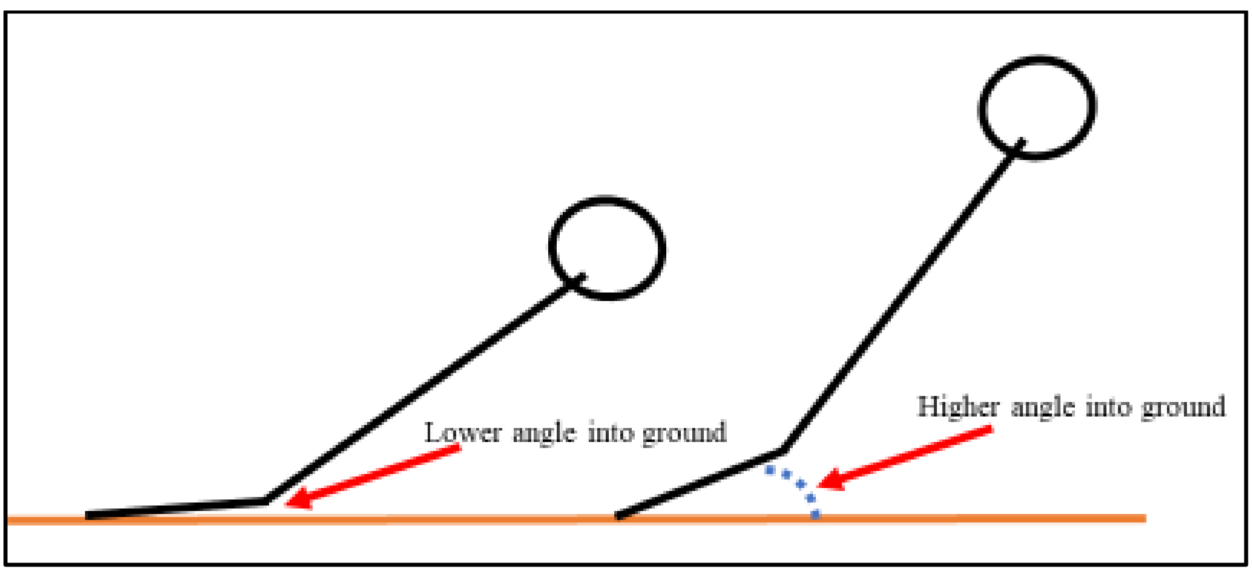

Figure2.14: Illustration of torsion weeder, showing the angle into ground.

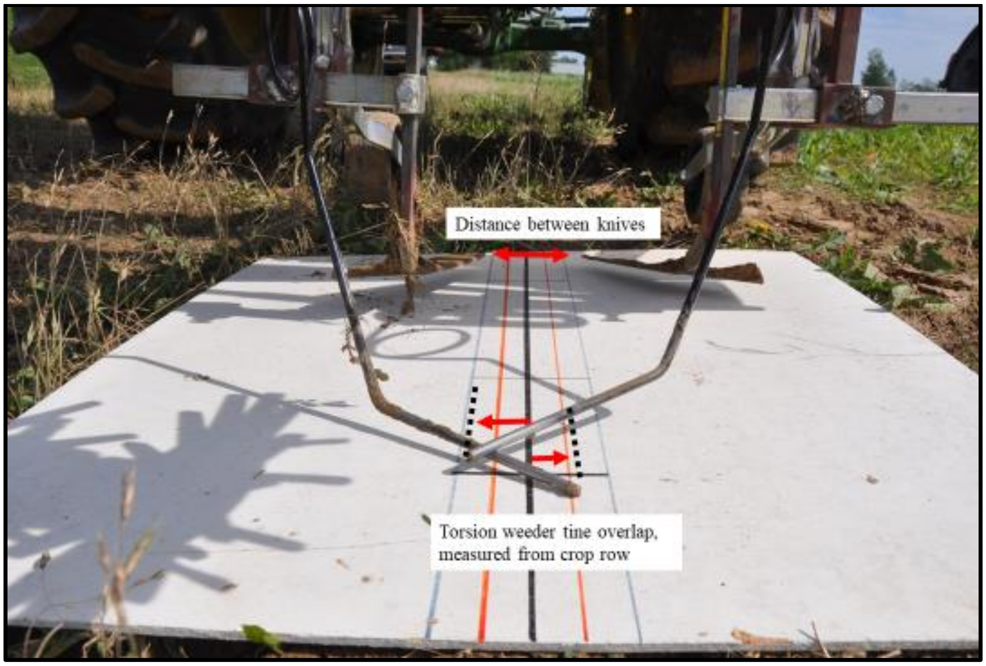

Figure 2.15: Torsion weeder on calibration board, showing the measurement recorded as distance of between-row knives, and the measurement recorded as torsion weeder tine overlap.

Figure 2.16: Finger weeder in carrots, showing distance between finger weeders; recorded as the closest distance between tips of opposing fingers when plastic fingers are bent upwards, parallel to the earth.

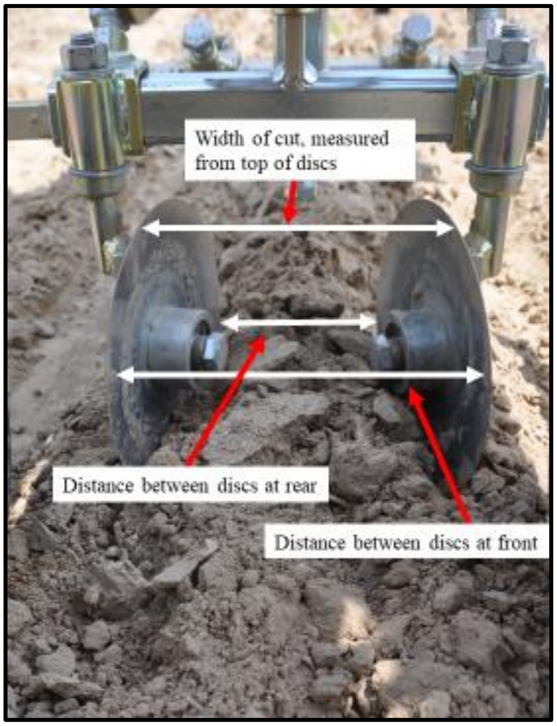

Figure 2.17: Hilling discs in carrots, showing how the calibration of the hilling discs was measured.

Figure 2.18: HAK steerable toolbar, floating arm, and researcher making adjustments. Showing the mounting of HAK floating linkages and of floating arm on toolbar.

Tool calibration and recording Table 2.2

The calibrated settings of each single tool for all three trials are shown in Table 2.3. Between-row knife distance was measured between the closest points of the knives (which was the in-row area, Figure 2.2). For the torsion weeder, the approximate angle of the tine into the ground was estimated by sight (Figure 2.14) and tine overlap was measured as the distance of the tine-tip from the crop row (Figure 2.15). For the flextine harrow, the tine angle and tension were measured based on the notch on which tines were set, with the first notch in the direction of travel recorded as notch '1' (Figure2.3). A higher notch number corresponds to a greater angle of the tine relative to the ground and hence greater down pressure.

For the finger weeder, down pressure was estimated by measuring the gap between the floating arm and the bottom of the bracket connecting the arm to the toolbar, while the fingers were engaged in the soil (Figure 2.6). By slightly lengthening the top-link of the 3-point linkage, the angle towards the ground of the toolbar to which the floating arm was connected could be increased, creating greater down pressure, corresponding to a larger gap. The distance between the fingers was measured as the closest distance between the tips of the two opposing fingers when the plastic fingers were bent upward, parallel to the ground, as they are when engaged in the soil (Figure 2.16).

For the hilling discs, the width of cut was estimated as the distance between the highest point on the discs. The angle of the discs towards the row was recorded by measuring the distance between the front of discs (towards direction of travel) and distance between the rear of discs (away from direction of travel) (Figure 2.17). A greater distance between the front of discs and a lessor distance between the rear of the discs moved more soil into the row.

Working depth for all tools was estimated by excavating soil after tools were applied, but whilst they were still engaged with the ground. Working depth was recorded by measuring from the lowest depth of soil worked by the tool to the soil surface (Figure 2.16).

In adjusting the tools our goal was to calibrate them as a farmer would, with the intention of killing weeds without inflicting greater than 10% crop damage (estimated by sight) (Vanhala et al. 2004). The calibration procedure began with a less aggressiveness setting and increased aggressiveness until crop damage visually appeared too high (>15%). Then tool aggressiveness was decreased unless visual damage to weeds was not observed, in which case an aggressive setting was maintained so as to have an observable effect on weeds. The result is that at times a higher carrot mortality was tolerated so that visible weed death occurred. We did not always succeed in achieving the tool affect desired on the experimental plots given differences in soil moisture and surface roughness, etc. between our calibration area and the experimental area. Others have suggested (Vanhala et al. 2004) that the most important tool data to record are not the tool-specific measurements themselves (that can change widely based on field and crop conditions), but rather the results of these calibrations – such as tool working depth.

The settings for tools used individually were not necessarily maintained for the tools run in combination. When combined, tools became more aggressive and required adjustment specifically for their combined use. Combinations of tools were found to be more aggressive than individual tools and if not re-adjusted for combined use, tool combinations could inflict almost total crop loss.

Table 2.2: Tool settings for single tool treatments with reference to illustrating figures.

Treatment	Trial A	Trial B	Trial C	Figure
Interrow hoe				
Working depth (cm)	2.5-7.6	3.2	NA	
Distance between hoes (between-row gap, cm)	10.1	14.0	NA	Fig. 2.2, 2.15
Torsion (T)				
Speed (kph)	6.4	6.4	4.8	
Approximate angle of tines into ground (degrees)	5.0	20.0	20.0	Fig. 2.14
Working depth (cm)	6.4	3.8	5.0	Fig. 2.16
Tine overlap (cm)	0.0	2.5	3.2	Fig. 2.15
Finger (F)				
Speed (kph)	6.4	3.2	3.2	
Down pressure (gap from arm to bracket, cm)	0.6	1.3	0.6	Fig. 2.6
finger offset (yes or no)	no	no	no	
Working depth (cm)	6.4	1.3	1.3	
Finger distance - gap (cm)	3.2	3.2	1.3	Fig. 2.16
Flextine (X)				
Speed (kph)	6.4	6.4	6.4	
Tine <, notches number from front	5.0	4.0	5.0	Fig. 2.3
Working depth (cm)	6.6	3.8	3.2	
Hilling disc (HD)				
Speed (kph)	6.4	2.8	2.3	
Distance between discs at bottom or top (width of cut, cm)	12.2	13.3	14.0	Fig. 2.17
Distance between discs at front (cm)	15.6	20.3	19.8	Fig. 2.17
Distance between discs at rear (cm)	11.9	12.7	8.9	Fig. 2.17
Working depth (depth of cut, cm)	0.8-1.3	1.9	1.9	

Experimental design Table 2.3

The 8 treatments were organized in a randomized complete block design with four spatial replications. Each plot consisted of a single row of carrots 17.4 m long. The carrot variety 'Bolero' was chosen as a popular fresh market variety after consulting with several fresh-market Midwestern Organic carrot growers. Carrot rows were spaced 60 cm apart, so that two rows could be planted at a time between the tractor's wheels, which were set 1.2 m apart. This row spacing, while slightly wider than a common fresh-market carrot spacing of 38-45 cm, allowed adequate space for in-row tools to be applied to one row while not impacting the nearby row. A relatively uniform and residue-free seedbed was created using various tillage tools (Table 2.2). Before planting, 56 kg/ha of nitrogen was broadcast in the form of urea, the recommended rate for carrots in Michigan, and shallowly incorporated (Warncke et al. 2004). Other nutrients were present in sufficient levels according to a soil test.

Carrots were seeded at a density of approximately 100 seeds per meter. This density was chosen by increasing the recommended commercial seeding rate by 8% to account for crop death due to propane flame weeding and in-row tools. One day prior to carrot emergence a propane flame weeder was applied to all plots to kill any ambient weeds germinating ahead of the carrots (a common practice for Organic carrot growers). Irrigation was applied equally to all plots by means of over-head sprinklers. As soon as possible between-row tools were applied in order to control ambient weeds. At approximately 2 weeks after planting (9 days after flaming) surrogate weeds were planted into 6 separate 125 x 7.6 cm quadrats within each plot. Quadrats were centered over the crop row and marked with numbered stakes driven into the ground. Yellow mustard (*Sinapis alba*) and either Japanese millet (*Echinochloa esculenta)* or German millet

(*Setaria italica*) were broadcast in the quadrats and covered with 0.4 cm of soil. Each plot contained 3 quadrats of millet and 3 quadrats of mustard.

Following suggestions from the literature, escaped ambient weeds that were as tall or taller than the crop were hand-weeded out of all plots before treatments were applied (Peruzzi et al. 2007). At approximately 20 days after carrot planting (DAP) carrot and surrogate weed density was assessed in each quadrat by a visual count. At this time two, 46 cm long wooden stakes per plot were driven to a depth of approximately 25 cm, and marked at the soil surface to evaluate subsequent soil movement (hilling) from each tool. Photographs were also taken of each quadrat illustrating soil surface condition as well as carrot and surrogate weed density. The following day each tool treatment was calibrated in the adjacent practice field containing carrots planted on the same day as those in the trial, being the same variety and seed lot, and receiving equal care. Tool settings were photographed and recorded (Table 2.3). Immediately after being calibrated each treatment was applied to the experimental plots.

At 1 day after cultivation (DAC), carrot and surrogate weed densities were evaluated in each quadrat by a visual count. Soil hilling was recorded by marking the post-cultivation soil line on each stake and then measuring the difference between pre-and post-cultivation lines. Approximately 5 DAC, carrot and surrogate weed density were re-evaluated in each quadrat (Table 2.2). Approximately 10 DAC, a timed hand-weeding was conducted to remove all surrogate and ambient weeds from each quadrat.

At approximately 30 DAP carrots were side-dressed with 31 kg/ha of nitrogen in the form of broadcast urea which was shallowly incorporated (Warncke et al. 2004). The carrots appearing healthy throughout their growth, no insect or disease products were applied. Between-row weeding tools were used as needed to control ambient weeds. At approximately 60 DAP carrots were harvested by quadrat and yield and quality were recorded.

This general sequence of events was repeated three times during the summer of 2017, with carrot planting occurring approximately one month apart in May (trial A), June (trial B), and July (trial C). Weather and irrigation conditions were recorded for all trials (Table 2.4).

Table 2.3: Timing of relevant field operations and data collection for each trial (A,B,C), recorded as number of days before or after carrot planting date.

	Operation	Trial A	Trial B	Trial C
Pre-plant	Disk	-21 & -12	-5	NA
	Field cultivator[1]	-12 & 0	-5	-17
	Cultimulch	NA	-5	NA
	Subsoil	-1[2]	NA	-1[3]
	Rototill	NA	NA	-17 & 0 [4]
	Fertilize[5]	-1	-1	-16
	Rolled bed	NA	-1	0
Planting and Preparation	Plant carrots	0	0	0
	Propane flame weeder	8	7	6
	Buddingh Basket weeder (between row)	13	NA	NA
	Kult-Kress Duo parallelogram (between row)	NA	9	11
	Budding Basket Weeder (x2)	20	NA	NA
	Kult-Kress Duo parallelogram (between row) x2	NA	NA	19
	Seed surrogate weeds	21	15	12[6] & 14[7]
	Weed and Crop density evaluated (pre-treatment)	28	20	19
	Handweed ambient weeds[8]	20	19	NA
Treatments applied - Harvest	Weeding tools applied	29	22	20
	Weed and crop density evalutated (1)	30	23	21
	Weed and crop density evalutated (2)	33	28	27
	Timed handweeding of all weeds	35[9] & 47	36 & 37	35 & 36
	Sidedress fertilizer and between-row cultivation[10]	35	34	29
	Harvest	62	62 & 63	75

[1]Danish S-tine cultivator with rolling basket harrow

[2] 20 cm depth

[3] 40 cm depth

[4] 10 cm depth

[5] Broadcast urea at a rate of 56kg N/ha and incorporated with rolling basket harrow

[6] Plant millet

[7] Plant mustard

[8] Only ambient weeds taller than carrots were pulled

[9] On day 35, only control plots were weeded

[10] Sidedress with urea at a rate of 31kg N/ha, applied in an 18" band between rows, incorporated 4 cm deep

Table 2.4: Environmental data for all trials. Air and soil temperature, rainfall, and solar flux are recorded from a weather station 1 km from experimental site.

		Date	Air Temperature (°C) Avg	Soil Temperature (°C) Avg	Rainfall & Irrigation (mm) Rain	Irrig	Total	Ave. Total Solar Flux PAR (kJ/m^2)	Ave. in-row Soil Moisture[1] VWC
Trial A									
	Carrot planting - Flaming	5/10-5/18	16.2	16.2	1.9	25	26.9	23439	
	Flaming-Cultivation	5/18-6/7	16.3	19.2	6.9	13	19.9	19181	
	Cultivation - 3 days after	6/7-6/10	18.6	23.9	0.5	0	0.5	24628	
	3-days after - harvest	6/10-7/11	21.1	25.4	9.3	13	22.3	20738	
	Carrot planting - Harvest	5/10-7/11	18.7	22.0	7.4	50	57.4	20644	
	Day of tool application	6/7							5.6
Trial B									
	Carrot planting - Flaming	6/7-6/14	21.2	25.4	2.2	14	16.2	24130	
	Flaming-Cultivation	6/14-6/29	19.9	24.2	8.7	0	8.7	18806	
	Cultivation - 3 days after	6/29-7/1	22.4	25.7	2.1	0	2.1	20189	
	3-days after - harvest	7/1-8/8	21.2	27.1	6.5	10	16.5	19506	
	Carrot planting - Harvest	6/7-8/8	20.9	26.1	6.9	28	34.9	19942	
	Day of tool application	6/14							11.3
Trial C	Carrot planting - Flaming	8/3-8/9	18.7	25.3	2.2	10	12.2	16661	
	Flaming-Cultivation	8/9-8/23	20.7	26.1	3.2	3	6.2	16618	
	Cultivation - 3 days after	8/23-8/26	14.8	23.2	0.0	0	0.0	17120	
	3-days after - harvest	8/26-10/18	16.9	21.5	9.7	0	9.7	12885	
	Carrot planting - Harvest	8/3-10/18	17.7	22.7	7.0	10	17.0	13938	
	Day of tool application	8/23							10.3

[1] Measured on day of trial, average of three readings per plot at a depth of 3.8 cm

Soil moisture and crop and weed size at time of cultivation Table 2.5

In-row soil moisture on the day of cultivation was estimated with a Field Scout TDR 300 Soil Moisture Meter with probes 3.8 cm long (Spectrum Technologies, Aurora, IL). Three readings were taken per plot and their arithmetic mean recorded as the percent volumetric water content (VWC) for that plot.

To characterize the size of carrots and weeds at the time of cultivation, approximately 10 seedlings of carrot, ambient monocot, ambient dicot, surrogate millet, and surrogate mustard were collected from each replication, for a total of approximately 40 seedlings of each species. Plants were gently pried out of the soil to collect the shoot and as much of the root as possible. These specimens were placed in plastic bags to retain moisture and digitally scanned using WinSEEDLE software and total plant area was recorded (Regent Instruments Inc., Québec, Canada). The approximate leaf number and height of each species was also recorded (Table 2.5).

Table 2.5: Size (total area, mm^2) of crop and both ambient and surrogate weeds, and their ratio (e.g. carrot/millet).

	Trial A	Trial B	Trial C
Average Leaf number			
Carrot	3.0	2.0	1.5
Millet	1.0	NA	1.8
Mustard	cotyledon	cotyledon	cotyledon
Ambient grass[1]	3.0	3.0	4.0
Ambient CHEAL[2]	4.0	5.0	3.5
Scan area (mm^2)			
Carrot	633	368	306
Millet	55	NA	72
Mustard	145	115	200
Ambient grass	148	141	150
Ambient CHEAL	NA	NA	236
Relative area			
Carrot/Millet	11.6	NA	4.2
Carrot/Mustard	4.4	3.2	1.5
Millet/Mustard	0.4	NA	0.4
Carrot/Ambient grass	4.3	2.6	2.0
Carrot/Ambient CHEAL	NA	NA	1.3

[1] Ambiant grasses, mostly Large crabgrass (*Digitaria sanguinalis*)
[2] CHEAL = Common lambsquarters (*Chenopodium album*)

Yield and quality

Carrots were harvested by hand approximately two months after planting in order to assess any treatment effect on yield or quality. The number of quadrats harvested varied with each trial (Table 2.8 footnotes). In trials B and C marketable and unmarketable carrots were separated, counted and weighed by category. Unmarketable carrots included those that were too small (< 2 cm diameter), forked, stubbed, or diseased (USDA 1997). Size was always the most common defect in each plot. Tops were removed from both marketable and unmarketable carrots and their fresh root weights were recorded. In trial A the same procedure was followed as above, except that carrot quality was graded by visually identifying the most common defect in each plot and unmarketable carrots were not weighed by type of defect.

Calculating survival and selectivity indices

The percentage of weeds and carrots surviving each cultivation event was estimated by comparing densities before and after cultivation. In trials A and C weed densities at 5 DAC were used to calculate survival. We preferred to use the weed densities taken at 5 DAC because at 1 DAC not all surviving seedlings were visible at due to burial, from which some seedlings subsequently emerged. In addition, it was thought that 5 DAC was a more accurate reflection of the final tool effect, as more time would allow damaged weeds to either die or recover from the cultivation treatment. However in trial B, because of sub-optimal timing of surrogate weed planting and uneven emergence, there were many un-germinated weeds at the time of treatment application, and as a result many surrogate weeds germinated after treatments were applied. Thus weed densities at 5 DAC were far higher than the pre-counts, so counts at 1 DAC were thought to better represent treatment effects, and these earlier counts were used for trial B. This choice could mean that in trial B some weeds were buried at the time weed densities were recorded (1 DAC) and thus not counted, but later recovered (Mohler et al. 2016). This would inflate selectivity in trial B compared to trials A and C.

Survival percentages based on actual field counts were normalized by dividing the observed survival percentage by the survival percentage of the control treatment for that trial and multiplying by 100.

To help interpret the practical impact of tools on selectivity, we defined selectivity indices (SI) for a given combination of the different plant species according to these equations:

(1) SIcg = (survival % of carrot crop)/(survival % of the millet)

(2) SIcb = (survival % of carrot crop)/(survival % of the mustard)

(3) SIgb = (survival % of millet)/(survival % of mustard)

A value of 1 implies that the tool was non-selective for the particular indices, whereas a value of greater than 1 implies that the tool was more effective at killing the plant in the denominator of the equation. To avoid undefined selectivity indices in cases where crop survival was zero, we added 1 individual of the denominator species to the observed post-counts from which survival percentage was calculated. Selectivity indices were computed using normalized survival percentages.

This definition of selectivity is conceptually very similar to the selectivity index defined by Rasmussen (1990)—who defined selectivity as the ratio of weed injury compared to crop injury—but differs slightly in interpretation. In both cases, when a crop and weed are considered, a higher selectivity index is desirable. However, in the Rasmussen definition, the selectivity index is undefined when the level of crop injury is zero, and becomes a very large number as crop injury approaches zero. The selectivity indices used in our study have the advantage that they are less sensitive to small changes in crop mortality when crop mortality is close to zero (as is often the case). They suffer from the same problem when weed survival is close to zero, but this is a less common occurrence in most cases.

Statistical analysis

The tool effects were analyzed using PROC GLIMMIX procedures in the Statistical Analysis System 9.4 with tool specified as a fixed effect and replication as a random effect (SAS Institute Inc. 2002-20012. Cary, NC). Because trial by tool interactions were significant for most response variables, each trial was analyzed separately, except where noted below. Mean value of all three trials are also presented for reference, although no mean separation was conducted for these means due to significant tool*trial interactions.

Where needed to improve assumptions of normality and equal variance, the data were transformed. All data presented has been back-transformed to the observable scale. In the case of carrot survival in Trials A and C and average soil hilling in trial B, no suitable transformations were found (accounting for normality and heterogeneity assumptions), so data were analyzed to account for heterogeneous structure by using the Glimmix Procedure in SAS (i.e., Gaussian data with heterogeneity) for a linear mixed model with unequal variances (Wolfinger 1996; Milliken & Johnson 2009). Treatment means separation occurred using Fisher's Protected LSD at α=0.05.

Linear regression analysis was conducted using the PROC REG procedure to evaluate the relationship between carrot density and yield, normalized crop and weed survival and soil movement (Littell et al. 2006). For carrot density and yield trials were analyzed separately, whereas for survival and soil hilling all three trials (A, B & C) were combined together to test the overall relationship (across trials).

Results and Discussion

Survival and selectivity of single tools, results Tables 2.6 & 2.7

Significant differences in crop and weed survival were observed between the single tools in all 3 trials (Table 2.6). Significant differences were also observed in the crop:weed selectivity indices (SIcg and SIcb) in most cases (Table 2.7). However, in no trial were there any detectable differences in grass vs broadleaf selectivity (SIgb) for the single tools (Table 2.6). In other words, while single tools varied in *efficacy* between carrots and weed species, there were few meaningful differences in *selectivity* between weed species.

The flextine harrow reduced millet, mustard and carrot survival only in trial B (Table 2.5), and the selectivity indices associated with flextine were never different from the control (Table 2.6); this tool was the least effective and least selective.

The finger weeder reduced grass survival in all three trials and mustard survival in two trials, while only reducing carrot survival in one trial (Table 2.5). Overall, carrot survival ranged from 74-97% whereas weed survival ranged from 12-91% (Table 2.6). Crop:weed selectivity of the finger weeder ranged from 1.1 to 1.7 but was significantly different from the control only once and was always similar to the flextine (Table 2.7); though effective in killing weeds, the finger weeder was not particularly selective.

The torsion weeder reduced survival of both grass and mustard surrogate weeds in all three trials, but also reduced survival of carrots in two trials (Table 2.6). Plant survival ranged from 20-49% for millet, from 29-70% for mustard and from 46-82% for carrots. In other words, the torsion weeder was not very selective; the crop:weed selectivity indices of the torsion weeder in the trials were generally low, with values ranging from 1.2 to 2.2, and did not differ markedly from the flextine harrow or finger weeder (Table 2.7).

The hilling discs reduced both grass and mustard survival in two trials. They significantly reduced carrot survival in only one trial, with carrot survival ranging from 66-87%. Survival of weeds following the hilling discs ranged from 8-86%. The selectivity of the hilling discs differed from the control in two trials, ranging from 1 to 25.2. Generally the crop:weed selectivity indices of the hilling discs did not vary markedly from the other single tools, except for its SIcg in trial B, where one of the highest selectivity indices of the entire project was observed. Overall the hilling discs were much more selective for grass than the other single tools and slightly more selective for mustard.

Table 2.6: Effect of tool on survival percentage of surrogate weeds and carrots. Data is normalized by plant species, showing survival percentage as percent of control treatment (None). Where different letters indicate significant differences between treatments at α=0.05.

	Carrots			Millet			Mustard			Average across trials A,B,C					
Treatment	Trial A[1]	Trial B	Trial C[1]	Trial A	Trial B	Trial C	Trial A	Trial B	Trial C	Carrot	sd	Millet	sd	Mustard	sd
	%									%					
None	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100	1	101	5	100	4
Flextine	94 ab	76 bc	79 ab	90 a	26 bc	87 a	74 ab	56 b	87 ab	83	3	68	11	72	6
Finger weeder	97 ab	82 b	74 ab	67 b	12 bc	48 bc	91 a	48 b	61 cd	84	4	43	7	67	6
Torsion	46 b	70 bc	83 a	20 cd	39 b	49 bc	29 cd	45 b	70 bc	66	7	36	8	48	7
Hilling discs	83 ab	66 c	87 a	33 c	8 c	52 ab	48 bc	17 c	86 ab	79	4	31	8	50	10
Finger + Hilling discs	61 b	66 c	59 b	9 d	4 c	3 d	9 c	32 bc	42 d	62	4	5	1	28	9
Finger + Flextine	78 ab	69 bc	62 b	53 b	30 bc	22 cd	46 c	50 b	45 d	68	4	35	6	47	3
Torsion + Finger + Flextine	63 b	74 bc	70 ab	24 cd	26 bc	26 bcd	29 cd	46 b	59 cd	69	4	26	4	44	5
Signficance (P-value)	0.0153	<.0001	0.0061	0.0014	<.0001	0.0001	0.0061	<.0001	<0.001						

[1] Run as unequal variance with residual as the random effect

Table 2.7: Effect of tool on selectivity, defined as % crop survival divided by % weed survival. Where different letters indicate significant differences between treatments at α=0.05.

	Trial A			Trial B			Trial C			Average across A,B,C			
Treatment	Sicg[1]	SIcb[2]	SIgb[3]	SIcg	SIcb	SIgb	SIcg	SIcb	SIgb	SIcg	sd	Sicb	sd
None	1.0 d	1.0 d	1.0	1.1	1.0 a	1.1	1.0 b	1.0 ab	1.0 a	1.0	0.1	1.0	0.0
Flextine	1.0 cd	1.2 cd	1.2	3.1	1.3 abc	0.5	1.1 b	0.9 a	1.0 a	1.7	0.3	1.1	0.1
Finger weeder	1.4 cbd	1.1 d	0.7	6.8	1.7 bcd	0.3	1.6 b	1.2 abc	0.8 ab	3.3	0.8	1.3	0.2
Torsion	2.2 bc	1.7 bcd	1.3	4.0	1.5 abc	1.2	1.7 b	1.2 abc	0.7 ab	2.7	0.8	1.5	0.2
Hilling discs	2.9 b	1.9 bc	0.9	25.2	3.9 d	1.2	3.9 b	1.0 ab	0.6 ab	10.7	3.8	2.3	0.7
Finger + Hilling discs	6.4 a	6.5 a	1.3	14.9	2.4 cd	0.4	30.0 a	1.4 c	0.1 c	17.1	5.3	3.4	1.1
Finger + Flextine	1.3 cbd	1.4 bcd	1.1	2.4	1.3 ab	0.6	6.1 b	1.3 bc	0.5 bc	3.2	1.3	1.3	0.1
Torsion + Finger + Flextine	2.7 b	2.2 b	0.9	3.9	1.6 bc	0.7	4.5 b	1.2 abc	0.4 bc	3.7	0.8	1.6	0.2
Significance (P-value)	0.0007	<.0001	0.91	0.2228	0.0068	0.4191	0.0142	0.1025	0.0058				

[1] SIab = normalized survival % of plant species a / normalized survival % of plant species b;
plant species include carrots (c); millet, a surrogate grass weed (g); and mustard, a surrogate
2 Selectivty of Millet = Carrot normalized survival % / Millet normalized survival %
[3] Selectivty of Mustard = Carrot normalized survival % / Mustard normalized survival %
[4] Selectivity of G/M = Millet normalized survival % / Mustard normalized survival %

Survival and selectivity of single tools, discussion

Of the single tools, the finger weeder appeared to exhibit the best balance of low crop damage with high weed mortality, as it affected crop survival in only one trial while reducing millet in all trials and mustard in two of three trials (Table 2.6). The hilling discs were second best in this regard, lowering crop survival in just one trial and significantly reducing millet and mustard in two trials respectively. However, when taking selectivity into account, the hilling discs appeared to perform better than the finger weeder, achieving a selectivity significantly different than the control twice for mustard and once for millet, whereas the finger showed a selectivity significantly different than the control only once.

Although the finger weeder achieved reductions in weed density in five instances and the hilling discs achieved reduction in only four, the hilling discs reduced weed densities to a greater degree than the finger weeder in three trials (Table 2.6). In judging the single tools by their effect on survival of carrots and weeds and their selectivity, the hilling discs and finger weeder appear to be the most appropriate choice for growers based on our data, where the hilling discs allow greater selectivity but the finger weeder inflicts less crop death.

Although the torsion weeder reduced both species of weeds in all three trials, it also reduced carrots in one trial and rarely achieved a significant selectivity index (Table 2.7). Additionally, the torsion weeder required the most time to adjust of all tools – so that it would need to perform better than the other tools to justify the time needed to calibrate it. The flextine harrow used alone does not appear to be an appropriate tool for early in-row carrot weeding, except perhaps for those growers who value minimal stand reduction above weed death, which, for reasons discussed in the yield section, may not be a concern of chief importance in carrots.

Neither the finger weeder, flextine harrow, nor the hilling discs were observed to significantly reduce carrot survival or final carrot density in two of three trials; this suggests that it is possible to apply some single in-row tools to carrots when they have just one true-leaf without significantly reducing survival percentage or final carrot density.

Survival and selectivity of combined tools, results Tables 2.6 & 2.7

In every trial the combined tools reduced carrot survival to comparable levels. Their effect on weeds was also similar, as significant differences in weed survival occurred only once between the combined tools (Table 2.6). However, some significant differences between combined tools were detected in their crop:weed selectivity indices (SIcg and SIcb) (Table 2.7).

The F+HD combination reduced both weed and carrot survival in every trial (Table 2.6). Survival of weeds following this combination ranged from 3-9% for millet, from 9-42% for mustard, and from 59-66% for carrots. In trials A and C, the F+HD showed a greater grass selectivity than all other tools, with SIcg indices of 6.7 and 37.5 respectively. Additionally, in trial A, the F+HD combination exhibited a significantly higher selectivity index for mustard compared to all other tools. The F+HD achieved the highest observed selectivity index of any trial: an SIgc of 30 in trial C. In the one trial where significant differences were observed in millet:mustard selectivity, the F+HD had an extremely low index of 0.1, meaning that it was much more selective for mustard over millet (Table 2.7).

The F+X treatment reduced weed survival in all three trials and carrot survival in two trials (Tables 2.6). Weed survival ranged from 22-53% and carrot survival from 62-74%. Selectivity of the F+X was never significant for millet (SIcg) or mustard (SIcb). In one trial it had a millet:mustard selectivity index of 0.5 (SIgb), meaning that it was twice as selective for mustard over millet (Table 2.7).

The T+F+X combination reduced weeds in every trial, with weed survival ranging from 24-59%. The T+F+X also reduced carrots in two trials, with carrot survival ranging from 63-74% (Table 2.6). This tool combination showed selectivity for millet or mustard in three of the five instances where significant differences were detected. In trial C, it was selective for mustard over millet, exhibiting a millet:mustard selectivity index of 0.4 (Table 2.7).

Survival and selectivity of combined tools, discussion

In several cases combining (stacking) two tools improved efficacy and selectivity compared to either tool alone (Tables 2.6 & 2.7). Most striking in this regard was the F+HD combination, which improved millet and mustard selectivity compared to either the F or HD individually in trials A and C. While in trial B it had similar mustard selectivity (SIcb) to the F and HD individually (Table 2.7). This F+HD combination was particularly effective at suppressing millet, while doing less damage to carrots and mustard, especially in trial C.

In contrast, the F+X combination did not result in any significant millet or mustard selectivity compared to either the F or X individually. Adding the torsion weeder for a three-tool combination (F+T+X) caused no observed improvement in millet or mustard selectivity compared to the F+X. Nor did the F+T+X tool combination generally provide greater selectivity compared to each of the tools used alone. Neither the F+X or F+T+X treatments ever had selectivity indices significantly different from each other (Table 2.7). It appears that adding the torsion weeder to the F+X combination did not improve performance and would suggest that whereas Brown (2017) and Gallandt et al. (2017) demonstrated synergies in *efficacy* (weed killing) by combining tools, there may be no such synergy reflected in *selectivity*.

Of the combined tools, the F+HD combination clearly had the greatest selectivity, while reducing carrots to similar levels as the other combined tools. For this reason the F+HD would appear to be a promising choice for carrot growers with similar soil conditions and carrot and weed growth stages. However, this treatment did reduce carrot survival in all trials by about 35%; too great of a stand reduction for growers to tolerate. If the F+HD could be calibrated so that carrot survival were at levels similar to either the HD or F individually, while maintaining its high selectivity, this tool could offer helpful in-row weed control to carrot growers. Seeding carrots at a greater density could further improve the performance of the F+HD combination; this is discussed further in the Yield and Quality section below.

In trial C, the only trial where significant differences were observed, the millet:mustard selectivity (SIgb) for every combined-tool treatment showed the tools selecting for mustard over millet. Why do the combined in-row tools appear to be more selective for mustard?

The most likely explanation is the mustard plants were larger than the millet at the time of cultivation and thus the larger plants showed greater resistance to the tools. Indeed, available data demonstrates that at the time of cultivation mustard was 2-3 times larger than millet (Table 2.5). It is also possible that the density of the surrogate weeds differed by species and that species having a greater density better resisted the tools, exhibiting greater survival. However surrogate weed densities at the time of cultivation were not consistently greater for one species relative to the other: In trial A millet was roughly twice as dense as mustard, in trial B mustard was roughly twice as dense as millet, and in trial C the densities were roughly equal (data not shown).

Another possible reason that the tools generally selected for millet over mustard could be that millet is more susceptible to a certain mode of action, like burial, uprooting, or both. But, in their fastidious research, Mohler et al. (2016) found no differences in recovery from burial between grasses versus broadleaves, which included barnyardgrass (*Echinochloa crus-galli*), giant foxtail (*Setaria faberi*) and common lambsquarters (*Chenopodium album*).

Selectivity discussion

Selectivity is based in part on physical differences between the crop and weed, either in height or rooting strength. And, "conditions for physical weed control are normally favorable where crop plants are larger than the weed plants" (Van Der Weide et al. 2008).

The ratio between both carrot and surrogate weeds and carrot and ambient weeds decreased with each successive trial, meaning that - other factors remaining equal - the theoretical selective potential (Kurstjens et al. 2002; Kurstjens 2000) of the tools likewise decreased, and was the greatest in trial A (Table 2.5). However, this is not generally what was observed: in trial A, the selectivity for millet (SIcg) was generally lower for most tools than it was in trials B and C, even though the carrot:weed size differential was greatest for millet in trial A (Tables 2.5 & 2.7). Instead, the greatest tool selectivity indices were observed in trials B and C, which had a lower crop:weed size differential. This suggests that while theoretical selective ability based on a crop-weed size differential is important, other factors such as operator ability in calibrating the tool and soil conditions (e.g. moisture and soil surface texture) are also important factors affecting the selectivity actually achieved.

Hand-weeding time Table 2.8

There were clear tool effects on the time required for hand-weeding where weeding time was evaluated (trials A and C) (Table 2.8). In both trials no significant differences were detected between the flextine harrow and the control, and in trial A no significant reductions in hand-weeding were detected for the finger weeder or the F+X. In trial C no significant reductions were detected for the hilling discs.

In trial C the finger weeder reduced hand-weeding time by 226 hr/ha. The torsion weeder reduced hand-weeding time by 921 hrs/ha in trial A and 172 hrs/ha in trial C. The hilling discs reduced hand-weeding time in trial A by 242 hrs/ha.

These results are consistent with other findings, where the Buddingh finger weed, Bezzerides torsion weeder and flextine harrow roughly halved the amount of hand-weeding (Ascard & Bellinder 1996). Other work demonstrated reduced hand-weeding by 40-70% using the European finger and torsion weeders (Van Der Weide et al. 2008).

Assuming labor of $15/hr, the F+HD would have saved $4,600-$5,100 dollars per hectare in hand-weeding costs compared to the control, while the torsion weeder would save from $2500-$4300 per hectare.

Although weeding times and costs were reduced in several cases, this often came at the expense of carrot mortality. For example, the F+HD combination showed substantial savings in hand-weeding time, but reduced carrot survival by approximately 40% in both trials A and C. Therefore, the net economic impact of these tools depends on the value of labor savings compared to the costs of lower yields or higher carrot seeding rates.

Table 2.8: Effect of tool on subsequent hand-weeding time. Where different letters indicate significant differences between treatments at α=0.05.

Treatment	Hand-weeding time (hours/ha) Trial A	Hand-weeding time (hours/ha) Trial C	Time saved (hr/ha) Trial A	Time saved (hr/ha) Trial C	$/ha saved[1] Trial A	$/ha saved[1] Trial C
None	440 a	538 a	0	0	$0	$0
Flextine	323 abc	433 abc	117	105	$1,754	$1,571
Finger weeder	351 ab	312 cde	89	226	$1,336	$3,388
Torsion	150 d	366 bcd	291	172	$4,360	$2,580
Hilling discs	198 dc	470 ab	242	67	$3,631	$1,006
Finger + Hilling Discs	131 d	194 e	309	343	$4,634	$5,150
Finger + Flextine	325 abc	291 de	115	247	$1,726	$3,704
Finger + Torsion + Flextine	268 bcd	319 cde	173	218	$2,589	$3,277
Signficance (P-value)	0.0029	0.0004				

[1] Cost of labor at $15/hr

Table 2.9: Carrot root yield, percent culls, final carrot density and average carrot weight. Where different letters indicate significant differences between treatments at α=0.05.

	Trial A[2]				Trial B[3]				Trial C[4]			
Treatment	Total Yield	Percent Culls[1]	Final Density	Ave. carrot Weight	Total Yield	Percent Culls[1]	Final Density	Ave. carrot Weight	Total Yield	Percent Culls[1]	Final Density	Ave. carrot Weight
	kg/m	--%--	#/m	--g--	kg/m	--%--	#/m	--g--	kg/m	--%--	#/m	--g--
None	1.2	20	32 a	38	1.3	20	39	34	1.5	62 ab	55 a	28
Flextine	1.0	14	28 ab	39	1.3	16	39	34	1.7	58 ab	54 a	32
Finger weeder	1.0	19	32 a	33	1.2	23	33	38	1.6	51 abcd	52 ab	31
Torsion	0.7	41	21 c	32	1.1	23	22	38	1.7	56 abcd	53 ab	34
Hilling discs	1.2	20	30 a	42	1.3	16	35	39	1.9	38 d	51 abc	39
Finger + Hilling discs	1.0	19	21 bc	49	1.1	20	32	33	1.3	47 bcd	40 d	35
Finger + Flextine	0.8	22	23 bc	39	0.9	22	24	38	1.2	65 a	44 bcd	29
Torsion + Finger + Flextine	0.8	17	21 bc	40	1.1	26	32	34	1.6	41 dc	42 dc	40
Signficance (P-value)	0.286	0.570	0.002	0.620	0.532	0.620	0.420	0.472	0.110	0.030	0.020	0.124

[1] As measured by weight. Carrots were culled for being forked, stubby, diseased, or small.

[2] 4 quadrats per plot were harvested

[3] 3 quadrats per plot were harvested

[4] 6 quadrats per plot were harvested

Table 2.10: Slope, intercept and significance of linear regression of carrot density at time of harvest (#/m) vs yield (kg/m). The predicted percent yield reduction in response to a 10% reduction in carrot density is also provided for reference.

	Slope	Intercept	P-value	R^2	Predicted % yield reduction at 10% stand reduction[1]
Trial A	0.0202	0.0444	<.0001	0.483	9.05
Trial B	0.0167	0.1394	<.0001	0.551	7.74
Trial C	0.0122	0.4310	0.007	0.219	5.20

[1] Calculated using the average pre-treatment carrot density (#/m) of each trial and the slope and intercept of the regression line.

Yield and quality Tables 2.9 & 2.10

Few significant differences were detected in carrot yield or quality. No significant differences in yield were detected in any trial (Table 2.9). Neither were significant differences observed in the type of root defects between tools (not shown). In trials A and B no significant differences were observed in the percentage of culls, but in trial C, the hilling discs and the T+F+X resulted in fewer culls than the control (Table 2.9).

It is striking that differences in yield between tools were not detected given that carrot survival ranged from 46-100% across treatments (Table 2.6). These differences in carrot survival persisted to harvest time, as reflected in the differences between carrot density at harvest observed in two of three trials (Table 2.9).

Although no tool effects on yield were detected, a strong positive relationship between carrot density and yield was observed in trials A and B, and a positive correlation was detected in trial C (Table 2.10); it appears that generally carrot density, for which significant differences were detected by tool, is related to yield. For example, a reduction in carrot density of 10% was associated with a decline in carrot yield of 9% in trial A, 8% in trial B, and 5% in Trial C (Table 2.10).

The differences in carrot density and the strong relationship of density to yield, suggest differences in yield between tools, especially in trials A and B. Such differences were likely not detected in the yield data due to high variability in the yield response, and hence low power to detect differences. Another possible explanation for the lack of detected yield response despite lower carrot density, especially in Trial C, is that individual carrots compensated by growing bigger. However, no differences in the average weight per carrot were detected in any trial (Table 2.9).

Others have found that for root crops a reduction in crop density up to roughly 10% did not result in yield loss (Ascard et al. 2000; Bleeker et al. 2002; Peruzzi et al. 2007). In two experiments Peruzzi et al. (2007) used a precision hoe with torsion weeders on carrots (unfortunately the growth stage at which tools were applied to carrots was not noted), they found that in-row cultivation did not lower yields in any years, but in two of four years carrots receiving in-row cultivation had a higher density of carrot plants and a higher root yield. Carrot physiology may favor applying in-row tools early, as Esau (1940) showed that the secondary cambium layer, which produces the storage tissue, is not present until carrots have two true-leaves. This suggests that applying in-row tools before the development of those root structures responsible for carrot root bulking could reduce yield-limiting damage to the plant.

For fresh market carrots the number of carrots as well as their size is important, as any reduction in the number of carrots from their optimal density could affect the number of marketable carrots. However, in cases where initial carrot density is higher than optimal, these in-row tools could be used to both kill weeds and thin the carrots, thereby improving marketable yield. Therefore, to fully understand the impact of these tools, a better understanding of optimal seeding densities is required. This information, coupled with grower knowledge of the level of thinning each tool can accomplish, should facilitate optimal final densities and yields.

Also, denser crop stands are generally more effective in competing with weeds (Weiner et al. 2001) (although to our knowledge this has not been demonstrated specifically in carrots). For these reasons, it may make sense for growers using these in-row tools, after some experience, to over-seed their carrot stand, resulting in better weed competition during the crucial early period where carrots are too small to apply in-row tools. Then later the application of an in-row tool could perform both weed control and carrot thinning. In addition to improving early carrot competition with weeds, over-seeding would allow the tools to be set more aggressively, likely improving selectivity.

Table 2.11: Showing the effect of tool on vertical soil movement in the row (hilling). Where different letters indicate significant differences between treatments at α=0.05.

	Average hilling		
Treatment	Trial A	Trial B[1]	Trial C
	----------------cm----------------		
None	0.0 d	0.0 c	0.0 d
Flextine	0.7 cd	0.9 b	0.6 cd
Finger weeder	0.5 cd	2.0 a	0.6 cd
Torsion	1.6 bc	1.1 ab	0.5 cd
Hilling discs	2.1 b	1.8 ab	1.0 bc
Finger + Hilling discs	3.6 a	1.8 ab	2.4 a
Finger + Flextine	1.4 bc	1.5 ab	1.5 b
Torsion + Finger + Flextine	1.7 bc	1.8 ab	0.9 bc
Signficance (P-value)	0.0001	0.0013	0.0001

[1]Run as unequal variance with residual as the random effect

Table 2.12: Slope, intercept and significance of the linear regression of hilling (cm) vs normalized weed and crop survival percentage.

	Mustard Survival by Soil Movement				Millet Survival by Soil Movement				Carrot Survival by Soil Movement			
Treatment	Slope	Intercept	P-value	R^2	Slope	Intercept	P-value	R^2	Slope	Intercept	P-value	R^2
None	0	100	NA	NA	0	100	NA	NA	0	100	NA	NA
Flextine	-2.244	74.00	0.845	0.1521	-26.04	86.64	0.210	0.1521	2.722	80.99	0.655	0.1521
Finger weeder	-15.82	83.20	0.037	0.5654	-22.88	66.25	0.005	0.5654	-1.715	86.01	0.717	0.5654
Torsion	-8.299	56.92	0.467	0.0893	-11.40	48.29	0.345	0.0893	-6.397	72.95	0.573	0.0893
Hilling discs	-20.79	84.22	0.043	0.0839	-8.09	44.21	0.361	0.0839	-0.7480	80.50	0.872	0.0839
Finger + Hilling discs	-10.41	54.39	0.228	0.0332	0.68	3.49	0.571	0.0332	-4.559	73.57	0.234	0.0332
Finger + Flextine	-3.455	52.04	0.733	0.0658	-19.28	62.93	0.421	0.0658	2.676	63.84	0.855	0.0658
Torsion + Finger + Flextine	-10.38	59.61	0.200	0.2238	-8.56	38.29	0.120	0.2238	-3.208	73.74	0.616	0.2238

Table 2.13: Slope, intercept and significance of the linear regression of soil moisture (VWC) vs normalized crop and weed survival percentage.

	Mustard Survival by Moisture				Millet Survival by Moisture				Carrot Survival by Moisture			
Treatment	Slope	Intercept	P-value	R^2	Slope	Intercept	P-value	R^2	Slope	Intercept	P-value	R^2
None	0.163	98.535	0.911	0.001	1.949	83.143	0.355	0.086	0.375	96.652	0.229	0.141
Flextine	-1.099	81.772	0.683	0.017	-6.580	124.232	0.175	0.176	-3.116	109.457	0.011	0.494
Finger weeder	-3.974	103.442	0.009	0.507	-5.239	90.853	0.002	0.652	-2.207	104.554	0.010	0.499
Torsion	5.432	-2.097	0.070	0.291	5.428	-13.930	0.095	0.254	4.786	21.905	0.114	0.231
Hilling Discs	-2.618	74.214	0.435	0.062	-2.048	49.745	0.442	0.060	-1.705	94.886	0.200	0.159
Finger + Hilling Discs	6.003	-24.870	0.041	0.354	-0.691	11.275	0.090	0.261	-0.239	64.003	0.869	0.003
Finger + Flextine	0.809	39.851	0.451	0.058	-5.304	82.551	0.020	0.433	-2.210	88.108	0.176	0.194
Torsion + Finger + Flextine	3.855	6.509	0.014	0.467	0.965	16.305	0.440	0.061	1.187	57.376	0.385	0.076

Hilling Tables 2.11

Significant differences in the vertical in-row movement of soil (hilling) were observed between tools in all three trials. The hilling discs moved the most soil in two of three trials, as did the torsion weeder. The finger weeder and flextine harrow did not move a significant amount of soil in two of three trials. In contrast, every combined tool hilled a significant amount of soil in each trial (Table 2.11).

Even without significant vertical hilling in trial B, the flextine harrow reduced millet survival to 26% and mustard survival to 56%, suggesting that its primary mode of action was not through burial (Tables 2.6 & 2.11). These results correspond with those of Kurstjens et al. (2000) who found in laboratory experiments that flextine harrowing uprooted up to 21% of seedlings and suggested that uprooting may play a larger role in flextine efficacy than previously thought.

In two of three trials the finger weeder did not move a significant amount of soil into the row. However in trial B, when the finger weeder did move soil into the row, it had a millet selectivity index (SIcg) of 6.8, is highest in all trials (Tables 2.7 & 2.12). The finger weeder also achieved its lowest weed survival of both species in trial B (Table 2.6). This could suggest that the finger weeder is more effective in killing weeds by burial than by uprooting, in which case this tool may be most effective when set to the greatest allowable working depth, so as to move more soil into the crop row. However, the physical forces involved when a tool moves through the soil are myriad (Duerinckx 2005) and it is possible that the finger weeder lifted up soil in the row rather than moving outside soil into the row, and that this uplifted in-row soil was then recorded as a change of in-row soil level.

The F+HD combination generally moved the most soil of all treatments (Table 2.11). This combination also had the greatest selectivity indices across trials (Table 2.7). Is burial the most selective mode of action?

Hilling regression Table 2.12

Hilling had a significant effect on surrogate weed survival for some tools. The finger weeder showed a highly significant negative relationship between hilling and survival in mustard, where a 1 cm increase of vertical soil movement decreased mustard survival by 16% (Table 2.12). The finger weeder also showed a highly significant negative relationship in millet, where a 1 cm increase of vertical soil movement was associated with a 23% decrease in mustard survival (Table 2.12). This clear and significant negative relationship between hilling and weed survival for both species suggests that burial is a primary mode of action by which the finger weeder kills weeds. Although, other modes of action may also be responsible and even interact with burial; for example, it could be that as the tool passes, weeds are initially uprooted and then buried. A detailed analysis of slow-motion video footage, following individual weeds as the tool passes, could help determine the interaction of the modes of action for the finger weeder. Similarly, soil-bin experiments where the movement of individual plants are tracked as a tool passes, such as the work performed by Kurtjens and Perdok, could also be helpful in this regard (Kurstjens et al. 2000).

In contrast to the finger weeder, no relationship was observed between hilling and weed death for the torsion weeder. That greater hilling did not increase weed death suggests that the torsion weeder does not to kill weeds through burial. Instead, the opinion of manufacturers and farmers that the torsion weeder kills weeds through uprooting appears likely (Hitchcock Tilton 2017).

The hilling discs exhibited a significant negative relationship between hilling and mustard survival, where a 1 cm increase in hilling was associated with a decrease in mustard survival of 21%. However no significant relationship was observed for the hilling discs in millet (Table 2.12). These results are in contrast to others who have found no difference in the recovery from burial of grasses versus broadleaf weeds (Mohler et al. 2016).

Although the finger weeder and hilling discs individually each exhibited a significant relationship between hilling and weed survival, such a relationship was not observed for the F+HD combination. This was surprising, and suggests that the F+D combination may not be killing weeds through burial, even though it appears that separately both the finger weeder and hilling discs do kill weeds through burial.

Soil moisture regression Table 2.13

The impact of soil moisture on the survival of weeds and carrots varied by tool (Table 2.1). For the finger weeder, greater soil moisture was associated with lower survival of both surrogate weeds and carrot: in both mustard and millet a 1% increase in VWC was associated with approximately a 5% decrease in weed survival percentage. Greater soil moisture also reduced survival of carrots in response to finger weeding, but the slope of this response was smaller, suggesting that more moist conditions would slightly improve selectivity. In contrast, Mohler et al. (2016) found that the ability of several weed species to survive following burial tended to increase with greater soil moisture. Perhaps there is a distinction between uprooting a weed versus breaking the capillarity of the soil around it.

Highly significant relationships between soil moisture and efficacy were also observed for the flextine harrow in carrots; a 1% increase in VWC was associated with a 3% *increase* in carrot survival percentage. The F+HD also exhibited a positive relationship between soil moisture and mustard survival, as did the T+F+X (Table 2.13). In contrast to the finger weeder, a positive relationship between soil moisture and weed survival was observed for the torsion weeder in both mustard and millet (though with marginal significance; mustard p-value 0.070, millet p-value 0.095): For both surrogate weeds a 1% increase in VWC was associated with a 5% increase in weed survival percentage (Table 2.13).

In order to better understand the contrasting effects of moisture on efficacy of finger weeders and torsion weeders, we ran a regression of soil moisture and height of hilling. The torsion weeder exhibited a negative relationship between soil moisture and hilling height (slope = -0.2; p-value=0.0435, r^2=0.3481) and the finger weeder showed a positive relationship (slope = +0.1; p-value=0.0878, r^2=0.2636). In other words, the relationship between soil moisture and hilling action varied with these two tools: for the finger weeder a 1% increase in soil moisture (VWC) was associated with a 0.1 cm *increase* in hilling height, whereas for the torsion weeder a 1% increase in soil moisture (VWC) was associated with a 0.2 cm *decrease* in hilling height (data not shown).

These regression analyses demonstrate consistent differences between the finger and torsion weeders: The finger weeder killed weeds by hilling whereas the torsion weeder did not (Table 2.12); the finger weeder killed more weeds under more moist soil conditions whereas the torsion weeder killed more weeds under drier soil conditions (Table 2.13); the finger weeder hilled more under more moist soil conditions whereas the torsion weeder hilled more weeds under drier soil conditions (data not shown). These result suggest that under our soil conditions and tool settings a farmer might choose to use either the finger weeder or torsion weeder based on soil moisture conditions and whether hilling is desired. The exact mechanism by which soil moisture impacts tool efficacy remains unclear. For the finger weeder it appears that greater soil moisture results in greater hilling and hence greater weed mortality by burial. In contrast, for the torsion weeder, drier soils result in more hilling which may increase weed mortality by burial. However, since the torsion weeder does not appear to kill weeds primarily by burial, the relationship between dry soil and torsion efficacy may be due to greater desiccation of weeds following uprooting.

Summary and Conclusions

We had hypothesized that tools used alone would vary in their selectivity for grass versus broadleaf weeds and for weeds versus carrots. We found little support that single tools vary in their selectivity for grass versus broadleaf weed (SIgb). We also found little support that single in-row tools vary in their selectivity for weeds versus carrots (SIcg & SIcb), with the notable exception of the hilling discs, which showed some marked selectivity.

We had hypothesized that combinations of tools would improve efficacy and selectivity. Both the T+F+X and F+HD showed some improvements in efficacy and selectivity. The F+HD showed the greatest improvements in efficacy and selectivity over the single tools. These results suggest that tools encompassing greater modes of action are more effective and selective.

We hypothesized that individual tools and tool combinations would vary in their impact on carrot quality and yield. There was no evidence suggesting that any in-row tool caused a decline in carrot quality compared with the control. We did not observe significant differences in yield, however significant differences in carrot density were observed. Due to the significant relationship between yield and carrot density we conclude that these tools do affect yield to the degree that they reduce carrot survival. We found evidence that carrot mortality of 10% reduced yield by between 5-9%.

We hypothesized that tool combinations which pull away soil from the crop row and then subsequently hill it up will be the most effective and selective. We found that the evidence supported this hypothesis. The F+HD combination generally showed the greatest efficacy and selectivity of all the tools. However this combination also reduced carrot survival and final stand to degrees unacceptable to commercial growers. For this tool combination to be successfully applied it must be calibrated so as not to reduce carrot density to such a drastic degree while maintaining selectivity. Coupling this tool with higher planting densities could also improve tool performance.

In our study both greater soil moisture and greater hilling into the row was associated with increased efficacy of the finger weeder in both millet and mustard weeds. This suggest that hilling is a significant mode of action through which the finger weeder kills weeds. We did not observe a relationship between soil moisture and degree of hilling. For the tool that killed weeds through hilling (finger weeder), greater soil moisture increased weed death, whereas for the tool that killed weeds through uprooting (torsion weeder), greater soil moisture decreased weed death.

However, the mechanisms responsible for these moisture interactions remain unclear. Additional research separating the impacts of soil moisture on soil movement (tool action), versus their impact on weed response (e.g. dessication) would be helpful for understanding and manipulating these tools and too combinations for improved weed management.

LITERATURE CITED

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CHAPTER THREE: In-row mechanical cultivation in carrots: Can “cultivation-tolerant” varieties improve selectivity?

Abstract

One approach to improving the selectivity of mechanical cultivation tools in carrots is to identify varieties that are most tolerant to those tools. Identification of such “cultivation-tolerant” varieties and their associated traits may also be helpful for breeding efforts aimed at reducing costs associated with weed control. Field trials were conducted on sandy soils in central Michigan to compare cultivar response to each of four types of in-row weeding tools (finger weeder, torsion weeder, hilling discs, flextine harrow). Tools were applied to eight different cultivars of commercially available carrots at three sites in 2016 and 2017. Characterization of root vs shoot partitioning for each cultivar was evaluated based on the area of fresh root and shoot tissue at the time of cultivation. Differences in the survival rate of carrot cultivars were observed for the torsion weeder at all three sites and for the flextine harrow in one of three sites, but not for the finger weeder or hilling discs. At the time of cultivation, carrot cultivars varied in their root size at all three sites, but varied in shoot size at only 1 of 3 sites. Over all sites, there was a positive relationship between carrot shoot size and tolerance to the finger weeder, and a positive relationship between carrot root size and tolerance to the torsion weeder, although both relationships were only marginally significant ($p=0.095$; $p=0.061$). These results demonstrate that commercially available carrot cultivars vary in their tolerance to cultivation tools, and suggest that early partitioning to root tissue confers tolerance to tools that uproot (torsion weeder), while early partitioning to shoot tissue confers tolerance to tools that bury (finger weeder). A relationship was also observed between cultivar seed size and plant size at the cotyledon and 1st true-leaf stage, suggesting that screening of carrot cultivars or seed-lots for

large seed size may be a useful strategy for improving carrot tolerance to cultivation tools, thereby improving the selectivity of those tools.

Keywords: cultivar specific differences, cultivation-tolerance, selectivity, in-row cultivation, carrot weed management

Introduction

Carrots are one of the least weed-competitive crops. For this reason they are exceedingly hard to grow without herbicides (Van Heemst 1985). A greater percentage of carrots are grown organically in the US than any other crop (USDA ERS 2016), but weed management remains a major challenge to production (Colqhoun 2016). Improving the efficacy of organic weed management in carrots would lower costs of production and increase net returns to farmers and potentially benefit consumers through lower prices.

One approach to improving weed management and lowering yield losses due to weeds is the use of weed-competitive cultivars. The ability of crops to be more or less weed-competitive based on cultivar is well-documented (Liebman et al. 2001). Most of this work has involved cereals. To evaluate weed-competitiveness, researchers typically plant different cultivars in the field under weedy and weed free conditions and compare crop and weed dry biomass and yield. Such studies demonstrate that both weed suppression and grain yield vary between cultivars for many crops, including spring barley (Christensen 1995), upland rice (Garrity et al. 1992), wheat (Wicks 2004), and soybean (McWhorter & Hartwig 1972).

Differences in weed-competiveness between cultivars has also been observed in carrots (William & Warren 1975). For example, the carrot cultivar 'Kuroda' had a 39% yield reduction in the presence of purple nutsedge (*Cyperus rotundus* L.), whereas the carrot cultivar 'Nantes' had a 50% yield reduction (William & Warren 1975). Additionally, the critical period of weed competition was between 3 and 7 weeks for 'Nantes', whereas 'Kuroda' had a shorter critical period of between 3 and 5 weeks.

Another approach to improving the competitive ability of crops, is to identify cultivars that are tolerant to practices which target weeds - including herbicides or mechanical cultivation. This approach has been widely used with herbicides, through development of herbicide-resistant or herbicide tolerant varieties that can withstand different formulations or higher doses of herbicides (Beckie et al. 2006).

Much less research has been done with *cultivation-resistant* or *cultivation-tolerant* cultivars of crops. Such cultivation-tolerant cultivars might serve an important role in improving the selectivity of weeding tools. Those cultivars that show more resistance to mechanical weeding tools, either through increased survival or yield, would indirectly be more weed-competitive, as weeding tools could be applied more aggressively to cultivation-tolerant cultivars, thus allowing greater weed mortality.

The potential value of this approach was explored by Rasmussen et al. (2009) and Hansen et al. (2008) who investigated the tolerance of barley cultivars to flextine harrowing. In both cases tolerance was defined as both crop resistance (the ability to resist soil covering) and crop recovery (the ability to maintain yield). Rasmussen et al. (2009) found "no evidence of differences between barley cultivars in terms of tolerance."

If significant differences do exist between crop cultivars in response to cultivation tools, what physical traits might be conferring tolerance: early emergence, large seed-size, early root growth? It would be helpful to identify the physical traits responsible for increased cultivation-tolerance to in-row weeding because 1) It would allow faster identification of cultivation-tolerant cultivars simply by measuring cultivar traits rather than the laborious field trials needed to measure cultivation-tolerance; 2) Knowing the specific traits that confer cultivation-tolerance would allow plant breeders to improve and amplify those traits, thereby breeding crops for increased cultivation-tolerance.

Research investigating the link between physical crop traits and physical responses to in-row weeding is limited. Toukora et al. (2006) found a strong correlation between root dry matter and plant anchorage force, as well as a correlation between root length and plant anchorage force in four weedy species. This correlation between increased root size and increased anchorage force was observed in carrots at different growth stages in the work of Fogelberg and Gustavsson (1998). Their work suggests that carrot cultivars with bigger or longer roots at the time of mechanical weeding might be expected to show greater resistance to those weeding tools that work by uprooting. However, to our knowledge, this hypothesis has not been tested for carrots or other crops.

Seed size is another physical trait that has been observed to affect plant vigor. Lafond and Baker (1986) found that wheat plants grown from small seeds emerged faster than plants grown from large seeds, but accumulated less shoot dry weight. Distinct differences between cultivars were observed in speed of emergence, speed of development, and seedling shoot dry weight.

There have been some notable studies focused on the traits of carrot seeds and cultivars. Tamet et al. (1996) tested carrot seeds of differing sizes and observed that heavier seeds had both longer hypocotyl lengths and greater growth forces (force with which the seedling pushes up). They surmised that these results explained why heavier seeds also showed better emergence from deeper sowing and in response to surface crusting. Perhaps those heavier-seeded carrot cultivars with longer hypocotyl lengths also have longer root lengths later, at the time of cultivation, which could increase tolerance to cultivation tools that uproot.

Other work in carrot traits have found no differences between carrot cultivars in how they partition sugars between shoot and root (Hole et al. 1983). Investigations into variation of carrot seeds concluded that the coefficient of variation (c.v.) of seedling weight was closely related to the c.v. of root length (Gray & Steckel 1983). Those carrot cultivars showing less variation in seed weight would then show less variation in root length, and thus less variation in plant uprooting force (Toukura et al. 2006). The work of Kurstjens et al. (2004) on theoretical selective potential suggests that those crops having greater mean and lower variance in anchorage force would allow a weeding tool to achieve greater selectivity.

While there is work currently underway investigating carrot cultivar differences and developing cultivars more suited to mechanically cultivated systems (Simons, USDA 2014), the author knows of no published work investigating the effect of weeding tools on carrot cultivars.

Differences between crop cultivars in weed-competitiveness have been observed in many crops and both fundamental and applied research suggests that there could be differences between cultivars in their response to weeding tools. Are certain carrot varieties more tolerant to in-row mechanical weeding tools than others, and if so, what physical traits are responsible? With these questions in mind, the primary objectives of our research were to investigate whether carrots differ by cultivar in their response to in-row weeding tools and to evaluate whether differences in size or root:shoot partitioning between carrot cultivars explain differences in survival, with the ultimate goal of discerning any qualities which make a carrot cultivar more tolerant of mechanical weeding tools.

Objectives and Hypotheses

We hypothesized that: 1) Carrot cultivars differ in their response to mechanical cultivation; 2) Cultivars with greater total size at the time of cultivation are more tolerant to cultivation tools than others; 3) For a given seedling size, cultivars that partition greater biomass to shoots (higher shoot:root ratio) are more tolerant to tools that bury and less tolerant to tools that uproot; 4) Within cultivars, heavier seeds in a seed lot will be more tolerant to cultivation than lighter seeds.

Materials and Methods

Experimental site

Field trials were conducted in 2016 and 2017 at the Michigan State University Horticulture Teaching and Research Center (HTRC) in East Lansing, Michigan (42.6734° N, 84.4870° W, elevation of 264 m). The site chosen was a Marlette Silt Loam with 74.8% sand, 17.8% silt, and 7.4% clay (mesic Oxyaquic Glossudalfs). Greenhouse trials were conducted at the Michigan State University research greenhouse.

Carrot cultivars

Popular fresh-market carrot cultivars were selected base on conversations with several Midwestern organic carrot growers (Table 3.1). After the 2016 field trials the carrot cultivars were modified: 'Nelson' was no longer commercially available and a purple carrot 'Dragon' and yellow carrot 'Yellowstone' were included so that a wider spectrum of genetic diversity would be represented. In addition, the heaviest seeds from 'Bolero' were separated and included as a separate cultivar in order to evaluate the importance of seed size within cultivars on seedling size and tolerance to cultivation. The 'Bolero' seeds were separated by weight using a model 757 seed blower (Seedburo Equipment Co. Chicago, Il) and the heaviest seeds were designated 'Bolero heavy-seeded'.

Weeding tools applied

In 2016 the in-row weeding tools were: 1) a HAK 9mm torsion weeder custom-mounted to a HAK floating linkage, mounted to a HAK, S-series steerable toolbar (HAK Company, Spectrumlaan 11 2665 NM Bleiswijk, Holland); 2) a pair of Kult-Kress finger weeders with yellow fingers 37 cm in diameter (KULT-Kress LLC, 3817C Ridge Road, Gordonville PA 17529). Finger weeders were mounted on a HAK floating arm connected to a HAK steerable toolbar; 3) A 2 m Einbock Aerostar flextine harrow (Einböck GmbH & CoKG, Schatzdorf 7 4751 Dorf an der Pram Austria).

In 2017 some of the in-row weeding tools were changed to incorporate tool improvements and included: 1) A Frato 7 mm torsion weeder mounted to a HAK floating linkage, controlled by a HAK steerable toolbar (The Frato Company, Postbox 240 Nl-6500AE Nijmegen, Holland); 2) A KULT-Kress finger weeder with yellow fingers 32 cm in diameter, mounted on a HAK floating arm connected to a HAK steerable toolbar; 3) A 2 m Einboch Aerostar flextine harrow; 4) A KULT-Kress Duo-parallelogram using discs to hill soil, the tool was steered by a HAK steerable toolbar (Table 3.2, Figures 3.1a - 3.1g)

Experimental design, field trials

In 2016 (site 1) six commercial fresh-market carrot cultivars (Table 3.2) were planted at the HTRC with a Jang seeder (Jang Automation Co. Seoul South Korea) to a density of approximately 80 seeds per meter. Two rows of carrots were planted in each bed with rows spaced 57 cm apart. Cultivars were arranged in a randomized complete block design with four replications. Separate field trials were conducted for each of the three cultivation tools (Torsion, Finger weeder, Flextine harrow) and for the hilling experiment. Each trial contained 24 plots (6 cultivars x 4 replicates). Each plot was 4.5 meters long and contained one permanent quadrat (125 x 7.6 cm), from which carrot densities were measured before and after each cultivation event.

Plots were watered with overhead sprinklers uniformly as needed. At approximately 10 days after planting a propane flame weeder was applied to all plots to remove any weed seedlings that had emerged prior to carrot emergence (a common practice among organic carrot growers). At approximately 35 days after planting and 10 days before cultivation, when carrots were in the 3 true-leaf stage, carrots stand counts were taken with in-row quadrats, recording carrot density in one 125 cm x 10 cm quadrat per plot.

On the day of treatment, tools were calibrated in an adjacent area on carrots (cultivar 'Bolero') planted on the same day as those in the trial. Tools were calibrated so as to inflict visible damage to carrot stand, beyond acceptable commercial levels. In-row tool treatments were applied to the carrot cultivars. Approximately three days after tool application carrot density was measured again in the same quadrats as pre-counts. Immediately before cultivation, ten carrot plants per plot were collected, separated into root and shoot tissue, blotted dry and digitally scanned within one week of collection to estimate tissue area using the Winseedle program (Regent Instruments Inc., Québec, Canada).

In 2017 additional field trials were conducted at the HTRC with several additional carrot cultivars (sites 2 and 3) and several additions and changes to cultivation tools (Table 3.2).

Tool by cultivar treatments were arranged in a split plot design with tool as the main plot factor, and cultivar as the subplot factor. Tool main plots consisted of one 80 m long row of carrots arranged in a randomized complete block design with four replications. Each main plot was divided into eight 17.4 m long sub-plots, with carrot cultivar as the sub-plot factor. Each sub-plot contained two 125 cm x 7.6 cm quadrats, from which carrot densities were measured.

Carrot rows were spaced 57 cm apart, so that two rows could be planted between the tractor's wheels, which were set 1.2 m apart. This row spacing, while slightly wider than a common fresh-market carrot spacing of 38-45 cm, allowed adequate space for in-row tools to be applied to one row, while not impacting the nearby carrot row. Fifty-six kg/ha of nitrogen in the form of urea was spread and incorporated before planting (Warncke et al. 2004). A seedbed was created by various field cultivators to obtain a seedbed of quality tilth (Table 3.3)

This trial was performed twice, with carrots being planted on May 15th (site 2) and two months later on August 17th (site 3). For site 2 carrots were seeded with a Jang seeder at approximately 180 seeds per meter. The resulting carrot density was too high and so plants were thinned by hand to approximately 70 carrot plants per quadrat (125 cm) before weeding tools were applied. For site 3 carrots were seeded at a density of approximately 91 seeds per meter using a Jang seeder. This density varied somewhat with the size of carrot seed. The carrot density achieved from the August 17th planting was adequate and no further thinning was performed.

One day prior to carrot emergence, a propane flame weeder was used to kill any ambient weeds germinating ahead of the carrots at all sites. Overhead sprinkler irrigation was applied across all plots for an hour per day from the day of planting until carrots were visible. Between-row weeding tools left only a narrow uncultivated band (approximately 8 cm wide) centered on the crop row. Quadrats were marked with numbered stakes driven into the ground. Pre-cultivation carrot density was recorded approximately two days before the application of weeding tools.

On the day of treatment approximately eight carrot plants of each cultivar from two replications were collected, for a total of approximately 16 carrots per cultivar. These plants were separated into root and shoot tissue and digitally scanned in the laboratory and their area analyzed using Winseedle software. Moisture measurements (percent volumetric water content) were also recorded for the in-row area to a depth of 3.8 cm using a Field Scout TDR 300 Soil Moisture Meter (Spectrum Technologies, Aurora, IL). Three measurements were taken per quadrat and their average recorded.

Cultivation treatments occurred approximately 30 days after planting. Four days (site 2) or six days after (site 3) days after treatments were applied carrot density was again measured by counting carrot plants within two quadrats per sub-plot.

Table 3.1: Carrot cultivars and seed sources for sites 1, 2, and 3.

Cultivar	Source	Site 1	Sites 2 & 3
Bolero	Johnny's Selected Seeds	X	X
Cupar	Bejo Seeds	X	X
Danvers[1], Organic	High Mowing Seeds	X	X
Dragon	Seed Savers Exchange		X
Napoli, Organic	Johnny's Selected Seeds	X	X
Negovia	Bejo Seeds	X	X
Nelson	Johnny's Selected Seeds	X	
Yellowstone	Fedco Seeds		X

[1] Open pollinated

Table 3.2: List of tools and their method of mounting to toolbar, with reference to illustrating figures.

	Treatment	Mounting system	Figure
Site 1	HAK Torsion weeder (9mm)	Custom-mounted to Hak telescoping linkage	Fig. 3.1a
	Kult-Kress finger weeder (37 cm)	HAK drive tines and Hak floating arm	Fig. 3.1b
	Einbock Flextine harrow (2m)	3-point linkage	Fig. 3.1c
	Treatment	**Mounting system**	**Figure**
Sites 2 & 3	Frato Torsion weeder (7mm)	Frato-mount on Hak telescoping linkage	Fig. 3.1d
	Kult-Kress finger weeder (32 cm)	Kult-Kress floating arm	Fig. 3.1e
	Einbock Flextine harrow (2m)	3-point linkage	Fig. 3.1c
	KULT-Kress Duo hilling discs	Kult-Kress Duo-parallelegram on Kult-Kress floating arm	Fig. 3.1f

Table 3.3: Timing of field operations and data collection, recorded as number of days before or after carrot planting date.

Operation	Site 1	Sites 2 & 3	
	----Days from planting----		
Disk	-1	-28, -19	NA
Perfecta[1]	NA	-19	-8
Subsoil	NA	-8	NA
Fertilize[2]	-1	-8	-1
Plant	0	0	0
Propane Flame weeder	6	NA	6
Thin by hand	NA	26, 27	NA
Basket weed (between row cultivation)	10	13	NA
Cut-away discs (between row cultivation)	NA	16	17
Hand-weed	NA	19	NA
Pre-counts	27	26[3], 27[4]	28
Apply in-row tools	41	29[3], 35[4]	29
Scan carrots	41	29[3], 36[4]	29
Post-count	45	33[3], 40[4]	35

[1] Danish S-tine cultivator with rolling basket harrow

[2] Broadcast urea at a rate of 56kg N/ha and incorporated with rolling basket harrow

[3] Torsion weeder and Flextine harrow

[4] Finger weeder and hilling discs

Figure 3.1: HAK 9mm Torsion weeder custom-mounted on HAK telescoping linkage, used on site 1.

Figure 3.2: HAK 37 cm yellow Finger Weeder mounted to HAK floating arm, used on site 1.

Figure 3.3: Einbock Aerostar Flextine harrow, used on site 1, 2, and 3.

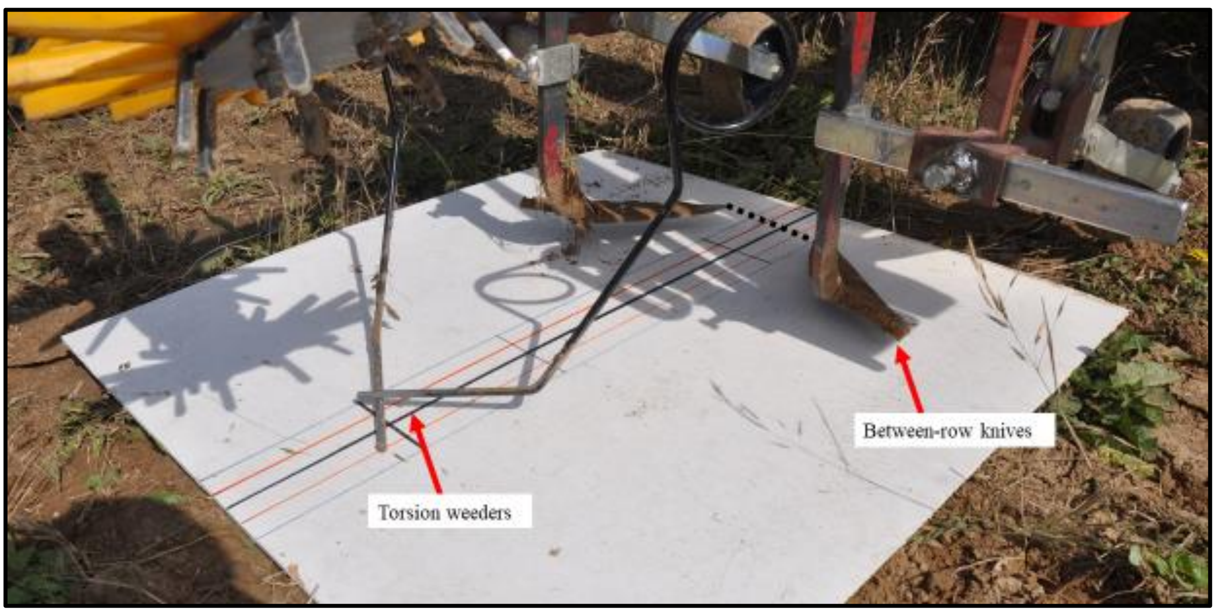

Figure 3.4: Torsion weeder used on sites 2 and 3, against calibration board, showing between-row knives. Direction of travel is towards the upper right-hand corner.

Figure 3.5: Finger weeder used on sites 2 and 3, against calibration board. Inset: closer view of finger weeder.

Figure 3.6: Hilling discs, used on sites 2 and 3, set to hill soil into the crop row. Looking towards the direction of travel

Experimental design, greenhouse trials

In 2016 carrots were grown in the greenhouses and growth chambers at Michigan State University. At different growth stages their roots and shoots were separated, digitally scanned, and analyzed for area using Winseedle software. The projected area of 100 seeds of each of the six carrot cultivars were also measured by scanning and digital analysis using Windseedle. The radicles were measured at both five and seven days after water addition. Two replications of twenty seeds of each of the six cultivars were placed on blotter paper in petri dishes. Five milliliters of distilled water was added to each petri dish and they were set in the growth chamber at 22°c. There were rehydrated once with one milliliter of water. After five or seven days the germinating seeds were removed and digitally scanned and their area analyzed with Winseedle software.

Root and shoot sizes of each carrot cultivar used at site 1 were also evaluated at later growth stages from greenhouse grown plants. Three replications of the six cultivars were planted in a peat-based potting soil in trays 3.8 cm deep and grown at a temperature of 25°c in the greenhouse. When they had attained an average of one true-leaf, approximately 25 plants of each cultivar from all three replications were digitally scanned as whole plants, and then separated and shoots were scanned. Scans were analyzed using Winseedle software.

The root and shoot size of eight carrot cultivars used in sites 2 and 3 at various growth stages were also evaluated from greenhouse grown plants. Three replications of the eight cultivars were planted in a peat-based potting soil in trays 3.8 cm deep and grown at a temperature of approximately 25°C in the greenhouse. When cultivars had emerged with cotyledons, 10 plants of each cultivar from all three replications were digitally scanned as whole plants, separated, and shoots scanned. Scans were analyzed using Winseedle software. To measure cultivars at the one true-leaf stage, four replications of the eight cultivars were planted in a peat-based potting soil in trays 3.8cm deep and grown at a temperature of approximately 25°C in the greenhouse until cultivars averaged one true-leaf. Ten plants of each cultivar from each of the four replications were then digitally scanned as whole plants, separated, and shoots scanned. Scans were analyzed using Winseedle software.

Statistical analysis

Carrot survival percentage in response to weeding tool treatments was defined as the post-count divided by the pre-count, and is reported as a percentage, or carrot survival rate.

All analyses were conducted separately for each site unless noted, using Statistical Analysis System 9.4 (SAS Institute Inc. 2002-20012. Cary, NC). The effects of tool and differences in carrots sizes were analyzed using analysis of variance (ANOVA). Analyses were conducted using the PROC GLIMMIX procedure for different response variables with replication as the random effect. Where needed the data were transformed to better meet normality assumptions. All data presented has been back-transformed to the observable scale.

Where two types of tissues had been analyzed but the third had not, e.g. roots and shoots but not whole plant, the third tissue-type was extrapolated by the following equation: average whole plant = average root + average shoot. Average sizes were taken from all individuals in each scanned slide (5 to 10 individuals). Treatment means separation was performed using Fisher's Protected LSD at $\alpha=0.05$.

The preliminary data were analyzed by mixed-design ANCOVA (analysis of covariance) for studying the relationship between carrot survival rate and carrot size (e.g., roots, shoots, and total) at the time of cultivation, conditional on a tool (Finger weeder, Torsion weeder, and Flextine harrow), over all the five different carrot cultivars present in all 3 sites (Bolero, Cupar, Danvers, Negovia, and Napoli). Note that for individual analysis by each site, an additional four varieties (Nelson, Yellowstone, Bolero heavy-seeded, and Dragon) and one more tool (hilling discs) were included for better generalization, while for overall analysis across the three sites only those carrot cultivars and in-row tools present across all three sites were considered and included in analysis.

Prior to statistical analysis, preliminary data were combined and aggregated from two experimental datasets in the three different experimental sites – (1) carrot survival rate for each tool and carrot cultivar; (2) carrot size at the time of cultivation for each tool and carrot cultivar. Since the data were combined from two studies with different experimental designs (site 1 versus sites 2 & 3), caution must be taken regarding the validity of the results, as aggregating data could lead to the so-called ecological inference fallacy (Freedman, 1999; Schwartz, 1994).

The effects of tool on carrot size and survival rate were tested using mixed effects ANCOVA models (using PROC MIXED, SAS Institute 2013). Note that the regression plots were produced by PROC SGPLOT (SAS Institute 2013), and that PROC REG (SAS Institute, 2013) with ANOVA (analysis of variance) models was used to examine the individual linear relationship for a given tool between survival rate and carrot size in each site. Overall, data were analyzed by a general linear mixed modeling approach with site as a main fixed effect and size as a continuous covariate (Littell et al. 2006; Milliken & Johnson 2009; SAS 2013; Melakeberhan et al. 2018).

To examine and compare the effects of carrot size (e.g., roots, shoots, and totals) on carrot survival rate, general linear mixed-effect models were employed. Since there were random variation errors (or statistical heterogeneity) among each experimental site, the mixed model in analysis of covariance (ANCOVA) was set with unequal variances between each site.

The statistical mixed-design ANCOVA model is shown as

$$Y = LME(Trial \mid Size) = [Trial] + [Trial \times Size] + \varepsilon = Intercept + Slope \times [Size] + \varepsilon$$

, where

Y is the carrot measure of interest (carrot survival rate) as an outcome variable; $LME(\cdot|\cdots|\cdot)$ signifies a linear mixed model with a nested interaction structure of selected predictors; one main effect is site of a given experiment, and this also represents a measure of regression intercept (i.e., an average survival rate when size is zero) in each trial; one two-way interactions *site×carrot size* is an interaction between Site and Size, while it indicates a measure of regression slope (i.e., an average change of survival rate when size is increased by one unit, e.g. square mm) in each trial; and ε is an individual error term.

Note that the overall ANCOVA model across all three sites for examining the relationship between carrot survival rate and carrot size at the time of cultivation is given by

$$Y = Intercept + Slope \times [Size] + \varepsilon$$

, where

Y is the overall carrot survival percentage for a given tool; Intercept is a baseline measure of the overall expected survival rate as Size is zero (i.e., $E[Y \mid Size = 0]$), and this also represents a measure of regression intercept (i.e. an overall survival percentage when size is zero across all three sites); Slope shows the overall relationship between Y (survival percentage) and Size, and indicates a measure of regression slope as well (i.e., an average change of the overall survival percentage over all three sites when size is increased by one unit, e.g. square mm); and ε is an individual error term.

The mixed modeling estimation is performed by the method of Restricted Maximum Likelihood (REML). The statistical inference is based on mixed effects Analysis of Covariance (ANCOVA) with Kenward-Roger Degrees of Freedom Approximation (i.e., modification of denominator or error degrees of freedom for fix effects). The main and interaction effects (e.g., site and a two-way interaction between site and size) are estimated via Least Squares Means (LS-Means) at the significance level of 0.05, or Type-I error rate α=0.05.

In all analyses, the assumptions of normality of statistical errors and homogeneity of variances were checked and met for avoiding biasing results from uncontrolled factors and thus for improving the generalizability and reproducibility of this study's findings. Note that Box-Cox power transformation was applied as a remedy for data with non-normality and/or heterogeneity, and that heterogeneous models were considered, especially when un-equal variances of a studied factor (e.g. tool or carrot cultivar) were diagnosed and could not be remedied simply by transformation.

Results

Effect of in-row weeding tools on survival of carrot cultivars

Significant differences were observed between carrot cultivars in their survival rate in response to in-row weeding tools (Table 3.4). In site one differences were observed between cultivar in response to the flextine harrow; ‘Cupar’ and ‘Negovia’ had a greater survival percentage than ‘Danvers’, ‘Napoli’, and ‘Nelson’. Marginally significant differences (p=0.07) were also observed in site one in response to the torsion weeder; ‘Negovia’ had a greater survival percentage than ‘Nelson’ and ‘Danvers’. In site two differences between cultivar were observed in response to the torsion weeder; ‘Bolero heavy-seeded’ had a survival percentage greater than all other cultivars except for ‘Yellowstone’ and ‘Danvers’ had the lowest survival percentage. In site three marginally signficant differences (p=0.08) were observed in response to the torsion weeder; ‘Bolero’, ‘Bolero heavy-seeded’, ‘Napoli’, and ‘Negovia’ all had greater survival rates than ‘Danvers’. When data was combined across all sites (Table 3.4), marginally significant (p=0.079) differences were observed on carrot cultivar survival rate in response to the torsion weeder; ‘Bolero’, ‘Napoli’, ‘Negovia’ had greater survival rates than ‘Danvers’. No differences in survival rate were observed in response to the other in-row tools.

Table 3.4: Effect of tool on survival percentage of carrot cultivars. Letters within a column indicate significant differences between treatments at α=0.05.

	Site 1			Site 2				Site 3				Across all three sites		
Cultivar	Flextine	Torsion	Finger	Flextine	Torsion	Finger	Hilling discs	Flextine	Torsion	Finger	Hilling discs	Flextine	Torsion	Finger
Bolero	56 ab	98 ab	63	75	66 bc	86	76	77	70 a	74	85	67	78 a	75
Bolero heavy-seeded	NA	NA NA	NA	87	88 a	80	66	90	56 a	78	99			
Cupar	72 a	97 ab	56	82	70 b	80	86	84	36 ab	59	105	80	68 ab	65
Danvers	50 bc	87 b	74	76	52 c	68	67	74	18 b	59	104	66	49 b	66
Dragon	NA	NA NA	NA	68	66 bc	78	87	84	37 ab	64	68			
Napoli	36 c	97 ab	69	88	66 bc	76	78	61	59 a	70	107	62	74 a	72
Negovia	71 a	101 a	60	87	69 b	62	76	75	69 a	64	67	78	80 a	62
Yellowstone	NA	NA NA	NA	90	79 ab	67	68	85	53 ab	51	84			
Nelson	33 c	87 b	66	NA	NA	NA	NA	NA	NA	NA	NA			
ANOVA						---------- Significance (P-value)----------								
	0.001	0.070	0.900	0.700	0.006	0.700	0.600	0.500	0.080	0.700	0.600	0.140	0.079	0.715

Table 3.5: Effect of carrot cultivar on size of root, shoot and whole plant at different growth stages. Letters within a column indicate significant differences between treatments at α=0.05.

	Greenhouse						Field (at time of cultivation)								
			Cotyledon		1 true-leaf		Site 1[2]			Site 2[3]			Site 3[4]		
Cultivar	Seeds	Radicle[1]	Whole plant	Shoot	Whole plant	Shoot	Shoot	Root	Whole plant[5]	Shoot	Root	Whole plant	Shoot	Root	Whole plant
			---mm²	---	---	---	---	---	---	---	---	---	---		
Bolero	4.9 b	12.5 ab	70 a	45 a	208 b	183 b	2,271	93 ab	1,580	928 ab	66 b	995 ab	388 a	114 a	503 a
Bolero heavy-seeded	5.2 a	15.4 a	71 a	49 a	235 a	209 a	NA	NA	NA	890 ab	89 a	982 ab	274 b	104 ab	380 b
Bolero light-seeded	4.7 b	10.5 bcd	59 b	40 bc	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cupar	4.1 d	12.2 ab	56 bc	45 ab	158 cd	133 cd	2,560	106 a	2,273	928 ab	64 b	993 ab	264 b	101 abc	367 b
Danvers	2.4 g	8.3 d	34 e	27 e	136 d	125 d	2,389	71 bc	2,193	567 c	42 c	610 c	175 cd	54 d	230 de
Dragon	3.4 f	15.2 a	50 cd	33 d	155 cd	149 c	NA	NA	NA	799 abc	60 b	859 abc	187 c	83 bc	271 cd
Napoli	4.6 c	10.9 bc	56 bc	37 dc	171 c	149 c	1,983	56 c	1,721	974 a	74 ab	1049 a	230 bc	75 dc	306 bcd
Negovia	4.2 d	13.0 ab	62 b	43 ab	167 c	154 c	1,962	59 c	1,767	733 abc	63 b	798 abc	229 bc	94 abc	325 bc
Yellowstone	3.8 e	9.2 cd	46 d	32 d	156 cd	145 cd	NA	NA	NA	659 bc	64 b	723 bc	106 d	53 d	160 e
ANOVA							---P-value---								
	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.500	<0.0001	0.500	0.071	0.001	0.063	<0.0001	<0.0001	<0.0001

[1] After seven days in the dark at 20°c

[2] 3-true leaves, 41 days after planting

[3] 3-true leaves, 29 days after planting

[4] 2-true leaves, 29 days after planting

[5] Average whole plant area

Size differences between cultivars

In general, significant size differences were observed between cultivars in both root and shoot size and throughout the several growth stages observed (Table 3.5). However, consistent differences in cultivar size were not detected across all growth stage evaluations.

Greenhouse studies revealed significant differences in size between cultivars during each of the early stages of growth (seed, radicle, cotyledon, 1-true leaf). Seed size was a good predictor for plant size at the cotyledon stage and the 1-true leaf stage (data not shown). At both the cotyledon and 1-true leaf stage, cultivars showed significant differences in size between whole plants and shoots alone. Some trends were visible; 'Danvers' was the smallest seed and generally remained the smallest plant throughout all growth stages observed. As can be seen from Table 3.5, although seed size was a good predictor of plant size at cotyledon and 1-true leaf stage, seed size was not a reliable predictor of plant size at the time of cultivation.

Significant size differences at the time of cultivation between whole plants were only observed in one of three sites; in the second site, 'Yellowstone' was the smallest, 'Danvers' the second-smallest, and 'Bolero' the largest cultivar.

The effect of seed size was evident during early growth stages, but differences were less pronounced at the time of cultivation (Table 3.5). Starting from seed, 'Bolero heavy-seeded' maintained a greater plant size than 'Bolero' through the radicle, cotyledon, and first true-leaf stage. Similarly, 'Danvers' was the smallest seed and generally also the smallest plant throughout growth stages. In the field 'Bolero heavy seeded' was significantly larger than 'Bolero' in one of two sites where they were planted, it also had significantly larger roots and shoots. However no significant whole-plant size differences were observed in site two; likely this is due to the high seeding density, which resulted in a very crowded stand where plants inhibited each other's growth. In the third site, where a normal stand density was achieved, the differences in plant growth habit between carrot cultivars was better manifested, as in site one.

Table 3.6: Slope, intercept and significance of the linear regression of carrot tissue area (root, shoot, and total plant size) at the time of cultivation vs survival percentage, by tool.

	Across all sites[1]											
	Shoot size				Root size				Total size			
Treatment	Slope	Intercept	p-value[1]	R^2	Slope	Intercept	p-value	R^2	Slope	Intercept	p-value	R^2
Finger weeder	0.0267	49.86	0.0963	0.3397	0.1088	56.21	0.1787	0.2799	0.0214	49.92	0.1052	0.3224
Flextine harrow	0.0088	61.19	0.7024	0.3246	0.1884	54.49	0.1398	0.4027	0.0104	59.91	0.5769	0.3315
Torsion weeder	0.0662	52.70	0.2269	0.7056	0.3849	41.68	0.0610	0.7373	0.0561	50.49	0.1923	0.7213

[1] For this overall regression, only those five cultivars were analyzed which were included in all three trials (Bolero, Cupar, Danvers, Napoli, Negovia)

[2] All p-values are those of the slope

Relationship between carrot tissue size and survival

Two marginally significant relationships ($p<0.1$) were detected between carrot tissue size and survival percentage for two of the in-row tools (Table 3.6). Carrot shoot size was marginally ($p= 0.0963$) positively associated with survival percentage in response to the finger weeder. Those carrot cultivars having larger shoot area showed an increase in survival in response to the finger weeder. Additionally, carrot root size was marginally positively associated ($p= 0.0610$) with survival percentage in response to the torsion weeder.

Discussion

All observed differences in carrot survival percentage by cultivar occurred in response to those tools that work principally by uprooting: the flextine harrow and the torsion weeder (Kurstjens et al. 2001; Hitchcock Tilton 2017). Based on the survival percentages, it would seem that the carrot cultivars differed more in their root size (resulting in varied anchorage forces) than in their top size, as no differences in survival rate were observed in those tools which hill soil (i.e. the finger weeder and hilling disc).

Whereas in the uprooting experiments of Fogelberg and Gustavsson (1998) differentiation in anchorage force between weeds and carrots did not occur until later in plant development (the 4-6 true-leaf stage), our carrot survival results suggest that differences in anchorage force between carrot cultivars may occur at early growth stages (at the time weeding tools were applied - between the 1 and 3 true-leaf stage), resulting in distinct degrees of cultivation-tolerance. Such early differences in root size and resulting anchorage force are important, because waiting to apply weeding tools at a later growth stage when differences in anchorage force may be more pronounced is less useful in carrots, where weeding tools must be applied early in order to be most economically valuable.

At the time of cultivation significant differences among carrot cultivars in shoot size were detected in one of three sites, whereas significant differences were observed in root size in all three sites. This suggests that carrots at the 1 to 3 true-leaf stage vary more in root size than in shoot size. If so, tools that uproot would likely show greater differences among cultivars in resulting survival percentage, rather than tools that bury. However, the size of carrot tissues at time of cultivation was twice as variable as that of root tissue (data not shown), which limited our ability to detect potentially important differences in shoot size.

Compared to the other in-row tools, the finger weeder appears to be more responsive to carrot shoot size. This would suggest that the finger weeder in our trial functioned primarily through burial, where shoot size is crucial for conferring tolerance (Mohler et al. 2016; Terpstra 1981) rather than by uprooting, where root size is more important (Fogelberg et al. 1998; Kurstjens et al. 2004). Similarly, these results suggest that the torsion weeders main mode of action is through uprooting, as those plants with larger roots exhibited a marginal tendency towards greater survival in response to the torsion weeder.

Summary and Conclusions

The primary objectives of our research were to investigate whether carrot cultivars differ in response to in-row weeding tools and to learn whether there are distinct differences in size or partitioning between carrot cultivars that may be related to variations in cultivator-tolerance.

We hypothesized that carrot cultivars would differ in their response to in-row mechanical weeding tools. Having observed differences ($p=<0.1$) in the survival rate between carrot cultivars for at least one in-row tool at every site, we found some evidence to support this hypothesis. Applying tools at later growth-stages or calibrating them more delicately may have shown more distinct results.

We hypothesized that cultivars with greater size (as measured by total projected area) at the time of cultivation would be more tolerant to weeding tools than others. We also hypothesized that those cultivars with larger shoots would be more tolerant to tools that hill, and those with larger roots would be more tolerant to tools that uproot. We did find some evidence for this. Over all sites, in response to the finger weeder we observed a marginally significant ($p=0.096$) positive relationship between carrot cultivars shoot size at the time of cultivation and survival. Similarly, in response to the torsion weeder, we observed a marginally significant ($p=0.061$) relationship between carrot cultivar root size at the time of cultivation and survival. These results suggest that carrot cultivars with larger roots show greater cultivator-tolerance to those tools that function through uprooting, while those cultivars with larger shoots show greater cultivator-tolerance to those tools that function through burial.

We hypothesized that within cultivars, heavier seeds in a lot would be more tolerant to cultivation than lighter seeds, and tested this hypothesis on a single cultivar (Bolero) using four tools at two sites. Interestingly, at one of two sites, we observed greater tolerance to the torsion weeder of Bolero plants originating from heavier seeds compared to those from light seeds. However, no differences in tolerance based on seed size were observed for any of the other tools at either site. We did observe that larger seeded cultivars generally resulted in larger whole-plant size at various early stages relevant for cultivation. This result suggests that screening of carrot cultivars or seed-lots for large seed size may be a useful strategy for improving carrot tolerance to cultivation tools, thereby improving their selectivity. Further evaluation of the relationship between cultivation-tolerance and seed size or other early seed or seedling characteristics may facilitate cultivar selection and plant breeding efforts to improve selectivity and reduce weed management costs in carrots.

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