Spring 5-5-2023

Deconstructing the Art of Physical Weed Control

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DECONTRUCTING THE ART OF PHYSICAL WEED CONTROL

By

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B.S. University of Maine, 2020

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Plant, Soil, and Environmental Science)

The Graduate School

The University of Maine

May 2023

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Thesis Advisor: Dr. Eric R. Gallandt

An Abstract of the Thesis Presented
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Farmers adjust physical weed control (PWC) tools to optimize efficacy based on observations of weeds, the crop, and soil conditions. These many variables make PWC research challenging. To study PWC tool settings more closely, we constructed a soil bin with a mobile tool carriage inside of a heated glasshouse. The soil bin was 2 m wide by 12 m long by 1 m high, with a tool carriage that can operate at 0.4 to 19.0 km h^{-1}. Tool angle, spacing, depth, and speed can all be precisely adjusted from the tool carriage and control panel. The goal of this research was to take the art out of PWC and provide farmers with researched based recommendations, as well as provide researchers with new methods on how to test PWC tools.

The aim of chapter one was to develop methods for a high-throughput system in a controlled environment with artificial weeds (AWs) to test PWC tools. Methods were developed using a simple tine weeder, wooden golf tees as AWs, and a soil bin. The tine weeder was chosen for methods development because it offers uniform soil disturbance and appears to have both uprooting and burial mode of action. Tine speed, angle, and depth were evaluated in both soil bin and field experiments. Tool efficacy from the soil bin were qualitatively compared to efficacy results using surrogate weeds in the field. Results suggest that the simplified conditions of the soil bin system may be useful to test and prioritize tool settings or adjustments for field studies.

Chapter two is about determining whether testing PWC tools in a controlled environment using a soil bin system, reflects treatment effects found in the field. A finger weeder was used and settings of angle, spacing, and speed were tested. The three angles tested were hilling (68º), standard (90º), and scrubbing (108º) with three spacings of 0.6 cm overlap, 0.0 cm fingers touching, and 2.5 cm gap. These angles and spacings were tested in a full factorial design with artificial crops (ACs, 6 mm dia. by 152 mm-long wooden dowels) and AWs (70 mm-long wooden golf tees). Three speeds were tested to represent speeds typical for walking (4 km h^{-1}), tractor cultivating (7 km h^{-1}), and a tractor with a camera guidance system (9 km h^{-1}). Experiments of angle, spacing and speed were replicated in the field. Hilling (68º) caused the greatest efficacy in the soil bin (78%) and in the field (62%). As spacing decreased, efficacy and AC mortality increased in the soil bin, but surprisingly, in the field, there was no difference. In the soil bin, higher speeds of 7 and 9 km h^{-1} increased efficacy by 77% when compared to 4 km h^{-1}. In the field however, no significant effects were detected between speeds. We conclude that the soil bin is a promising research tool for testing PWC tools.

ACKNOWLEDGEMENTS

The author expresses his sincere gratitude to his advisor, Dr. Eric Gallandt, for his mentorship and support throughout his graduate career. The author would also like to thank his graduate committee members, Dr. Bryan Peterson and Dr. Mark Hutton for their guidance and knowledge. Gratitude is extended to Joe Cannon Jr. and Tom Molloy for helping implement experiments and fix equipment. To Dr. Rebecca Champagne, M.S. graduates Johnny Sanchez and Ruth Clements, and graduate student Anthony Codega, the author thanks you for your contributions made as colleagues. The author thanks the collaborators at Michigan State University for insight and guidance, Dr. Dan Brainard, Daniel Priddy, and Jo Flies. Many thanks to Brad Libby for assisting in greenhouse services as well as Bradley Denholm, Kyle Forsythe, and the research team at the Advanced Manufacturing Center for constructing the soil bin and providing services. Gratitude is extended to Professor Emeritus William A. Halteman, for statistical services and guidance. The author also extends his thanks to all the research assistants who helped collect data in the field and in the soil bin, Camille Kavanah, Sonora Ortiz, Margo Roberts, Joey Lopez Wilen, Louise Debondans, Emma Gibbons, Tommy Owen, and Noah Fink, thank you. The author would also like to thank all his friends and family for believing in him and helping him grow into the person he is today. This work was supported by the USDA National Institute of Food and Agriculture Hatch Project, "Efficacy and sustainability of seedling- vs. seed-focused weed management." Accession Number 1006745; Project Number ME021606; E. Gallandt, Project Director. This work was also supported by USDA NIFA Organic Agriculture Research and Extension Initiative Award 2018-51300-28426. Title: Integrating Advanced Cultural and Mechanical Strategies for Improved Weed Management in Organic Vegetables Project Director: E. R. Gallandt.

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LIST OF ABBREVIATIONS

AC	Artificial Crops
ANOVA	Analysis of Variance
AW	Artificial Weed
C	Celsius
cm	Centimeter
d	Days
$f\ s^{-1}$	Frames per Second
h	Hours
kg	Kilogram
$kg\ ha^{-1}$	Kilograms per Hectare
$km\ h^{-1}$	Kilometer per Hour
m	Meter
$m\ s^{-1}$	Meter per Second
MLR	Multinomial Logistic Regression
mm	Millimeter
OR	Odds Ratios
PWC	Physical Weed Control
$t\ ha^{-1}$	Metric Tons per Hectare

LIST OF EQUATIONS

CHAPTER 1 TESTING PHYSICAL WEED CONTROL TOOLS WITH ARTIFICIAL WEEDS IN A HIGH-THROUGHPUT CONTROLLED ENVIRONMENT

Introduction

Physical weed control (PWC), also called, 'mechanical weed control' or 'cultivation,' is a foundational practice for organic farmers. PWC tools kill weeds by various mechanisms, including uprooting, burying, and/or slicing (Terpstra and Kouwenhoven, 1981). Unfortunately, weed control efficacy, the proportion of weeds killed, is generally low and variable and is affected by crop and weed species, their growth stages, as well as soil conditions and tool effects (Gallandt et al., 2018).

Farmers choose and adjust tools based on their past experiences, improving with experience over time (Bowman, 2002). Developing the skills to set up tools correctly is a key factor affecting their performance (Bond et al., 2007). Given enough experience, a farmer can evaluate their weeds, crop, and soil conditions to determine which tool to use and optimally adjust it (Bowman, 2002). Research based information related to how various tool settings, e.g., speed, angle, depth, and spacing, affect efficacy would accelerate the learning curve regarding PWC.

Given the multitude of weed, crop, tool, and soil variables affecting efficacy, it is difficult to design field experiments to optimize PWC. High-throughput, controlled environment testing could help to prioritize tool design, angle, speed, depth, and spacing for subsequent field testing and farmer tool adjustments. Ideally, high-throughput PWC tool testing would be representative of field results, repeatable, and cost-effective. An artificial arena such as a soil bin system may be useful in this regard.

Soil bins have been used in agricultural engineering to control otherwise variable environmental conditions and can be used to test a wide range of soil-tool interactions (Clark and Liljedahl, 1968, Durant et al., 1980, Mahadi et al., 2017). A soil bin contains field soil, sand, or a similar substrate through which tools can be operated to evaluate effects of tool design, speed, and adjustment, as well as various substrate effects. We found four published examples of PWC tool research using soil bins. Terpstra and Kouwenhoven (1981) tested the efficacy of a Steketee hoe, varying depth and angle, in a soil bin using *Lepidium sativum* L. (garden cress) as a surrogate weed. They found that using a steep angle with a shallow cultivation depth offered the greatest tool efficacy (Terpstra and Kouwenhoven, 1981). Kurstjens and Perdok (2000) tested tine harrow speed and working depth in a soil bin and found dry soil to more easily bury *Lolium perenne* L. (ryegrass) at higher speeds and greater working depths. Duerinckx et al. (2005) tested a tine harrow at three angles and three speeds; the steeper angle caused the tine to vibrate more in the soil resulting in a predicted increase in weed damage, but possibly increasing crop damage as well. Zhang and Chen (2017) evaluated soil movement, cutting forces, and efficacy with different sweeps and found sweep angle to affect uprooting, cutting widths, and soil throw.

Soil bins are used with standardized experimental conditions. Soil preparation generally starts with soil mixing or tilling, followed by leveling and rolling to compact the working zone to a desired bulk density (Kshetri et al., 2019, Mahadi et al., 2017, Rosa and Wulfsohn, 2008). Soil moisture may be managed by saturating the soil or spraying with a predetermined amount of water and allowing the soil to drain over night before testing begins (Kshetri et al., 2019, Mahadi et al., 2017, Zhang and Chen, 2017). Alternatively, researchers may use a completely artificial soil in which field soil is dried, sieved, and mixed with a light oil to mimic a specific soil moisture. Clark and Liljedahl (1968) found that a clay-sand-spindle oil mix had a low evaporation rate and offered a high level of repeatability when analyzing tillage tools. Research on tillage tools usually focuses on soil disturbance, tool draft force, or wear. PWC research on the other hand, aims to improve weed control by both increasing efficacy and reducing crop damage.

Evaluating tool efficacy data in the field can be difficult as weeds are often very patchy (Vanhala et al., 2004). Some researchers use surrogate weeds, i.e., crops that are similar in seed mass and seedling architecture to their weedy relatives for PWC studies (McCollough et al., 2019, Melander and McCollough, 2020, Rasmussen, 1991). Artificial weeds (AWs) are an alternative to both real and surrogate weeds. AWs can be used to remove biological variability and rapidly simulate potential weed damage (Kshetri et al., 2019). However, few researchers have used AWs as a means of evaluating PWC tool efficacy. Kshetri et al. (2019) simulated weeds in a soil bin by inserting wooden cylinders (2 mm dia. by 70 mm long) into a loam soil to a depth of 51 mm. Disturbance was scored by classifying the cylinders by level 1 as unaffected, level 2 slightly tilted, level 3 displaced but still vertical, level 4 displaced and tilted, and level 5 completely dislodged (Kshetri et al., 2019). Kshetri et al. (2019) found that tine depth and rotational speed had significant effects on the disturbance of wooden cylinders. From here on, tool efficacy using AWs will be defined as tool efficacy$_{AW}$.

Here we present methods we developed to use a soil bin system to study a wide range of operational settings for PWC tools. Our objectives were to: (1) develop protocols for rapidly testing PWC tools based on simple AWs; (2) establish methods to prepare and maintain a soil bin substrate to optimize repeatability of PWC assays; and (3) test the newly developed soil bin system using a simple but representative PWC tool and compare efficacy measured in the soil bin to field measurements.

Materials and Methods

Soil Bin

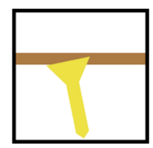
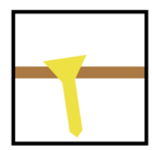
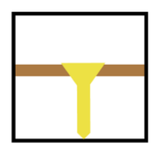
A soil bin based on the design of Mahadi et al. (2017) was constructed inside a heated glasshouse at the University of Maine, Orono. The design was modified to accommodate the attachment of various PWC tools; dimensions of the soil bin were 2 m wide by 12 m long by 1 m high (Fig. A.1). The soil bin was filled with a locally sourced coarse sand (Owen J. Folsom, Greenbush, ME, USA) composed of 95% sand, 2% silt, and 3% clay, we refer to this as our "soil." An electric motor drives a notched belt to move a tool carriage along a set of rails on top of the bin. Working depth and angle were adjusted following mounting to the tool carriage, and the speed adjusted at a control panel from a range of 0.4 to 19.0 km h^{-1}. The glasshouse had an average temperature of 24º C and an average relative humidity of 37% for all experiments.

Before a cultivation event, soil was placed in front of an adjustable leveler attached to the tool carriage, and then moved across the testing area. A rolling compactor was next attached to the tool carriage with a 16 kg weight and rolled twice across the testing area. AWs were placed into the testing area and a cultivation event was performed.

Artificial Weeds

We chose 35 mm-long wooden golf tees (Golf Tees Etc., Aurora, CO, USA) to serve as our AWs. AWs of a unique color were randomly dropped into each sampling quadrat to eliminate confusion if AWs were moved to another sample area during cultivation. AWs were pushed into the soil until nearly flush with the soil surface, with only the top 2 mm of the golf tee above the soil surface. A five-level categorical scoring system ranging from undisturbed to completely disturbed was developed to quantify efficacy (Table 1.1).

Table 1.1 Artificial weed (AW) disturbance scoring system for wooden 35 mm-long golf tees. Scores 1, 2, and 3 were classified as "dead" and scores 4 and 5 were "alive" when calculating tool efficacy.

Score	Category	Description	Illustration
1	Completely Disturbed	Completely pulled out of the soil and/or bottom point is showing	
2	Disturbed	Top of the tee is between 90° and 45° relative to the soil surface and/or the tapered collar is showing	
3	Buried	≥ 95% of the top is covered with soil	
4	Partially Disturbed	Disturbed by the tool, but slightly varies from original position	
5	Undisturbed	Has not been disturbed from its original position	

Optimizing Artificial Weed Density in the Soil Bin

To test for possible density dependent efficacy effects on the AWs, densities of 10, 20, 30, 40, 50, and 60 were placed in a 50 cm by 50 cm (0.25 m^2) quadrat. A tine rake (53 cm wide, Johnny's Selected Seeds, Waterville, ME, USA) was the tool chosen for these experiments. This tine rake offered uniform soil disturbance of inter- and intra-row areas, with likely mechanisms of both uprooting and burial. Four replications were completed, and the experiment was repeated a week later. The tine weeding tool was set to a working depth of 30 mm, a tine angle of 109°, and a speed of 1 m s^{-1}. GoPro Hero 8 (GoPro, Inc., San Mateo, CA, USA) action cameras were used to record slow-motion video at multiple angles with 1080 pixels and a frame rate of 240 f s^{-1} to visually observe the action of the tool in experiments. After each cultivation, tool $efficacy_{AW}$ was scored as described above (Table 1.1).

We then examined AW densities to optimize labor for sample setup. Six plots were placed into the testing area of the soil bin consisting of 10, 20, 30, 40, 50, and 60 AWs per sample area. The sample area was adjusted to maintain a constant density of 120 AWs m^{-2}. The tine weeding tool was operated using the same settings as stated above and the experimental design was the same as above.

Soil Preparation

We tested the addition of soil disturbance with a garden rake before the leveling and compacting protocol. The constant AW density experiment described above was repeated with and without the addition of soil raking to a depth of 55 mm to the entire soil bin before soil leveling and compacting.

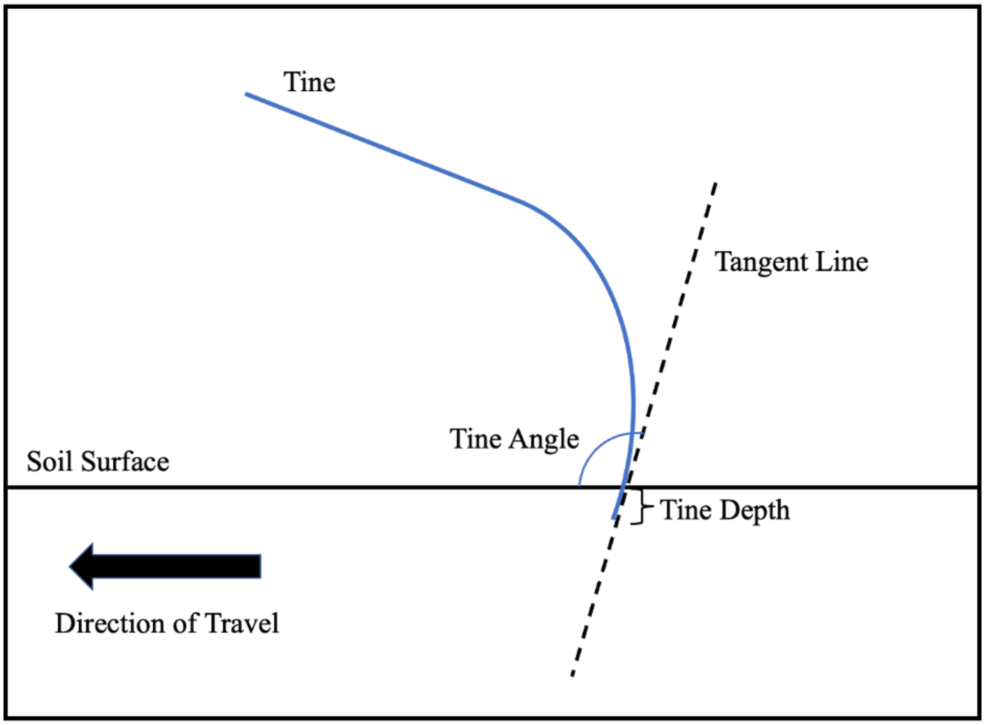
A soil moisture experiment was conducted to determine whether drying soil over time would affect PWC tool efficacy measurements. The soil bin was watered to field capacity and left to drain for 24 h. Six 0.25 m^2 sample areas were placed in the soil bin with a density of 120 AWs m^{-2}. The testing area was cultivated with a tine weeding tool adjusted to the same settings described above. Once tool $efficacy_{AW}$ was scored and collected, a 60 mm deep by 55 mm wide core was randomly collected within each sample area to measure gravimetric soil moisture content.

Evaluation of a Tine Weeding Tool

We chose a tine weeding tool as a test case to evaluate settings a farmer could change to optimize performance including angle, depth, and speed. The tine weeder was chosen because it provides uniform soil disturbance, unlike torsions, disks or finger weeders that are designed to target the intra-row area near crop plants. Tines are also a common weeding design, used for so-called blind-cultivation (Kolb and Gallandt, 2012, McCollough et al., 2019, Melander et al., 2005) and may be used as part of a stacked sequence of tools (Brown and Gallandt, 2018).

The weeding tool was tested using five different tool handle angles of 26º, 31º, 35º, 40º, and 44º. The minimum angle was found by lowering the tool as far as possible while not impairing the weeding ability of the tool then measuring the angle with a digital angle meter. This process was also done for the maximum angle. The middle angle of the range was calculated along with the angles between the middle and minimum and between the middle and maximum angles. Tool handle angle was then used to set up the tool in the soil bin tool carriage. Once the tool was set to the desired depth, the tine rake was pushed into level soil. A squared piece of cardboard was placed adjacent to the tine and the tine was traced on the cardboard. Five randomly selected tines were traced with the addition of a tangent line to mark where the tine entered the soil. The angle from the tangent line to the soil was measured and defined as the tine angle (Fig. 1.1). We wanted to test a range of tine angles, so tool handle angle was set at 26º, 31º, 35º, 40º, and 44º. Unfortunately, when we later measured tine angles, we found that the curvature of the tines (Fig. 1.1) resulted in tine angles 101º, 104º, 117º, 102º, and 121º. Since three of these angles were very similar, we only report data on the extremes of 101º and 121º. These angles are not representative of how this tool can be used in the field, but rather, capture the minimum and maximum working angles for the tines themselves. For these studies tines were set at a working depth of 30 mm and a speed of 1 m s^{-1}. Tine angle treatments were tested in a random complete design using three AW subsamples of the same density per replication with four replications.

Figure 1.1 Diagram showing a single curved tine from the weeding tool used to develop soil bin research methods. Tine angle was measured based on the soil surface and a tangent line relative to the point of entry in the soil. Tine depth was also measured.



A tool handle angle of 35º was selected due to its low variability and lower than optimum efficacy so possible treatment effects of depth and speed would be detected. The working depths tested were 10, 20, and 30 mm and the speeds selected were 0.9, 1.1, and 1.3 m s^{-1}. The corresponding tine angles were 123º, 122º, and 117º, respectively. Speeds were chosen by walking a known distance at a slow working speed, a normal working speed for a farmer, and a fast-working speed. Depths were chosen by using the tine rake in the soil bin at different working pressures. Under typical use representative of a farm setting, depth averaged 20 mm. The tine rake was then stopped and held in position while the sides of the tines were excavated to measure depth of three random tines. This process was completed three times for each depth to determine a minimum, middle, and maximum tine depth. A full factorial experiment examining three speeds and three depths was performed using a randomized complete design with three subsamples per replication with four replications.

Artificial Weed Field Experiment

The tine rake was also tested in a field experiment using AWs and two tine angles. The field site had a stony sandy loam soil type and was located on the University of Maine, Orono campus (44.900956º N, -68.660262º W). Environmental conditions for the first experiment were sunny with a daily average of 12º C and the second experiment seven days later had sunny conditions with a daily average of 7º C. The field was cultivated with HAK 26 cm wide sweeps (HAK Schoffeltechniek, Bleiswijk, Netherlands) and a Tilmor© basket weeder (Tilmor© LLC, Dalton, OH, USA) to create a uniform soil bed and kill ambient weeds before the experiments.

The experiments were established using a randomized complete block design, with eight replications. Each plot contained three subsamples, each with 30 AWs 0.25 m^{-2}. The tine weeding tool was tested at tine angles of 101º and 121º. AWs were randomly dropped into sample areas, and then "planted" as described previously. Speed was calculated by timing the operator walking between two flags at the start and end of a plot. Once a treatment was cultivated, tool $efficacy_{AW}$ was scored as described previously.

Field Experiments Comparing Artificial Weeds to Real Weeds

Tool $efficacy_{AW}$ from the Johnny's Selected Seeds tine rake in the soil bin was compared to a larger tine harrow field experiment conducted at a nearby field site using *Brassica juncea* L. (brown mustard), *Guillenia falvescens* Hook. (yellow mustard), and *Raphanus raphanistrum* L. (wild radish) in the field with the same tine rake and tool settings (Sanchez and Gallandt, unpublished).

Data Analysis

Statistical analyses were processed using JMP® Pro student version 15.2.0 (SAS Institute Inc., Cary, NC, 1989-2021). Analysis of variance (ANOVA) was used to test main effects and interactions for significance. Model residuals were checked for normality and homoscedastic variance to satisfy the assumptions for ANOVA. Data were transformed using a logit function Eqn (1) when appropriate.

$$logit(Efficacy) = \log\left(\frac{Effficacy}{1-(Efficacy)}\right) \quad (1)$$

Significant effects were subjected to mean separations using a Tukey Honest Significant Difference test or a Student's t test where $\alpha = 0.05$. Linear regression was used to explain gravimetric soil moisture over time, with model residuals checked for normality and homoscedastic variance.

To further explore tool efficacy$_{AW}$ data, specifically differences in mechanisms e.g., disturbance vs. burial, a multinomial logistic regression (MLR) was used for analysis of individual AW disturbance scores. A logistic regression can model two categorical outcomes, e.g., Dead or Alive, whereas a MLR can model more than two categorical outcomes (Agresti, 2012). This type of statistical test is widely used in medical, education, and ecological research (Asdigian et al., 2018, Mickelsson, 2022, Rao et al., 2021).

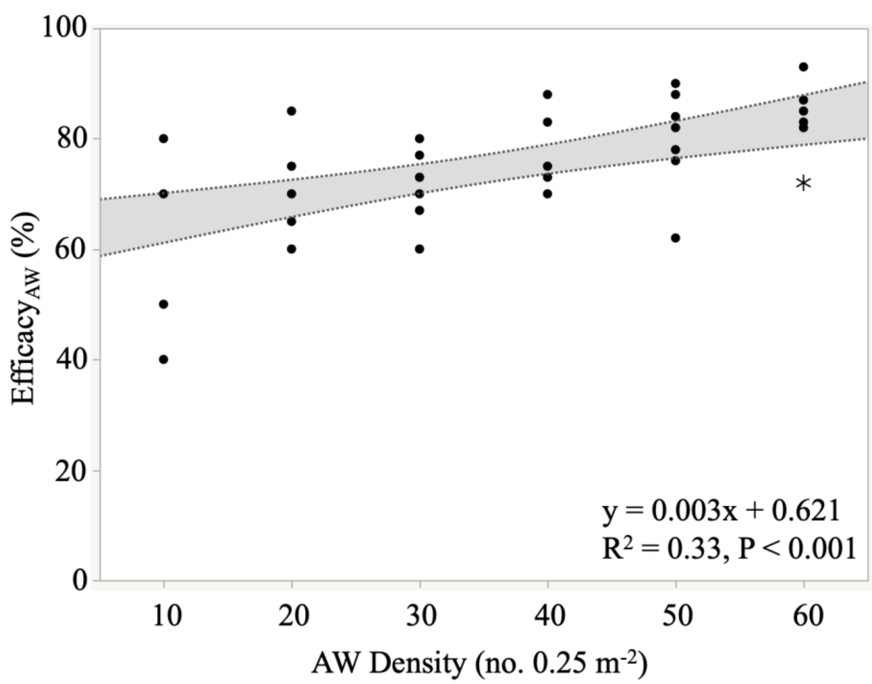
Instead of only reporting tool efficacy$_{AW}$, a MLR can measure differences between uprooting, disturbed, buried, partially disturbed, and undisturbed with tine angle, depth, and speed. The test reports odds, probabilities, and odds ratios (OR). A mosaic plot of probabilities can be a useful way to visualize tool mechanisms at difference settings while the odds ratios incorporate the model's variability and show the magnitude of an effect when making treatment comparisons (Agresti, 2012).

Results

Optimizing Artificial Weed Density in the Soil Bin

As the sample density of AWs increased, the mean $efficacy_{AW}$ increased ($P = 0.001$) (Fig. 1.2). When the AW density was held constant at 30 AWs 0.25 m^{-2} with its corresponding area, tool $efficacy_{AW}$ did not differ by sample area ($P = 0.704$, data not shown).

Figure 1.2 Evaluation of tool efficacy using artificial weeds (AWs) (35 mm-long wooden golf tees) by sample density in a soil bin. AWs were placed in a 0.25 m^2 quadrat and cultivated with a tine weeding tool at a tine angle of 109°, working depth of 30 mm, and a speed of 1 m s^{-1}.



Soil Preparation

Varying disturbance and moisture of the soil was tested for effects on tool $efficacy_{AW}$. Raking soil to a depth of 55 mm, followed by leveling and rolling compaction before cultivation events, did not affect tool efficacy$_{AW}$ (Fig. 1.3). However, as soil moisture in the soil bin decreased, tool efficacy$_{AW}$ increased (Fig. 1.4).

Figure 1.3 Effect of soil raking to a depth of 55 mm on tine rake efficacy$_{AW}$ with other factors held constant (P = 0.071). Outlier shown as asterisk.

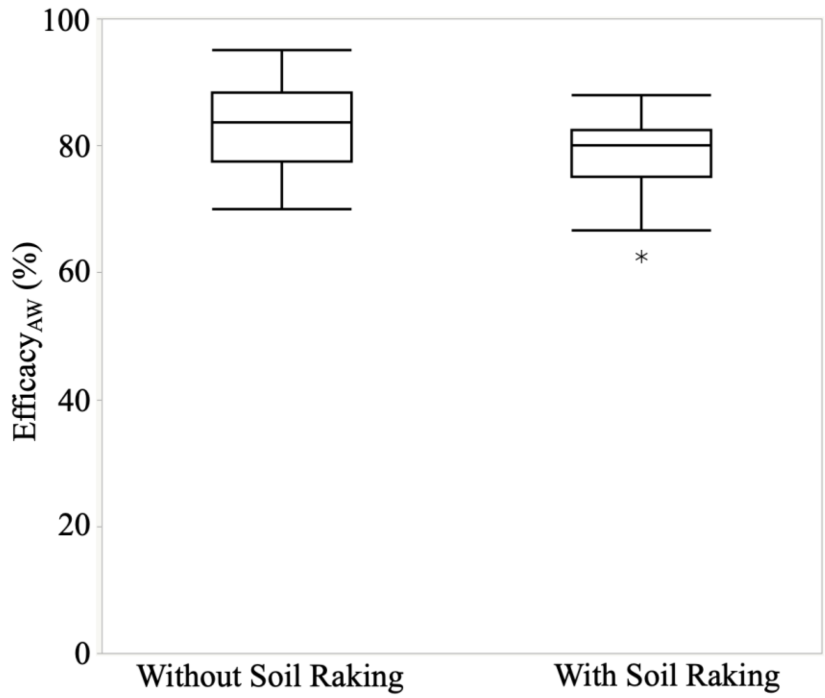
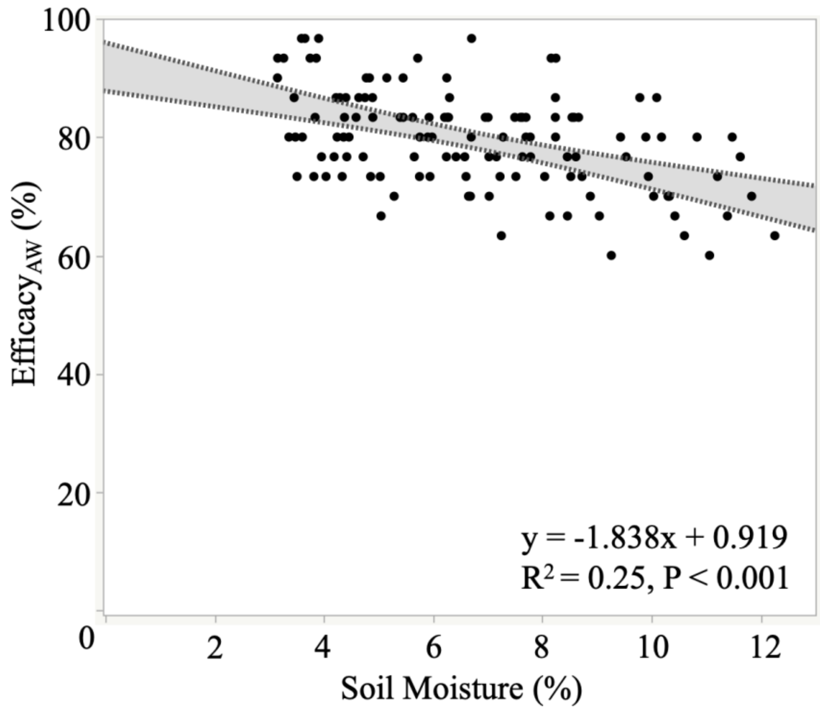


Figure 1.4 Relationship between gravimetric soil moisture and tine weeding tool efficacy using artificial weeds (AWs) (35 mm-long wooden golf tees) in a soil bin. A tine weeding tool was used at a tine angle of 109º, working depth of 30 mm, and a speed of 1 m s^{-1}. Two replicated experiments are shown.



Evaluation of a Tine Weeding Tool

Efficacy$_{AW}$ was significantly affected by tine angle (P = 0.031); efficacy$_{AW}$ was 93% at the maximum tine angle (121º) and 80% at the minimum tine angle (101°) (data not shown). Based on our MLR analysis, tine angle was significant between the five scoring categories (P < 0.001). A contingency table is provided to show scoring results of the tine angle comparison (Table B.1).

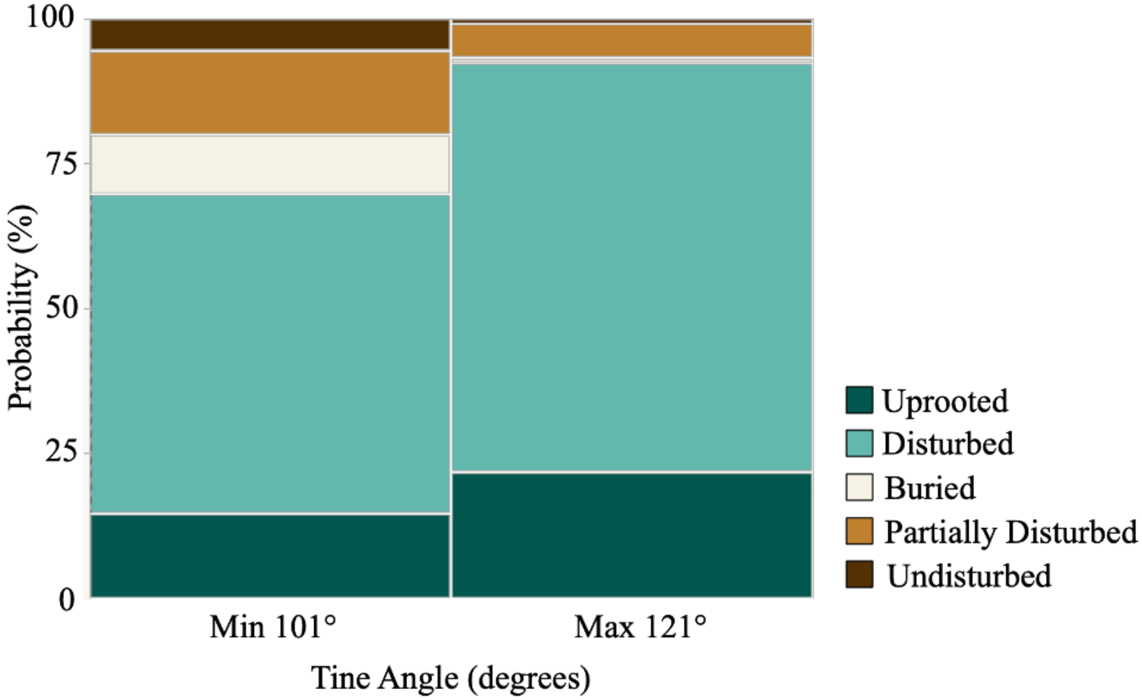
The odds ratio of getting an uprooting score vs. undisturbed using a maximum (121º) tine angle is significantly higher than when using a minimum (101º) tine angle (Table 1.2). The odds ratio of getting a buried score vs. uprooted using a minimum (121º) tine angle is significantly higher than when using a maximum (121º) tine angle (Table 1.2). By using a minimum (101º) tine angle, the probability of getting a burial score is significantly higher than when using a maximum (121º) tine angle (Fig. 1.5). Moreover, the probability of getting an uprooting score using a maximum (121º) tine angle is significantly higher than using a minimum (101º) tine angle (Fig. 1.5).

Table 1.2 Odds ratios showing the likelihood of an artificial weed (AW) (35 mm-long wooden golf tee) receiving a score of uprooted, disturbed, buried or partially disturbed vs. undisturbed and buried vs. uprooted for tine angles 101° (Min) and 121° (Max). The tine weeding tool was set to a working depth of 30 mm and a speed of 1 m s^{-1}. Larger values indicate increased likeliness of and an event occurring.

Odds Ratios	**Uprooted vs. Undisturbed***	**Disturbed vs. Undisturbed***	**Buried vs. Undisturbed**	**Partially Disturbed vs. Undisturbed**	**Buried vs. Uprooted***
Minimum vs. Maximum Tine Angle	0.10	0.12	1.85	0.37	18.38
Maximum vs. Minimum Tine Angle	9.94	8.55	0.54	2.69	0.05

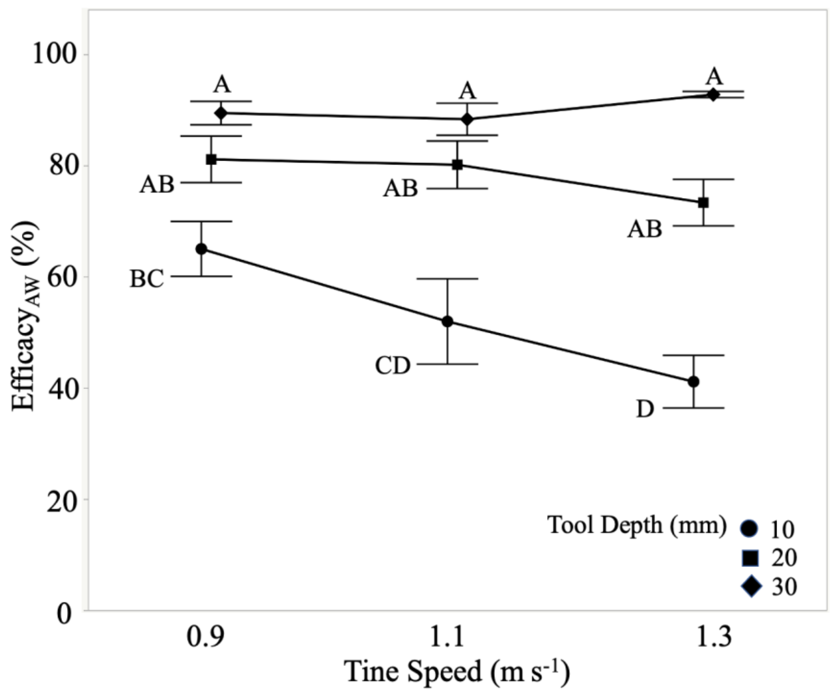
*P ≤ 0.05, according to a Chi-squared test

Figure 1.5 Mosaic plot from a multinomial logistic regression showing probability of artificial weed (AW) (35 mm-long wooden golf tees) disturbance scores for a minimum (101°) and maximum (121°) tine angle using a tine weeding tool in a soil bin. The tine weeding tool was set to a working depth of 30 mm and a speed of 1 m s^{-1}.



As tine depth increased from 10 to 30 mm, tool $efficacy_{AW}$ increased 70% ($P < 0.001$). As speed increased from 0.9 to 1.3 m s^{-1}, tool $efficacy_{AW}$ decreased 13% ($P = 0.042$). There was an interaction between of speed and depth ($P = 0.055$) (Fig. 1.6). $Efficacy_{AW}$ was not affected by speed at 20 and 30 mm tine depths, but decreased from 65% to 41% at 10 mm (Fig. 1.6). Based on MLR, tine depth, speed, and the interaction were all significant for the five score categories ($P < 0.001$). A contingency table is presented to show disturbance scoring for tine depth and speed (Table B.2).

Figure 1.6 Mean tool efficacy$_{AW}$ and standard error of three speeds (0.9, 1.1, 1.3 m s^{-1}) and three depths (10, 20, 30 mm) in a soil bin using a tine weeding tool. Due to the curvature of the tines, tine angle varied with working depth; 10, 20, and 30 mm working depths corresponded with tine angles 123º, 122º, and 117º respectively. Means with the same letters are not statistically different using the Tukey HSD at an $\alpha \leq 0.05$.



As speed increases at a tine depth of 10 mm, the probability of scoring an undisturbed increases and burial decreases (Table 1.3; Fig. 1.7). Increasing speed at a 30 mm, increases the probability of scoring an uprooted, but decreases probability of burial (Fig. 1.7).

Figure 1.7 Mosaic plot from a multinomial logistic regression showing probability of artificial weed (AW) (35 mm-long wooden golf tees) disturbance scores for tine depths 10, 20, and 30 mm and speeds 0.9, 1.1, 1.3 m s^{-1} using a weeding tool in a soil bin. Due to the curvature of the tines, tine angle varied with working depth; 10, 20, and 30 mm working depths corresponded with tine angles 123º, 122º, and 117º respectively.

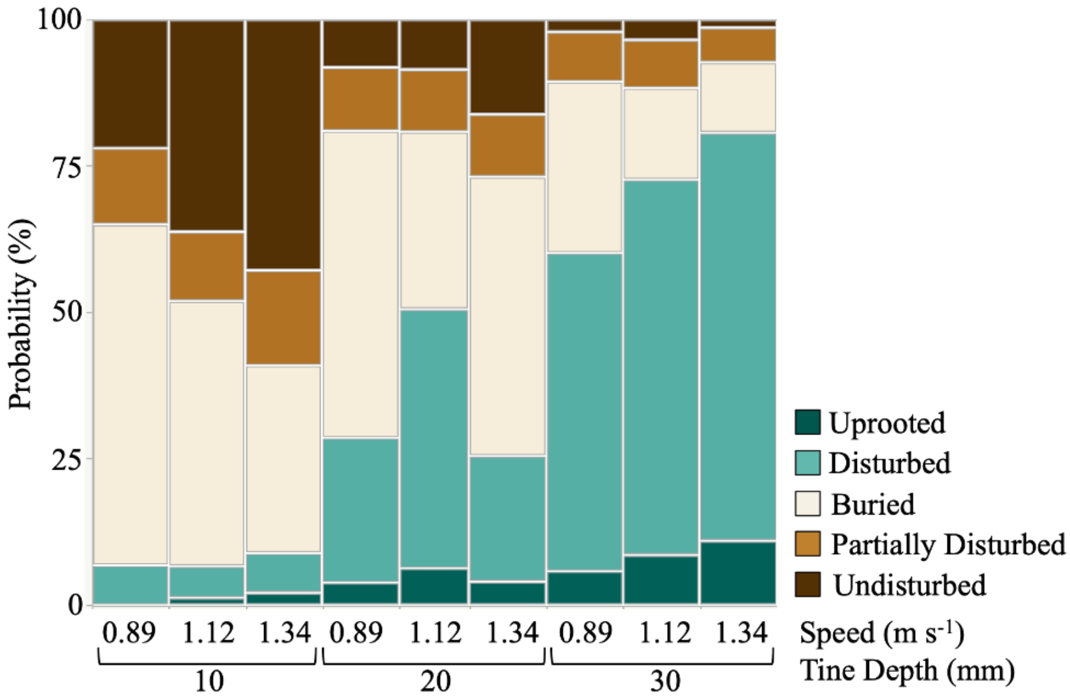


Table 1.3 Odds ratios explaining the likelihood of an artificial weed (AW) (35 mm-long wooden golf tee) being buried vs. undisturbed, uprooted vs. undisturbed, and uprooted vs. buried by a tine weeding tool in a soil bin. Tine speeds tested were 0.9, 1.1, and 1.3 m s^{-1} and the working depths tested were 10, 20, 30 mm; tine angles were 123º, 122º, and 117º respectively. Larger values indicate increased likeliness of and an event occurring.

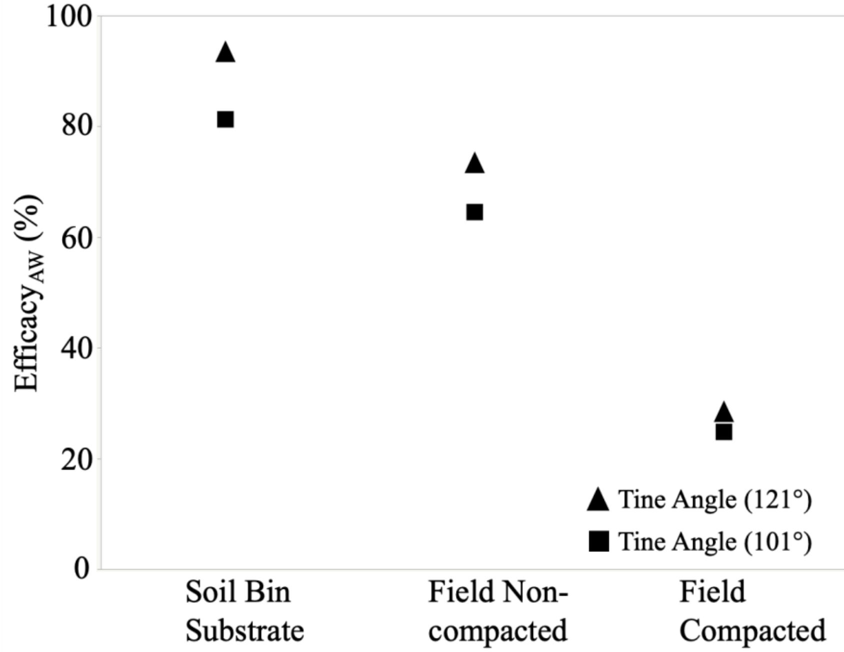
Odds Ratios		**Buried vs. Undisturbed**	**Uprooted vs. Undisturbed**	**Uprooted vs. Buried**
Speed (m s^{-1})	**Tine Depth (mm)**			
0.9	30 vs. 10	5.67*	—	—
0.9	10 vs. 30	—	5.92×10^{-9}	3.36×10^{-8}
1.3	30 vs. 10	11.42*	154.00	13.49
0.9 vs. 1.3	10	3.51*	3.42×10^{-7}	9.74×10^{-8}
0.9 vs. 1.3	30	1.74*	0.38	0.22

*P ≤ 0.05, according to the Chi-squared test

Soil bin and Field Comparisons of Artificial Weed Efficacy

Tool $efficacy_{AW}$ of the minimum (101º) and maximum (121º) tine angles were tested the field and soil bin. The two field experiments were analyzed separately due to a compacted soil vs. a non-compacted soil from rainfall events ($P < 0.001$) (Fig. 1.8). The soil bin environment resulted in the greatest $efficacy_{AW}$ and the compacted soil resulted in the lowest $efficacy_{AW}$ ($P < 0.001$). Within each field experiment, there was no statistical difference between the minimum (101º) and maximum (121º) tine angle ($P = 0.154$). However, there was a main effect of tine angle between all three soil environments where the maximum (121º) tine angle caused greater $efficacy_{AW}$ than the minimum (101º) tine angle ($P = 0.004$) (Fig. 1.8). There was no interaction between tine angle and soil condition ($P = 0.139$).

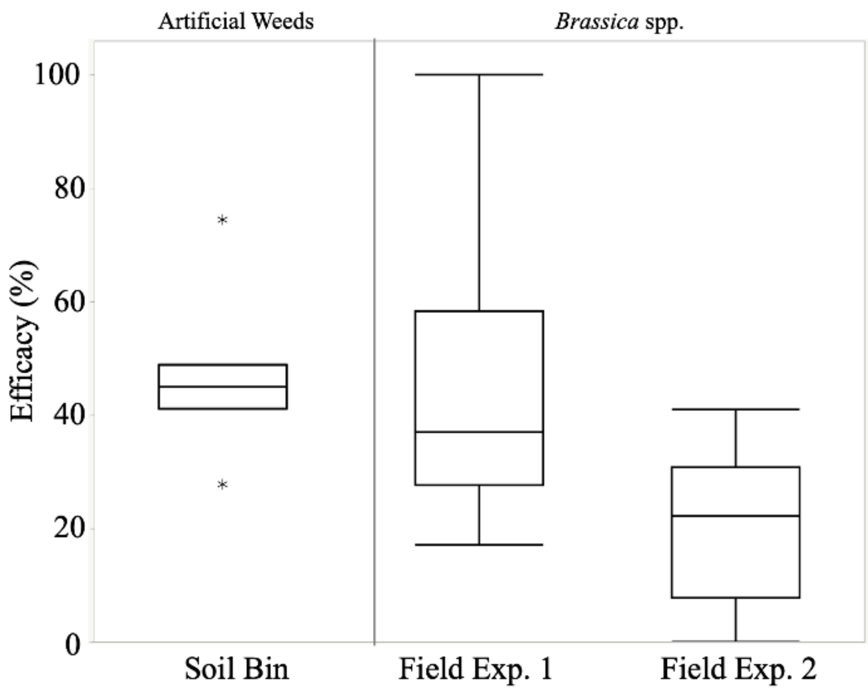
Figure 1.8 Back-transformed mean efficacy using artificial weeds (AWs) (35 mm-long wooden golf tees) from logit transformation. Tine weeding tool used at a minimum (101º) and maximum (121º) tine angle at a speed of 1 m s^{-1} in a soil bin and in the field.



Artificial Weed and Real Weed Comparison

Efficacy data at the 117º tine angle in the soil bin were qualitatively compared with data collected in the field using surrogate and real weeds (Fig. 1.9).

Figure 1.9 Tine rake efficacy$_{AW}$ in the soil bin compared to *Brassica* spp. in field experiments. Tine rake used at a tine angle of 117° and a speed of 1 m s^{-1} in 2019 and 2020 field experiments with Brassica surrogate weeds *B. juncea* and *G. flavescens,* and a real weed *R. raphanistrum.* Outliers shown as asterisks.



Discussion

The controlled conditions of a soil bin, and AW could allow study of many PWC tools and their settings quickly to prioritize later field experiments. We had previously tested wooden golf tees in field experiments, and they appear to be a simple "artificial weed" to observe disturbance caused by PWC tools. After testing 10 to 60 AW 0.25 m^{-2}, we chose a density of 30 AW 0.25 m^{-2} for all future experiments. Variability was unacceptably high at 10 AW 0.25 m^{-2}, and based on observation of slow-motion video footage, at densities greater than 30 AW 0.25 m^{-}

^{2}, the golf tees appeared to be interacting with each other causing indirect, density-dependent effects on tool efficacy$_{AW}$.

Tilling before leveling and compacting is widely used by researchers to reach specific uniform bulk densities in soil bins (Kshetri et al., 2019, Mahadi et al., 2017, Rosa and Wulfsohn, 2008). Preliminary trials were conducted without the addition of soil raking in the leveling and rolling compaction protocol. Over time it was observed that the sides of the soil bin were becoming more compact than the area where cultivation was occurring. This was discovered by observing the resistance from pushing AWs by hand into the cultivation zone compared to the undisturbed sides. However, soil raking before leveling and compacting did not affect efficacy$_{AW}$ (Fig. 1.3). To minimize labor, soil raking was omitted from the soil preparation protocol before cultivation events. This test should be included in future research with new PWC tools.

Tool efficacy$_{AW}$ increased as soil moisture decreased (Fig. 1.4), which led to development of standardized uniform soil conditions. Dry soil in a soil bin has been found to amplify tool working depth and speed effects for tine harrows when cultivating *L. perenne* (Kurstjens and Perdok, 2000). Because we wanted to evaluate precise tool adjustments, we needed to have uniform soil moisture to minimize masking effects of other tool settings. We settled on the following methods for all future tests: the soil bin was watered to field capacity 24 h before a cultivation event to ensure adequate draining and uniform soil moisture (Kshetri et al., 2019, Mahadi et al., 2017, Zhang and Chen, 2017).

Using Newly Developed Methods for Evaluating a Typical PWC Tool

Tine angle, working depth, and speed were evaluated with the tine weeding tool. Steeper tine angles have been observed to increase weeding intensity (Duerinckx et al., 2005, Gerhards et al., 2020), which was observed with the maximum (121º) tine angle (Fig. 1.5). By using a steeper tine angle, the tine oscillates at a higher rate than a shallow tine in the soil while also moving soil upward (Duerinckx et al., 2005). This tine movement would explain the increase in uprooting and the 93% of AWs scored as ‘Dead’ observed in the soil bin at the maximum (121º) tine angle in the MLR analysis (Fig. 1.5).

Slow motion camera footage recorded soil following the curve of the tine creating a ‘wave’ of soil which was able to bury more AWs at the minimum (101º) tine angle. This burial mechanism was also observed by using the MLR to separate score categories (Table 1.2; Fig. 1.7). However, this burial mechanism was achieved by using a steeper tine angle in Gerhards et al. (2020), which is opposite of what we observed. Kurstjens and Perdok (2000) found that increased soil moisture causes the soil to hold its structure, so the curved shape of the tines and the moist sand substrate in the soil bin could have caused a ‘wave’ effect which increased AW burial.

Working depth depends on tine speed, because as a tine increases speed in the soil, the force exerted from the soil on that tine increases, causing the tine to move vertically, thus affecting working depth (Duerinckx et al., 2005). Adjusting tine angle creates uniform soil coverage (Sogaard, 1998). Kurstjens and Perdok (2000) found that increasing tine harrow speed, increased burial of *L. perenne* and *L. sativum*. However, the tines used in the study were vertical, which mitigated the tine depth and speed interaction.

MLR was a useful method to examine the interaction and further explain what the mode of action was at these depths and speeds (Table 1.3; Fig. 1.7). At the 10 mm depth, the amount of burial decreased with increasing speed, which means the tine was not deep enough in the soil to uproot or create a ‘wave’ of soil to cause burial (Fig. 1.7). The number of undisturbed AWs at this depth also increased with increasing speed, which means the tine was not able to cause enough force to disturb the AWs (Fig. 1.7). When increasing the working depth, uprooting increased with increasing speed, but burial decreased (Fig. 1.7). Duerinckx et al. (2005) found high speed, deep working depth, and a steep tine angle to increase the uprooting mode of action for the tine. Increased uprooting was also observed in *L. perenne* and *L. sativum* when increasing tine depth (Kurstjens and Kropff, 2001). The 10 mm tine depth at the 0.9 m s^{-1} setting did not score any uprooted AWs, which means that calculating an odds ratio with a zero in the denominator is undefined (Table 1.3).

Effects of tine angle found in the soil bin were also reflected in the field with AWs (Fig. 1.8). The maximum (121º) tine angle produced the highest efficacy in the soil bin substrate (93%), non-compacted soil (73%), and compacted soil (28%) (Fig. 1.8). Multiple rain events occurred on the field before conducting the experiment causing soil compaction. AWs required more force to push into the soil and were firmly anchored once placed. The second experiment had no rain events and irrigation was not implemented due to freezing temperatures which caused a looser soil structure.

Comparing surrogate and real weeds to AWs can help us determine if the AWs are a viable design to represent what is happening in the field. The first qualitative comparison was done using field data previously collected with the same tine weeding tool at a tine angle of 117º and a walking speed of 0.9 m s^{-1} (Fig. 1.9). Surrogate weed species of *B. juncea* and *G. flavescens* and a real weed, *R. raphanistrum* were used in the field experiment. The field experiment was compared to a soil bin trial using AWs with the same tine weeding tool, speed, and tine angle with a working depth of 10 mm (Fig. 1.9). Based on a qualitative comparison, soil bin data is within the variation of field experiment 1 but is above field experiment 2 (Fig. 1.9).

Limitations

There are some limitations with our research that we recognize. Golf tees may not be the best choice as an artificial as it lacks the flexibility of a real plant. Also, when using the golf tee, only 2 mm is exposed to the surface, making it easier to bury than if it were made of a taller more flexible material. The type of golf tee we used may be suitable for tine harrows, but tools with different modes of action will likely need refined AW designs.

It would be ideal if we could evaluate different soil types. Because the soil bin has solid sides, we would have to greatly change the design to accommodate separate bins of soil. We would also like to test real plants in the soil bin. Plants could be grown in a container outside of the soil bin then add the container when the plants are ready to be cultivated. To keep the soil bin free of organic matter or weed seeds, the container must be removed after cultivation. Alternatively, research and development of realistic AWs could allow us to conduct experiments without the limitations of real plants.

CHAPTER 2 FINGER WEEDER TESTING USING ARTIFICIAL WEEDS IN A CONTROLLED ENVIRONMENT TO OPTIMIZE EFFICACY

Introduction

Physical weed control (PWC), also known as cultivation, involves moving tools through the soil to physically kill weeds. The main issue farmers face with PWC is that weed mortality is often low and highly variable (Gallandt et al., 2018). Soil type and moisture, crop species and growth stage, weed species and growth stage, cultivation tool design and settings can all affect efficacy (Gallandt et al., 2018, Gerhards et al., 2020, Kurstjens and Perdok, 2000, Rueda-Ayala et al., 2010). Efficacy refers to the proportion of weeds killed. It is measured by counting weeds within a known area before a cultivation event and again after (Gallandt et al., 2018). Generally, efficacy is lower in the area closest to the crop row, the "intra-row," and greater in the area between crop rows, or the "inter-row" zone (Gallandt et al., 2018). Effective PWC typically depends on the presence of a large crop-to-weed size differential (Van Der Weide et al., 2008) allowing tools to target the intra-row zone more aggressively with reduced risk of crop injury.

Farmers generally learn to improve PWC performance by way of experience, and trial-and-error, also known as the 'art' of PWC (Bowman, 2002). Systematic testing of PWC tools and their operational settings could accelerate this learning curve. Settings would best be tested in field experiments, but these are expensive and time-consuming. Testing PWC tools within a controlled environment may help prioritize settings for later field experiments offering, high-throughput testing in a controlled environment. Kshetri et al. (2019) and Parks and Gallandt (unpublished) measured PWC tool disturbance using artificial weeds (AWs) and crops (ACs) in a soil bin.

A soil bin is generally filled with field soil or other substrate, through which tools are moved at precise settings of angle, spacing, depth, or speed. Soil bins have typically been used by agricultural engineers (Clark and Liljedahl, 1968, Durant et al., 1980, Mahadi et al., 2017), but there are also examples of them being used to evaluate PWC tools. Duerinckx et al. (2005) studied the forces exerted on a tine harrow at different speeds and tine angles and found that using a steep angle at a slow speed and constant depth could increase tool efficacy and cause less crop damage. Kurstjens and Perdok (2000) cultivated *Lepidium sativum* L. (garden cress) and *Lolium perenne* L. (ryegrass) with a tine harrow at three depths, four speeds, and three soil moisture levels and measured plant burial. They found that increasing speed increased soil covering but not burial depth, and dry soil was able to spread over a greater area (Kurstjens and Perdok, 2000). Zhang and Chen (2017) tested four different style sweeps and measured cultivation width, burial width, and uprooting width and they found that the greatest efficacy was achieved with the three-quarter-conventional sweep and fin sweep.

Finger weeders are a popular PWC tool because they target the intra-row zone, offering relatively high efficacy and good crop/weed selectivity (Van Der Weide et al., 2008). Despite their popularity, especially in vegetable crops, there is little research on evaluating finger weeder tool settings.

We hypothesized that changing finger weeder angle, spacing, and speed could each affect tool efficacy. Not surprisingly, angle affects the efficacy of sweeps (Terpstra and Kouwenhoven, 1981) and tine harrows (Duerinckx et al., 2005, Gerhards et al., 2020, Rasmussen et al., 2008), with more aggressive angles moving more soil. Finger weeders, however, are often manufactured to operate at a single angle, generally close to 90º. The HAK tools we tested are unique in this regard with a mechanism that allows the tools to be angled anywhere from 68º to

108º relative to 90º. Brown and Gallandt (2018) adjusted finger weeder angle to cause soil hilling in the intra-row zone which improved tool efficacy.

Decreasing finger weeder spacing is suggested to improve efficacy as the crop gets bigger and more tolerant of direct cultivation (Bowman, 2002, Van Der Weide et al., 2008). Van der Schans et al. (2006) recommends starting with a 2 cm gap between fingers when the crop is small, moving to a 5 cm overlap as the crop becomes larger and better rooted. While decreasing finger weeder spacing will increase intensity, it is worth noting that this tool only controls small weeds in the area disturbed (Machleb et al., 2021). As expected, increasing tool spacing decreases crop injury (Cloutier et al., 2007). When cultivating onions (*Allium cepa* L.) at the 1 leaf and 2-4 leaf stage, Ascard and Bellinder (1996) used finger weeders at a 2.5 cm spacing and with fingers touching, respectively. The 2.5 cm spacing reduced onion stand by a third and caused onions to produce thick necks, but very little damage was caused by the second cultivation event with touching fingers (Ascard and Bellinder, 1996).

Increasing speed can also affect efficacy in certain tools; however, this effect may vary with tool design and settings. For example, increasing tine harrow speed causes tines to lift, decreasing working depth, which decreases uprooting ability (Duerinckx et al., 2005); however, if tine working depth can be fixed, increasing speed can increase uprooting (Kurstjens et al., 2000). Van der Schans et al. (2006) recommended using finger weeders at speeds ranging from 4 to 12 km h^{-1}, similar to the 5 to 10 km h^{-1} suggested by Bowman (2002). Machleb et al. (2021) fabricated motors to increase rotational speed independent from tractor speed and found that increasing finger weeder rpm increased tool efficacy when compared to conventional ground-driven designs. While a promising result, this concept has not yet been commercialized.

While tool setting recommendations for finger weeders are relatively common, both in online videos and in extension publications, little research has been done to systematically test the effects of finger weeder settings including angle, spacing, and speed. In the present study, we tested these variables in both a controlled environment soil bin system, and in the field. If the soil bin can reliably predict treatment effects in the field, then rapid testing of PWC tools may be possible to help prioritize field experiments. The objectives of this study were to, (1) determine whether using a soil bin is a viable research tool for evaluating PWC tool settings and (2) provide farmers with researched based recommendations on how to increase finger weeder performance by adjusting angle, spacing and speed.

Materials and Methods

Soil Bin

A soil bin was constructed based on the design of Mahadi et al. (2017) described in detail previously (Parks and Gallandt, in review). Dimensions of the soil bin were 12 m by 2 m (Fig. A.1). Landscaping fabric lined the soil bin with a 36 cm layer of gravel and a 10 cm layer of soil substrate on top, comprised of 95% sand, 2% silt, and 3% clay (Owen J. Folsom, Greenbush, ME, USA). Finger weeders were mounted to an electric belt-driven tool carriage transported on rails above the soil. Adjustments of angle and working depth could be made from the tool carriage, and adjustments of cultivation speeds, ranging from 0.4 to 19 km h^{-1}, could be made from the soil bin control panel. Soil preparations, including leveling, compacting, and watering were as described previously (Parks and Gallandt, in review).

Soil Bin Angle, Spacing, and Speed Trials

Two experiments tested finger weeder angle and spacing, and another two experiments tested speed. Angle and spacing experiments were a full factorial, completely random design with four replications; each experiment was replicated twice. AWs consisted of 70 mm-long wooden golf tees that were pushed into the soil to a depth of 42 mm. From here onwards, tool efficacy using AW will be defined as tool efficacy$_{AW}$. Artificial crops (ACs) consisted of 6 mm dia. by 152 mm-long wooden dowels that were pushed into the soil to a depth of 70 mm. A 10 by 125 cm quadrat was split with a string into a 5 cm intra-row zone and a 5 cm near-row zone. Centered within the intra-row zone of the quadrat, a row of 16 ACs were placed at a 7.6 cm spacing. Then 15 AWs were placed randomly in the intra-row zone, and 15 AWs were placed in the near-row zone. To measure tool efficacy, a disturbance scale developed previously was used to score AWs and ACs following cultivation (Parks and Gallandt, in review).

The finger weeders tested were from HAK (HAK Schoffeltechniek, Bleiswijk, Netherlands). They were 26 cm dia. and attached to a toolbar with an adjustable down pressure spring and an adjustable angle mount. This finger weeder was used in our previous research on tool stacking (Brown and Gallandt, 2018). Treatments consisted of three angles, 68º which caused hilling in the intra-row zone, 90º which is the standard setting for most finger weeders on the market, and 108º which caused a scrubbing action, moving soil away from the intra-row zone. The three spacings evaluated were: 2.5 cm gap between fingers; 0.0 cm, with fingers touching; and a 0.6 cm overlap of fingers. Treatment selection was informed by observations of efficacy and crop/weed selectivity in table beet (*Beta vulgaris* L.). Angles 68º and 108º were selected by finding the minimum and maximum functioning angle for the finger weeder, respectively. Spacing treatments were selected based on visual estimates of weed control and crop damage in our related field studies. When finger weeding at a 90º angle, with 2.5 cm gap, 0.0 cm, and 0.6 cm overlap, efficacy and selectivity were suboptimal, optimal, and too aggressive, respectively. In experiments evaluating the effects of angle and spacing, speed was held constant at 7 km h^{-1}.

ACs were marked to keep planting depth constant and to measure soil movement. Following cultivation, soil height was measured on upright ACs. Values above the pre-treatment line were denoted as positive soil movement and values below the pre-treatment were denoted as negative soil movement.

Finger weeder experiments were done using a similar speed and experimental design. Treatments were selected to represent speeds typical for walking (4 km h^{-1}), tractor cultivating (7 km h^{-1}), and a tractor system with camera guidance (9 km h^{-1}). In speed experiments, finger weeders were set at an angle of 84° with fingers overlapping 0.6 cm. This optimal setting was determined by observations made in the field when cultivating bush bean (*Phaseolus vulgaris* L.) practice rows.

Field Trials

Angle, spacing and speed were also tested in field experiments conducted at the University of Maine's research farm in Old Town, Maine (44.930223° N, -68.694414° W; Rogers Farm) in 2021 and 2022. The weather in 2021 was a lot drier in June, but July was wetter than normal. In 2022, the weather was a lot drier than normal for the season (Table C.1). The soil was a Nicholville very fine sandy loam. Field sites were chisel plowed and disced, followed by smoothing and leveling with a 3 m Rigid Perfecta II Harrow field cultivator (Unverferth Manufacturing Co. Inc., Kalida, OH, USA). Fields were fertilized uniformly with pelleted organic chicken manure 4-1-2 at a rate of 2.8 t ha^{-1} (Envirem Organics Inc., Fredericton, NB, Canada). Based on soil test results, boron was also applied uniformly to fields using 20 Mule Team Borax Solubor DF at a rate of 17 kg ha^{-1} (Fedco Seeds, Clinton, ME, USA).

Surrogate weeds *Brassica juncea* L. Czern. (condiment mustard) and *Amaranthus tricolor* L. (garnet red amaranth) (Johnny's Selected Seeds, Winslow, ME, USA) were broadcast seeded with a walk behind EarthWay bucket spreader (EarthWay Products, Inc., Bristol, IN, USA) at a rate of 861 seeds m^{-2} per species. To prepare a seedbed for the surrogate weeds, the inter-row zone, up to 5 cm from the crop row, was raked by hand with a tine rake (Johnny's Selected Seeds, Winslow, ME, USA) 22 d after planting table beets. Then, the inter-row zone was raked in the opposite direction 5 cm from the crop row to cover the newly sown seeds. Due to poor establishment of *A. tricolor,* it was omitted and only results from *B. juncea* are reported. Ambient and surrogate weeds were counted separately in the intra- and near-row zones before cultivating. If pre-treatment weed counts totaled < 40 per subsample, additional quadrats were counted moving down the row. Post-treatment counts were collected 48 h after cultivation. From here on, tool efficacy using surrogate weeds is defined as tool $efficacy_{SW}$.

Field Tool Angle and Spacing Experiments

Finger weeder angle and spacing were tested in a full factorial randomized complete block design with four blocks; the test crop used was organic red table beet, F1 hybrid 'Boro' (Johnny's Selected Seeds, Winslow, ME, USA). Table beets were direct seeded with a Wizard vacuum seeder (Wizard SRL, Pontebbana PN, Italy) to a depth of 1.3 cm, a plant spacing of 3.8 cm within rows, and a row spacing of 51 cm. At the cotyledon stage, table beets were thinned by hand to a within-row spacing of 7.6 cm for a target density of 104 plants m^{-1} row.

Treatment plot dimensions were 1.2 m by 15.2 m, containing two crop rows spaced at 51 cm. Within the plot were three randomly placed permanent subsamples. Within each subsample, a 125 cm by 5 cm quadrat split with a string was used to measure tool efficacy with surrogate and ambient weeds in a 2.5 cm intra-row and 2.5 cm near-row zone. Inter-row ambient weeds were controlled with 15 cm diameter cut-away disks and 26 cm wide sweeps operating 8 cm from the crop row to ensure minimal damage until the crop was developed enough to handle finger weeding treatments. This weeding event was completed using a HAK LTC 1 tool carrier (HAK Schoffeltechniek, Bleiswijk, Netherlands), which was also used for finger weeder treatments. After using the cut-away disks, intra-row ambient weeds that were first true leaf and larger were hand-pulled.

Once the crop was at the 9-10 leaf stage and surrogate weeds were at the cotyledon to first true leaf stage, ambient weeds, surrogate weeds and crop plants were counted. The three most abundant ambient weed species in 2021 were *Portulaca oleracea* L. (common purslane), *Capsella bursa-pastoris* L. (shepherd's purse), and *Stellaria media* L. (common chickweed). In 2022 the three most abundant weed species were *P. oleracea*, *Chenopodium album* L. (common lambsquarters), and *Digitaria sanguinalis* L. (large crabgrass).

Soil movement was measured using the same protocol as in the soil bin, with one round wooden dowel (6 mm dia. by 152 mm long) in each subsample. The wooden dowel was randomly placed in line with the crop row without damaging counted surrogate and ambient weeds. Finger weeder angle and spacing treatments were as discussed previously for the experiments. Speed was 7 km h^{-1}.

Surviving weeds and crop plants were counted 48 h after finger weeder treatments. Ambient and surrogate weed counts were also collected 14 d after cultivation to measure subsequent recruitment. Fresh crop biomass was collected by sorting beets into categories marketable, unmarketable, and marketable with defects according to the United States Department of Agriculture standards for bunched table beet (USDA, 2016).

Field Speed Trials

Speed effects on finger weeder efficacy using surrogate and ambient weeds were tested using a randomized complete block design with four replications. Three speed treatments were as described previously. The test crop was an organic bush bean, 'Provider' (Johnny's Selected Seeds, Winslow, ME, USA). Bush beans were directly seeded with a Wizard vacuum seeder to a depth of 2.5 cm, crop spacing of 3.8 cm within rows, and 51 cm rows. The achieved plant density was 10 plants m^{-1} of row. Plot dimensions, subsampling procedure, quadrats, finger weeders, and tool carrier were as described above. Due to labor constraints, crop biomass and weed recruitment data were not collected in the speed trials.

Finger weeders were adjusted to perform optimally by using practice rows in the experimental area. The desired outcome of the optimal tool setting was to have minimal visual crop damage within (< 5%) and high visual weed mortality (60 to 80%). Aggressive, optimal and suboptimal settings were identified to ensure proper tool setup for the soil conditions and weed and crop growth stage. Optimal tool settings for 2021 were an 87º tool angle and a 0.0 cm spacing, and settings were an 84º tool angle and a 0.6 cm overlap spacing for 2022. In 2022 an additional neutral tool treatment of 90º angle and 0.0 cm spacing was added to contrast the optimal tool setting treatment.

Data Analysis

The statistical software used for data analysis was JMP®, Pro 16.0.0 (SAS Inc., Cary, NC, 1989-2021). Analysis of variance (ANOVA) was used to explore main effects, interactions, and random effects. The assumptions of normally distributed and homoscedastic residuals were verified using the Shapiro-Wilks test and observations of Studentized residual plots, respectively.

Data were transformed if the assumption of normality was not met, and back-transformed means are reported throughout the results.

When soil bin experiments were compared to field experiments, a narrow-sense conclusion was used to analyze how the treatment effects differed between environments (Glaz and Yeater, 2020). A narrow-sense conclusion uses location or environment as a fixed effect in an ANOVA to test the differences between environments. To test differences between the soil bin environment and the field environment, the full ANOVA model used to analyze angle and spacing included the fixed variables: Angle; Spacing; Angle * Spacing; Location; Location * Angle; Location * Spacing; and Location * Angle * Spacing.

A broad-sense conclusion was used in the model when comparing experiments done over multiple years in different locations to explain treatment effects over different environments (Glaz and Yeater, 2020). A broad-sense conclusion uses experiments conducted over multiple years and/or environments by using year or environment as a random effect in an ANOVA to test for the overall treatment effect across years and/or environments. The full ANOVA model used to analyze angle and spacing experiments included the fixed variables: Angle; Spacing; and Angle * Spacing, as well as random variables, Year; Block nested within Year; Year * Angle; Year * Spacing; and Year * Angle * Spacing.

If no significant year-by-treatment effects were observed, random interaction terms were dropped from the model, beginning with the highest-order term. Model reduction was concluded if a fixed variable p-value was ≤ 0.05, or if only Year and Block nested within Year remained as random effects. Significant main effects and interactions were followed by mean comparisons using a Tukey's Honest Significant Difference test using $\alpha = 0.05$.

A logistic regression (Agresti, 2012) was used for skewed data where the assumptions of ANOVA could not be met using transformations. AC mortality in the angle and spacing trial and near-row AW efficacy in the speed trial conducted in the soil bin were organized into the categorical variables, “Dead” or “Alive,” and analyzed using a chi-squared test in a logistic regression model. The odds from the model were saved and used to calculate the odds ratios to compare significant treatment effects.

Results

Soil Bin Tool Angle and Spacing

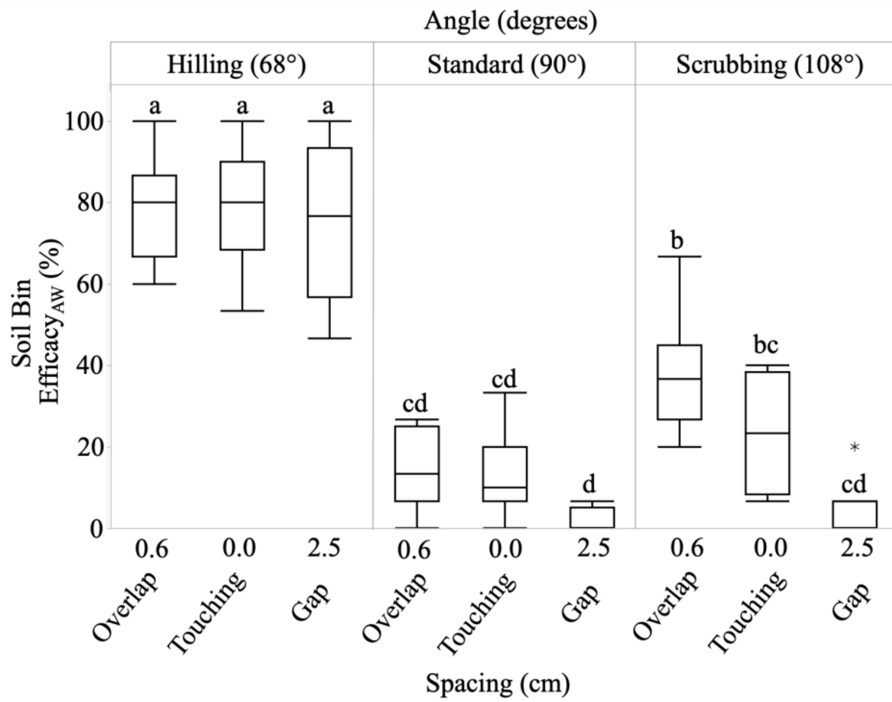
Soil bin experiments started with three finger weeder angles and three spacings. Tool $efficacy_{AW}$ was significantly higher in the near-row zone than the intra-row zone and was separated for analysis ($P < 0.001$). There was an interaction between angle and spacing where $efficacy_{AW}$ did not change between spacings at a hilling angle but decreasing spacing at a scrubbing angle increased $efficacy_{AW}$ (Table 2.1; Fig. 2.1). Angle and spacing tool $efficacy_{AW}$ in the near-row zone followed the same trend as what was seen in the intra-row zone, but at an overall greater efficacy (data not shown).

Table 2.1 The effect of finger weeder angle and spacing on efficacy using artificial weeds (AW, 70 mm-long wooden golf tees), surrogate weed (*B. juncea*), and ambient weeds in soil bin and field experiments. Angles included, hilling (68º), standard (90º), and scrubbing (108º), while spacing included 0.6 cm overlap, 0.0 cm fingers touching, and 2.5 cm gap. All treatments were tested at 7 km h^{-1}.

	Efficacy			
ANOVA	**Soil bin**		**Field***	
	intra-row	**near-row**		
	Artificial Weeds		***B. juncea***	**Ambient weeds**
Angle	< 0.001†	< 0.001†	< 0.001†	< 0.001†
Spacing	0.001†	0.015†	0.129	0.737
Angle x Spacing	0.032†	0.689	0.074	0.558

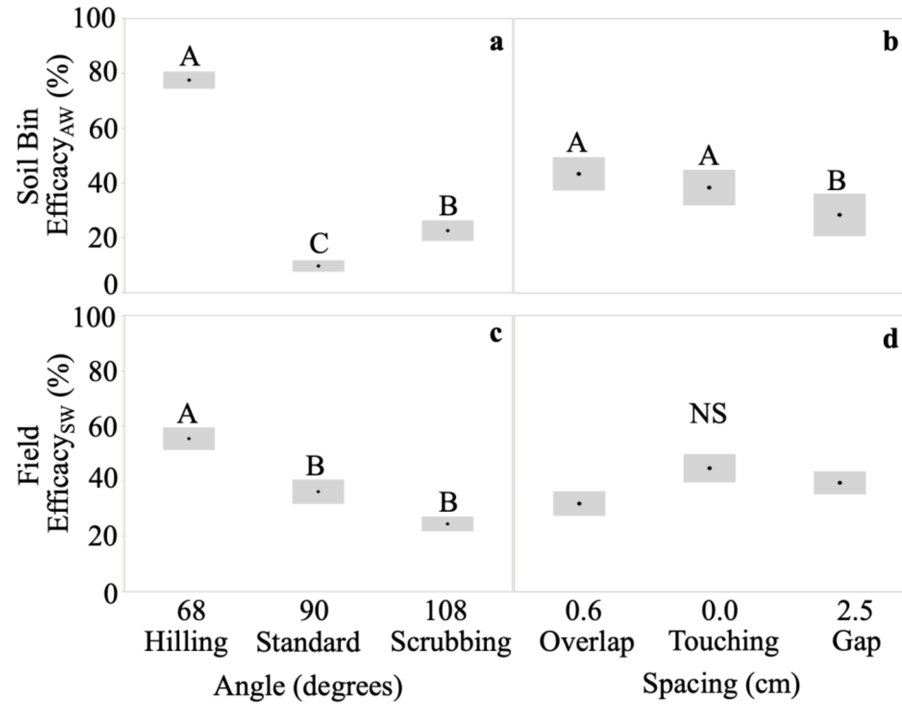
*intra- and near-row combined, †P ≤ 0.05

Figure 2.1 Finger weeder spacing by efficacy$_{AW}$ in a soil bin. Treatments with common letters are not statistically different using the Tukey HSD at an $\alpha \leq 0.05$.



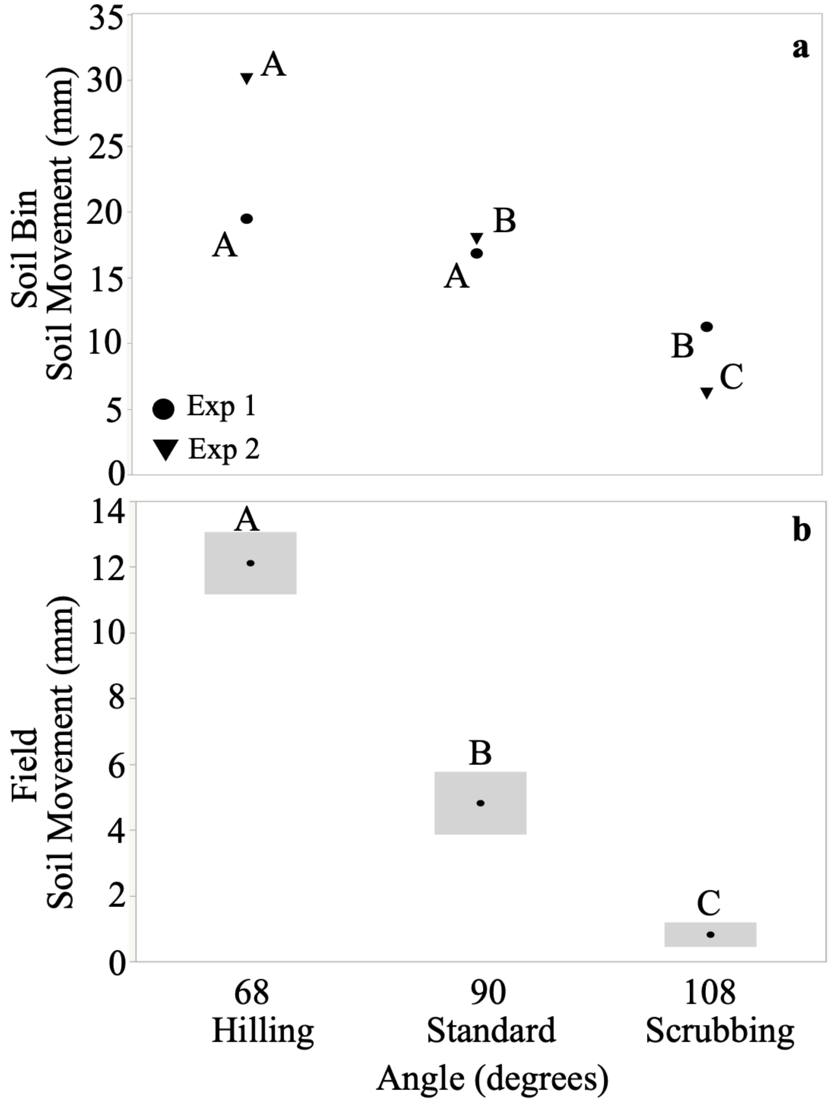
Intra-row tool efficacy$_{AW}$ was greatest with hilling (78%) and much lower with both the standard angle (10%) and scrubbing angle (23%) (Fig. 2.2a). The hilling angle also offered the greatest efficacy$_{AW}$ in the near-row zone (96%). Intra-row efficacy$_{AW}$ was greater when fingers overlapped than when there was a gap between fingers; however, there was no difference between the overlapping and touching spacings (Fig. 2.2b). In the near-row zone, efficacy$_{AW}$ for the overlapping fingers (86%) was greater than for the gap spacing (72%).

Figure 2.2 Finger weeder artificial and surrogate weed efficacy by angle and spacing. Shaded bands represent standard error around the mean. Mean values presented alongside similar letters are not statistically different using the Tukey HSD at an $\alpha \leq 0.05$.



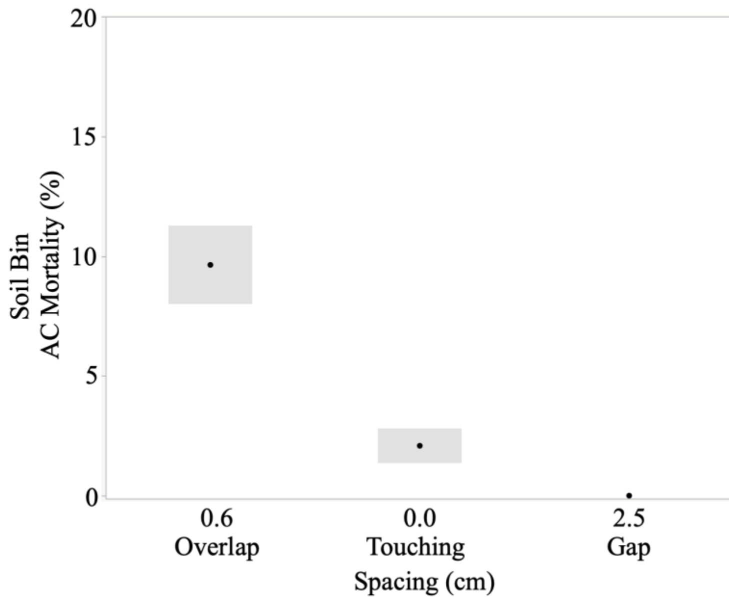
Soil movement differed in the two trials ($P < 0.001$). In experiment one, soil movement was similar in both hilling and standard angle treatments ($P = 0.105$) and spacing had no significant effect ($P = 0.189$). In experiment two, hilling moved 120% more soil than the standard angle ($P < 0.001$) and the gap spacing moved 75% more soil than the overlapped spacing ($P = 0.003$). In both experiments hilling moved 25 mm of soil on average into the crop row (Fig. 2.3a).

Figure 2.3 Finger weeder soil movement in the intra-row zone. In Fig. a, data underwent a square root transformation before analysis and back-transformed means are reported. In Fig b., shaded areas represent standard error. Mean values presented alongside similar letters are not statistically different using the Tukey HSD at an $\alpha \leq 0.05$.



AC mortality was determined using the same scoring method that was used for AWs. Angle did not affect AC mortality (data not shown). As spacing decreased, AC mortality increased ($P < 0.001$) according to a chi-squared test using logistic regression (Fig. 2.4). The odds ratio for the main effect of spacing is 4.71×10^{-8} times likely to be scored as "Dead" when using a gap of 2.5 cm compared to an overlap of 0.6 cm.

Figure 2.4 Finger weeder spacing by artificial crop mortality. Shaded bands represent standard error around the mean. Spacing was significant ($P < 0.001$) according to Chi-squared test.

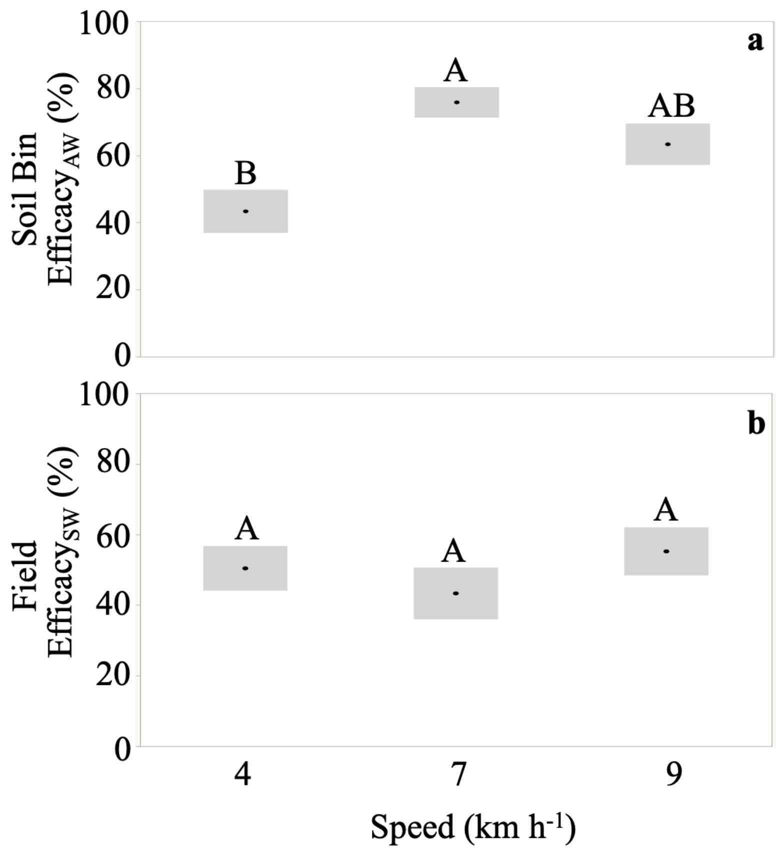


Soil Bin Speed

Tool efficacy$_{AW}$ in the near-row zone was greater than intra-row zone and was separated for analysis ($P < 0.001$). The two higher speeds 7 and 9 km h^{-1} increased intra-row efficacy$_{AW}$ by 77% compared to 4 km h^{-1} ($P = 0.002$) (Fig. 5a). Based on logistic regression, increasing speed increased near-row efficacy$_{AW}$ ($P < 0.001$). At the highest speed tested (9 km h^{-1}), AWs were

10.82 times more likely to be scored "Dead" when compared to 4 km h^{-1} (P = 0.024). Higher speeds (7 and 9 km h^{-1}) also moved 36% and 18% more soil into the crop row compared to 4 km h^{-1}, respectively (P = 0.001) (data not shown). AC mortality was not affected by speed (data not shown).

Figure 2.5 Finger weeder efficacy effects by speed using artificial and surrogate weeds. Shaded area around the mean represents standard error. Mean values presented alongside similar letters are not statistically different using the Tukey HSD at an $\alpha \leq 0.05$.



Field Tool Angle and Spacing

Angle and spacing experiments were replicated in the field to determine whether treatment effects reflected soil bin results. In 2022, data from one block skewed tool efficacy with surrogate and ambient weeds and masked treatment effects due to a rocky outcropping, so the block was removed from the data set. Efficacy with surrogate and ambient weeds from the intra- and near-row zones were not significantly different from each other (data not shown); thus, combined data from the two zones is presented.

Hilling consistently resulted in the greatest efficacy_{SW} (62%) ($P < 0.001$) (Fig. 2c) and efficacy in ambient weeds (64%) ($P < 0.001$). In contrast, spacing did not affect efficacy_{SW} (Fig. 2.2d) or tool efficacy of ambient weeds. Hilling resulted in more soil movement in the field than the standard and scrubbing angles ($P < 0.001$) (Fig. 2.3b). Angle and spacing did not affect *B. juncea* or ambient weed recruitment 14 d after cultivation (data not shown).

Angle and spacing had no effect on marketable or unmarketable yield components (data not shown). The marketable with defects category was analyzed separately by year. In 2021 the scrubbing angle with fingers touching caused more damage to table beets than all other treatments ($P = 0.012$), but in 2022 there were no significant effects (data not shown). Total table beet fresh weight was not affected by treatment in either year (data not shown). In 2021, the standard angle at a touching spacing caused the greatest table beet mortality but changing spacing to an overlap resulted in the lowest mortality ($P = 0.010$); whereas in 2022, no crop mortality was observed for any treatment (data not shown).

Field Speed

Speed effects on efficacy were tested in field experiments. Only intra-row efficacy$_{SW}$ is reported due to poor surrogate weed germination rates in the near-row zone in 2022. Intra-row tool efficacy$_{SW}$ was affected by speed (P = 0.048) (Fig. 2.5b).

A standard tool setup was only tested in 2022 to compare to the optimal tool setting. Efficacy$_{SW}$ of the optimal tool setting and the standard (90º angle and, 0.0 cm spacing) were similar (data not shown). Surprisingly, in the field, speed also did not affect intra-row ambient weed efficacy, soil movement or bush bean mortality (data not shown).

Discussion

Using the Soil Bin as a Tool for Physical Weed Control Research

We expected finger weeder angle would affect efficacy in both the soil bin and field. Brown and Gallandt (2018) found that an 84º angle caused a hilling effect with finger weeders tested in Maize (*Zea mays* L.). We found finger weeders at a 68º angle caused hilling and the greatest efficacy in both the field and the soil bin (Fig. 2.2). The comparatively loose sand substrate in the soil bin is easily moved by the finger weeders, which could explain why there was less soil movement in the field (Fig. 2.3).

In the field, hilling resulted in soil movement into the intra-row zone achieving a burial depth of 12 mm, which is below the lethal burial depth of 100 mm for most plants (Merfield et al., 2020). However, by using mini-ridgers, 100 mm tall plants perished from 10 to 20 mm of soil coverage if the whole plant was covered (Merfield et al., 2020). Furthermore, Terpstra and Kouwenhoven (1981) killed 25-30 mm tall *L. sativum* using a Steketee hoe that resulted in a burial depth of 15 to 20 mm. Kurstjens and Perdok (2000) were able to bury *L. sativum* and *Lolium perenne* L. (ryegrass) with 10 to 15 mm of soil using a tine harrow, but efficacy was reduced because plants were not entirely covered. These studies suggest that our finger weeder hilling treatment may be more aggressive in disturbing the intra-row zone by suppressing weeds with 12 mm of soil movement than the standard and scrubbing angles with 5 mm and 1 mm, respectively (Fig. 2.3).

We expected to increase $efficacy_{AW}$ with decreasing spacing but were surprised to find this effect depend on angle (Fig. 2.1). When using a hilling angle, finger weeder spacing was not important, but when a scrubbing angle was used, decreasing spacing increased $efficacy_{AW}$ in the soil bin. Decreasing finger weeder spacing can increase the aggressiveness of a cultivation event and is recommended as the crop develops (Bowman, 2002, Van Der Weide et al., 2008). In the field however, we failed to detect an effect of spacing on surrogate or ambient weed efficacy, or table beet yield (data not shown). We did observe that the scrubbing angle with fingers touching caused table beet leaf damage and hypocotyl blemishes, but this was only seen one of the two years. Asaf et al. (2023) used a 5-6% finger overlap on table beets at both 6 leaf and 8-10 leaf stages, which resulted in greater crop mortality relative to an herbicide treatment. We judged our finger weeder settings as optimal for both crop/weed selectivity weed control and based on how we thought a farmer would adjust the tool. In future work it would be informative to include a setting aggressive enough to detect a reduction in crop mortality and yield.

In the soil bin, $efficacy_{AW}$ increased with increasing speed (Fig. 2.5a), but this was not observed in the field (Fig. 2.5b). Motorized finger weeders increased efficacy at a higher rpm than conventional finger weeders in sugar beet (*Beta vulgaris* subsp. Vulgaris, Altissima Group), but efficacy was similar between the slow and fast rpm settings (Machleb et al., 2021). In explicably, Brown and Gallandt (2018) observed a negative effect on efficacy as speed increased (1.6, 4.8, 8.0, and 11.2 km h^{-1}) when testing finger weeders and stacked tools. The effect of speed detected in the soil bin could be an artifact of the sand substrate. Our results suggest however, that increasing finger weeder speed in the field may not result in significant changes in performance.

Our aim with this work was to determine whether the controlled conditions of a soil bin could be useful for testing PWC tools. The soil bin detected more significant effects for finger weeder angle, spacing, and speed in the intra- and near-row zone when compared to field experiments. Although the effects of spacing and speed were not significant in the field, hilling was detected in both systems (Fig. 2.2). We conclude that the soil bin is a promising research tool environment for testing PWC tools. Evaluating finger weeder angle, spacing, and speed in a controlled environment allowed us to see treatment effects that were not observed in the field. It is expected that improvements made to AWs would improve response resemblance to that of real and surrogate weeds. The development of a more realistic AW would allow us to examine PWC tool settings more closely within the soil bin.

Recommendations on Finger Weeder Tool Settings

Our work has practical implications for vegetable farmers, and we recommend they adjust finger weeders to cause hilling if possible. We observed improved efficacy with this setting in the field and the soil bin (Fig. 2.2a and 2.2c). Spacing, in contrast, was less important than expected, and did not affect efficacy (Fig. 2.2d) or table beet yield in the field (data not shown). However, spacing effects on AW efficacy and AC mortality were both detected significant in the soil bin (Fig. 2.2b and 2.4). This discrepancy between the field and soil bin could indicate that there is an effect of spacing, but the magnitude of effects were not large enough to be detected. Farmers should adjust spacing based on crop size to minimize damage and yield loss (Van Der Weide et al., 2008). Speed was significant in the soil bin, but not in the field (Fig. 2.5), suggesting that hand tools could offer similar weed control to mounted tractor tools.

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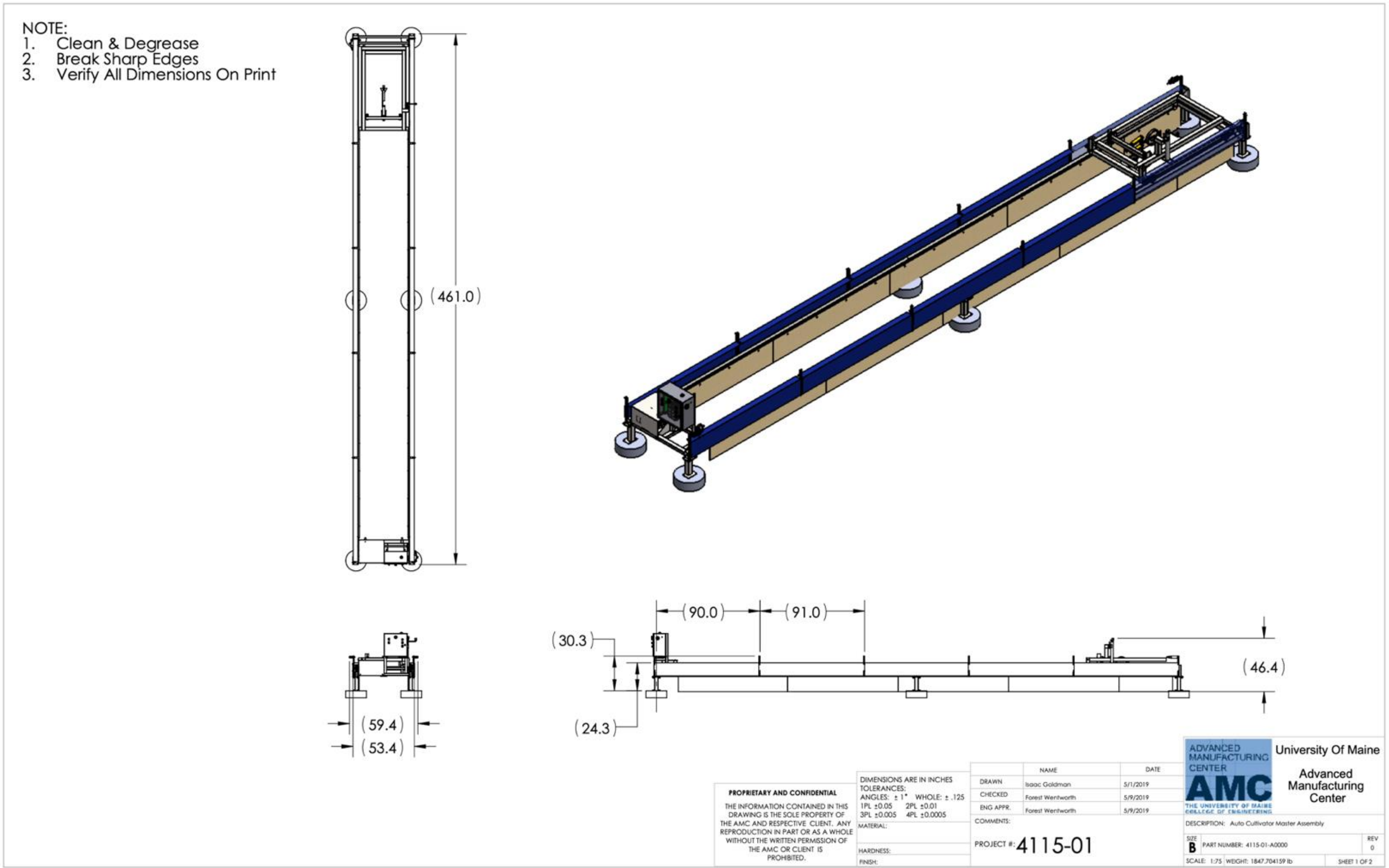
APPENDICES

APPENDIX A. SOIL BIN SCHEMATIC

Figure A.1 Schematic of the soil bin built by the Advanced Manufacturing Center at the University of Maine, Orono, ME, USA.



APPENDIX B: CHAPTER ONE SUPPORTING INFORMATION

Table B.1 Contingency table showing how many artificial weeds (AW) (35 mm-long wooden golf tees) were scored in each disturbance category between the minimum (101º) and maximum (121º) tine angles. Counts are used to calculate odds and odds ratios. The Row % is the probability of a certain score occurring at the specific tine angle.

Count Total % Column % Row %	**Uprooted**	**Disturbed**	**Buried**	**Partially Disturbed**	**Undisturbed**	**Total**
Minimum Tine Angle (101°)	53.00	198.00	37.00	52.00	20.00	360.00
	7.36	27.50	5.14	7.22	2.78	50.00
	40.15	43.81	92.50	71.23	86.96	
	14.72	55.00	10.28	14.44	5.56	
Maximum Tine Angle (121°)	79.00	254.00	3.00	21.00	3.00	360.00
	10.97	35.28	0.42	2.92	0.42	50.00
	59.85	56.19	7.50	28.77	13.04	
	21.94	70.56	0.83	5.83	0.83	
Total	132.00	452.00	40.00	73.00	23.00	720.00
	18.33	62.78	5.56	10.14	3.19	

Table B.2 Contingency table showing how many artificial weeds (AW) (35 mm-long wooden golf tees) were scored in each disturbance category between tine depths 10, 20, 30 mm and speeds 0.9, 1.1, 1.3 m s^{-1}. Counts are used to calculate odds and odds ratios. The Row % is the probability of a certain score occurring at the specific tine depth and speed. Treatment 20 mm and 1.1 m s^{-1}, the total is 330 instead of 360, due to an error with data collection and the subsample was omitted from analysis.

Count / Total % / Column % / Row %		Uprooted	Disturbed	Buried	Partially Disturbed	Undisturbed	Total
Depth (mm)	**Speed (m s^{-1})**						
10	**0.9**	0.00	25.00	209.00	47.00	79.00	360.00
		0.00	0.78	6.51	1.46	2.46	11.21
		0.00	2.36	18.13	13.74	15.74	
		0.00	6.94	58.06	13.06	21.94	
10	**1.1**	5.00	19.00	163.00	43.00	130.00	360.00
		0.16	0.59	5.08	1.34	4.05	11.21
		3.23	1.80	14.14	12.57	25.90	
		1.39	5.28	45.28	11.94	36.11	
10	**1.3**	8.00	24.00	116.00	58.00	154.00	360.00
		0.25	0.75	3.61	1.81	4.80	11.21
		5.16	2.27	10.06	16.96	30.68	
		2.22	6.67	32.22	16.11	42.78	
20	**0.9**	14.00	89.00	189.00	39.00	29.00	360.00
		0.44	2.77	5.89	1.21	0.90	11.21
		9.03	8.41	16.39	11.40	5.78	
		3.89	24.72	52.50	10.83	8.06	
20	**1.1**	21.00	146.00	100.00	35.00	28.00	330.00
		0.65	4.55	3.12	1.09	0.87	10.28
		13.55	13.80	8.67	10.23	5.58	
		6.36	44.24	30.30	10.61	8.48	
20	**1.3**	15.00	77.00	172.00	38.00	58.00	360.00
		0.47	2.40	5.36	1.18	1.81	11.21
		9.68	7.28	14.92	11.11	11.55	
		4.17	21.39	47.78	10.56	16.11	

Table B.2 continued

30	**0.9**	21.00	196.00	105.00	31.00	7.00	360.00
		0.65	6.11	3.27	0.97	0.22	11.21
		13.55	18.53	9.11	9.06	1.39	
		5.83	54.44	29.17	8.61	1.94	
30	**1.2**	31.00	231.00	56.00	30.00	12.00	360.00
		0.97	7.20	1.74	0.93	0.37	11.21
		20.00	21.83	4.86	8.77	2.39	
		8.61	64.17	15.56	8.33	3.33	
30	**1.3**	40.00	251.00	43.00	21.00	5.00	360.00
		1.25	7.82	1.34	0.65	0.16	11.21
		25.81	23.72	3.73	6.14	1.00	
		11.11	69.72	11.94	5.83	1.39	
Total		155.00	1058.00	1153.00	342.00	502.00	3210.00
		4.83	32.96	35.92	10.65	15.64	

APPENDIX C: CHAPTER TWO SUPPORTING INFORMATION

Table C.1 Precipitation and temperature data averages from 1991-2020 in Old Town, ME, USA and total precipitation with average temperatures from 2021 and 2022 are presented.

	Month	**Total Precipitation (mm)**	**Average Maximum Temperature (°C)**	**Average Minimum Temperature (°C)**
1991 to 2020	June	106*	22.7	9.8
	July	88*	26.2	13.3
	August	80*	25.4	11.9
2021	June	27	26.0	12.0
	July	162	23.3	12.7
	August	77	26.1	15.2
2022	June	39	22.4	9.4
	July	64	27.7	13.2
	August	90	26.2	14.4

*Average monthly precipitation

BIOGRAPHY OF THE AUTHOR

Jordan W. Parks was born in Reno, Nevada on June 15th, 1990, and raised by parents, Miriam Parks and W. Wright Parks III. He graduated from the Academy of Arts, Careers and Technology high school in 2009. He started a job at the 327 Apex mine as an underground miner and welder for four years. He then moved on to a welding job making oil water separator tanks and food grade stainless steel containers. He then attended the University of Nevada, Reno as an atmospheric science major. After a few years, he decided to change his major, which led him to the University of Maine to pursue agriculture. He graduated in 2020 with a Bachelor's in Science degree in Sustainable Agriculture. He wanted to learn how to conduct agricultural research to help farmers face a changing future. He enrolled in graduate school in 2020 at the University of Maine to begin a Master's program in Plant, Soil, and Environmental Science. After receiving his degree, Jordan will pursue a field and research technician job at Maine Cooperative Extension studying wild blueberry production with Dr. Lily Calderwood. Jordan is a candidate for the Master of Science degree in Plant, Soil, and Environmental Sciences from the University of Maine in May 2023.