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INVESTIGATING EFFECTS OF INTERACTION OF SINGLE TINE AND ROTATING TINE MECHANISM WITH SOIL ON WEEDING PERFORMANCE USING SIMULATED WEEDS.

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ABSTRACT.

Mechanical weeding augmented with automation technology should results in highly effective weeding systems. However, the interaction between controlled weeding mechanisms and soil and weeding performance is not well understood. Moreover, soil is highly variable and makes studying this interaction challenging. The main objective of this research was to develop a method to investigate the effects of mechanical tool-soil interaction on weeding performance for different operating conditions in a controlled environment. Experiments were conducted in an indoor soil bin with loam soil, and the weeding performance was studied using small wooden cylinders as simulated weed plants. The investigations featured a single cylindrical tine and a rotating tine mechanism, vertically-oriented and inserted into the soil. Total width of soil disturbance and potential weeding rate were evaluated for the single cylindrical tine at different levels of operational factors namely: tine diameter (6.35 mm, 7.94 mm and 9.53 mm), working soil depth (25.4 mm, 50.8 mm and 76.2 mm) and tine speed (0.23 m/s and 0.45 m/s). Potential weeding rate was examined for the rotating tine mechanism across two operational factors: working soil depth (25.4 mm and 76.2 mm) and rotational speed (25, 50 and 100 rpm). Statistical analysis was performed using ANOVA at $p < 0.05$. A simulation of the rotating tine mechanism was developed which estimated disturbed area. For the single tine, soil disturbance width was independent of the test speeds; however, diameter and depth had significant effects as the width increased with increased levels of these two parameters. All three parameters had significant effects on potential weeding rate of the single tine, and the rates were observed to increase for higher levels of the operating parameters. For the rotating tine mechanism, both depth and *rotational speed were significant. The potential weeding rate for the mechanism was found to increase for higher levels of these parameters. The results showed that although the width of soil disturbance due to a cylindrical tine are affected by tine diameter and working soil depth, operating parameters such as increased longitudinal and rotational speeds also affect plant disturbance. The percentage of disturbed soil area in simulation followed similar patterns as the percentage disturbed plants observed in the experiments.*

Keywords.

Intra-row weeding, Inter-row weeding, Mechanical weeding, Rotating tine mechanism, Soil disturbance, Tine

INTRODUCTION

Weed control is important for higher crop production. Weeds compete with crops or vegetable plants for nutrients, water and sunlight (Slaughter et al., 2008; Weide et al., 2008) and have faster growth rate compared to crops (Ahmad et al., 2014). Therefore, proper management is necessary to prevent weed infestation and thus improve crop yield and quality.

Chemical, biological, thermal and mechanical, including manual hand weeding, weed control methods can be used for weed management in agricultural fields. Among these methods, chemical and mechanical weeding are currently the most relied upon techniques in conventional cropping systems (Young et al., 2014). Chemical weed control, which involves the use of herbicides to kill weeds, is an economically effective way to control weeds. However, growing concern about the impact of herbicides on the environment and increasing consumers demand for organic foods has resulted in increased interest in mechanical weed control techniques (Griepentrog et al., 2006; Slaughter et al., 2008; Young et al., 2014).

Mechanical weed control is divided into two weeding strategies based on the spatial relationship between crop and weed plants: (1) inter-row weeding and (2) intra-row weeding (Ahmad et al., 2014). Inter-row weeding is performed between the crop rows, while intra-row weeding is conducted near and between the crop plants within a crop row. Intra-row weeding is more challenging compared to inter-row weeding because it involves control of weeds growing close to the crop plants without causing excessive crop damage. As a result, increased research efforts can be found focusing on the development of efficacious intra-row weeding systems (Perez-Ruiz et al., 2012). These efforts have also led to the development of automatic intra-row weeding systems with intelligent technologies integrated to minimize human interventions and increase work rates (Melander et al., 2015; Astrand and Baerveldt, 2002; Griepentrog et al., 2006).

Slaughter et al. (2008) organized robotic or automated weeding research into four core technologies: (a) guidance, (b) detection and identification, (c) precision-in-row weed control, and (d) mapping. Vehicle guidance enables accurate positioning of the autonomous vehicle or weeding system required for weeding. Plant detection and identification is required to separate weeds from crop plants. After separating crops and weeds, in-row weeding mechanisms (for mechanical weeding) or spray nozzles (for chemical weed control) are used to precisely target the weed plants and damage their structure disrupting their growth or killing them. Mapping is a technique in which crops, crop seeds and weed population are georeferenced in the field and stored in a map. This map could facilitate weed control actions and management decisions. Several research studies have used these core technologies in the development of mechanical weeding systems (Astrand and Baerveldt, 2002; Griepentrog et al., 2006; Slaughter et al., 2008; Tillett et al., 2008, Van der Weide et al., 2008). Similarly, some automated weeding technologies have been commercialized. For example, the Greenbot (Conver BV), the OZ and COSI (Naio technologies), Robovator (F. Poulsen Engineering) and Robocrop (Garford) are some of the weeding robots available in the market (Melander et al., 2015; Merfield, 2016).

Despite the focus on these technologies and developments to improve mechanical weeding, little work has been done to explore the interaction between weeding implements or tools and the soil with respect to weeding performance of the automatic mechanical weeder. Understanding how weeding tools interact with soil can provide key insight into their performance in eliminating or disturbing weed plants. However, there are several factors that make weeding tool and soil interaction studies very challenging, which may also explain why little research has been conducted on weeder tool-soil interaction for autonomous weeding systems. One factor that complicates such studies is the properties of soils, which are dynamic, spatially-varying, and thus uncertain. Consequently, investigating soil-weeding tool interaction on uncertain and highly variable soil can result in inconsistent outcomes.

Therefore, controlled experiments could be conducted to examine interaction between weeding tools and soil on weed control performance. Controlled experiments would not only establish better understanding of relationships between interaction and weeding performance for given soil properties, but also aid in the design and development of mechanical weeders for precision weeding. Individual mechanical weeders have specific designs and several adjustable parameters such as tool width, angle, and soil depth. Determining the efficacy of these designs or identifying optimal parameter values for effective weeding may be possible only if the tests are conducted in a controlled environment with consistent soil conditions. Further, the ability to control the experimental conditions may make the experiment less time consuming and inexpensive to establish the efficacy of the weeding system. Therefore, the methodology described in the paper is intended to be the first step in an engineering approach to understand the interactions between tool, soil, and plants and relationships between operational parameters and weeding performance.

Objectives

The objective of this research was to develop a methodology that could capture interactions between soil and a weeding tool in a controlled environment and evaluate its performance in weeding. The specific objectives were to:

1. investigate the effect of a single tine on width of soil disturbance and potential proportion of weeds damaged with changes in three operational factors: tine diameter, working soil depth and tine speed, and

2. examine the effect of working soil depth and rotational speed on potential proportion of weeds damaged due to a rotational weeding mechanism.

Materials and Methods

Description of soil and soil bin

Two experiments were performed in a 2.44 m diameter circular soil bin located in the Advanced Machinery Laboratory Systems (AMSL) lab at Iowa State University, Ames, Iowa (fig. 1). A hydraulic power unit was used to rotate the soil bin at different angular speeds. The soil was classified as loam soil with 32% sand, 43 % silt and 24% clay. The soil was sieved to a maximum size of 5 mm. A soil conditioning routine was used, which involved spraying the soil with water and leaving it overnight, to maintain a consistent soil moisture content before the tests. The soil was then mixed using a tiller to a depth of 150 mm and leveled with horizontal scraper blade. This soil preparation process was followed before each test to achieve similar soil conditions for all the tests. The bulk density of soil was 1.27 g/cm^3, and the average moisture content was measured to be 17% using the ASTM D4318 standard procedure with an industrial oven.

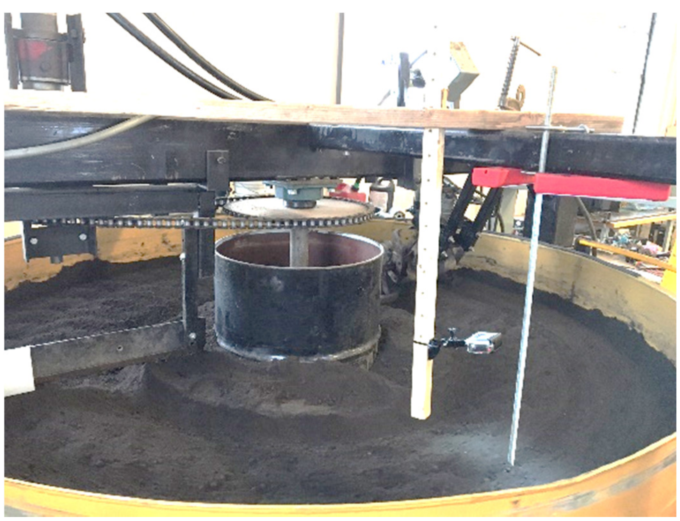


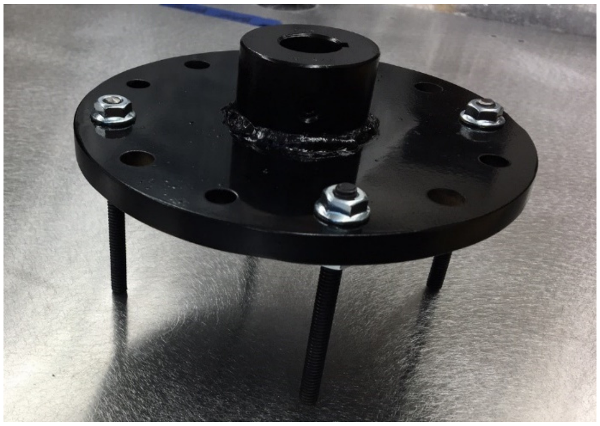
Figure 1. The circular soil bin used for the experiments in which the soil bin was turned and tools remained stationary.

EXPERIMENT WITH SINGLE TINE

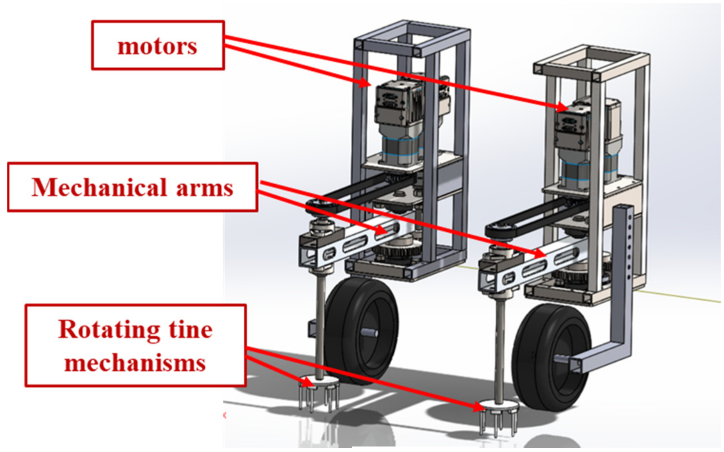
The first experiment was conducted to investigate how a single tine disturbs soil while moving linearly and how three operational parameters or factors affect soil disturbance and weeding performance. The factors were: (i) tine diameter, (ii) working soil depth and (iii) tine speed. Cylindrical tines with diameters of 6.35 mm, 7.94 mm and 9.53 mm were used for the test. The three working soil depths were 25.4 mm, 50.8 mm and 76.2 mm. The tine speeds used for investigation were 0.23 m/s (0.5 mph) and 0.45 m/s (1 mph). These speeds were achieved by keeping the tine stationary while rotating the soil bin to achieve the desired test tine speeds. Therefore, the tine speeds were relative to the rotating soil bin. The design of the experiment was completely randomized. The experiment consisted of 18 (3 x 3 x 2) treatments arising from combinations of different levels of the three factors. Each treatment was replicated three times and thus, 54 tests were conducted in total corresponding to 54 (18 x 3) experimental trials.

EXPERIMENT WITH ROTATIONAL WEEDING MECHANISM

In the second experiment, a circular rotating tine mechanism was used, and its weeding performance was examined for two operating factors: (i) working soil depth and (iii) rotational speed (rpm) of the mechanism. The mechanism was a steel disc holding of four cylindrical tines (fig. 2 (a)). The rotating tine mechanism was designed and developed to function as part of an automatic intra-row mechanical weeder that was developed at Iowa State University (fig. 2(b); Gai et al., 2019). The mechanism affects the intra-row weeds by disturbing the soil through horizontal rotation of four tines that are in direct contact with the soil. The disc of the mechanism was 152.4 mm in diameter and had four 7.94 mm diameter tines which were coaxially arranged and equally spaced around a 127 mm diameter circle. The working soil depth levels used in this test were 25.4 mm and 76.2 mm, and the three rotational speeds of the mechanism were 25, 50 and 100 revolutions per minute (rpm). In this experiment, the soil bin was rotated at a specific uniform speed such that the soil moved past center of the mechanism at constant linear speed of 0.45 m/s. This experiment had a completely randomized design consisting of 6 (2 x 3) treatments. There were three replications for each treatment, resulting in a total of 18 experimental trials.



(a)



(b)

Figure 2. (a) Rotational weeding mechanism consisting of a circular disc with four cylindrical tines. (b) The prototype of automatic intra-row mechanical weeder developed at Iowa State University.

METHODOLOGY AND SET UP TO MEASURE SOIL-TINE INTERACTION

When a tine is moved in a soil, the soil shears in a specific pattern around the tine. This shearing process is called soil failure (Mckyes,1985; Hettiaratchi et al., 1966; Godwin and Spoor, 1977). The nature of soil failure depends on soil properties and geometry of the tine (Godwin and O'Dogherty, 2007). The cylindrical tines used in this study were categorized as narrow tines and typical soil failure pattern for such tines can be seen in figure 3. The profiles and extent of soil failure or disturbance could vary widely for the operational factors used in this study. However, it may not be clear how these soil disturbances relate to the weeding performance as the degree of impact on the weed may vary around the tine in different soil disturbance regions.

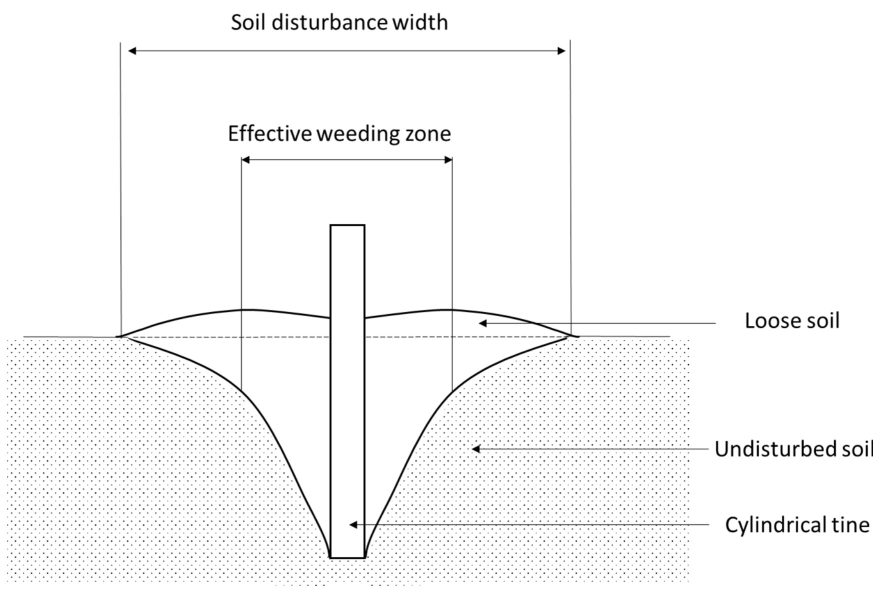


Figure 3. Cross section of typical tine failure soil profile (adopted from Godwin, 2007).

To study the impact of operating factors on soil disruption and subsequent effect on weed plants, thin wooden cylinders were used as simulated small young weed plants. In other research, Paarlberg et al. (1998) used wooden dowels to measure soil movement into crop rows, and Zhang and Chen (2017) used wooden skewers to measure burial depth of weeds. The experiments associated with both of these research used inter-row sweeps to affect intra-row weed mortality with burial. In our study, simulated weed plants were used to understand how local soil disturbance affected plant disturbance. This simulated weed approach was advantageous over approaches using real weed plants because it enable the tests to be performed in a controlled manner in less time under similar soil conditions and provide flexibility and control in arranging cylinders on the soil.

The wooden cylinders used in the research did not capture all the biological variations associated with different weed species; however, the focus of this work was on very early weed growth stages when their root structure is relatively weak and can be easily disturbed or damaged through weeding action. This assumption also facilitates estimating damage of weeds due to a single tine because single tine is more likely to damage young weak weeds by primarily uprooting and sometimes cutting them. To account for different biological variations in the weeds, higher fidelity physical models can be designed and used for simulation or specific plants can be used as surrogate weeds (Brown and Gallendt, 2018).

The wooden cylinders were used for both single tine and rotating mechanism experiments. Each cylinder measured 70 mm in length and 2 mm in diameter. The arrangements of these cylinders were similar in both the experiments. Each experimental trial consisted of five rows of wooden cylinders that rotated along with the soil bin (fig. 4(a)). The cylinders were placed perpendicular to the tine travel path and spaced in the row so that the center cylinder of the row was in line with center of the rotating tine mechanism and the line of action of the tine in the respective experiments (fig. 4(b)). The cylinders were inserted 50.8 mm into the soil in all the experiments. For the single tine experiment, each row had 15 wooden cylinders inserted into the soil at a uniform spacing of 6.35 mm (fig. 4(b)). However, for the rotating tine mechanism experiment, each row consisted of 21 wooden cylinders uniformly spaced at 12.7 mm apart. More cylinders were used for the rotating tine experiment to capture wider soil disturbance due to larger diameter of the tine mechanism.

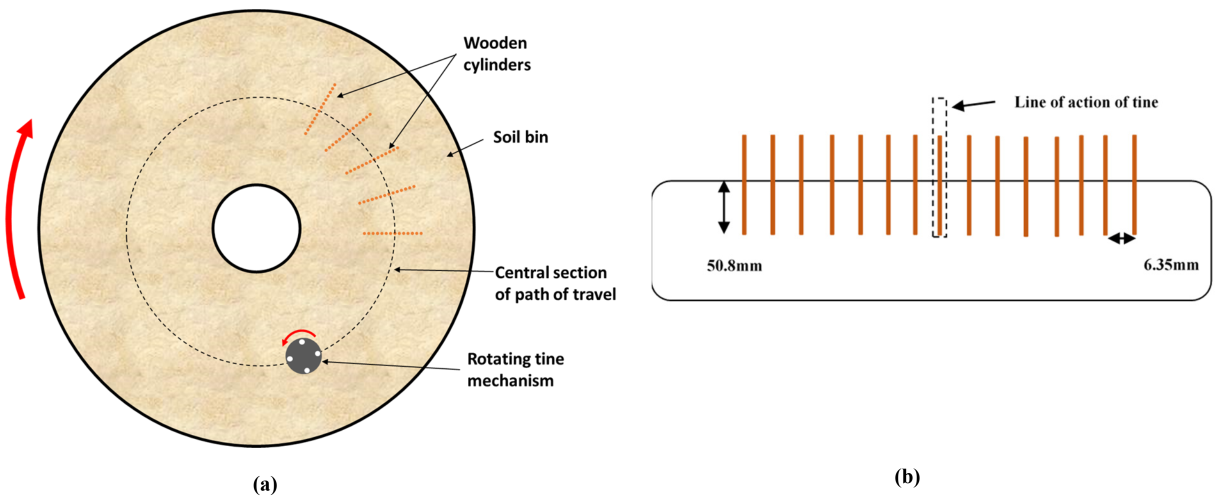


Figure 4. (a) Top view of rotational circular soil bin with five rows of wooden cylinders that move along the path of travel and intersect with rotating tine mechanism. (b) The wooden cylinders' arrangement in a row for single tine experiment.

The effect of the tines on the wooden cylinders was observed, and this effect on each cylinder was classified into five levels according to the cylinder's orientation and displacement from the original location. Cylinders completely dislodged from the soil were classified as level 5. Those displaced from their original location and tilted were classified as level 4. Level 3 included cylinders that were displaced from their original location but were still oriented vertically. The unmoved but tilted cylinders were classified as level 2. Finally, the cylinders unaffected by the tine mechanism were classified as level 1.

SIMULATING SOIL DISTURBANCE OF ROTATING TINE MECHANISM

A simulation was performed using a model of the kinematics of the tine mechanism rotatory and linear motion. A model of the motion of each of the four tines in the mechanism was developed to calculate the tine paths for the different rotational speeds and implemented in Matlab script (The MathWorks, Natick, MA). In addition, the effective weeding width from the single tine experiment was used to estimate the soil disturbance area around each tine path. The simulation results were placed into a binary image with black pixels representing areas where the soil had been disturbed and white pixels representing areas where no disturbance occurred (fig. 5) and image analysis was used to find the soil distance area.

The percentage of soil disturbance area over the maximum possible effective area of soil disturbance for all the treatments was compared with the percentage of count of highly impacted simulated weeds from the experiment over the count of simulated weeds (12) that were within the maximum possible effective width. The maximum possible effective area of soil disturbance was the product of the length in the longitudinal direction corresponding to length of a window (fig. 5) selected for image analysis and the maximum possible effective width, which was the extent of soil disturbance lateral to tine mechanism linear motion.

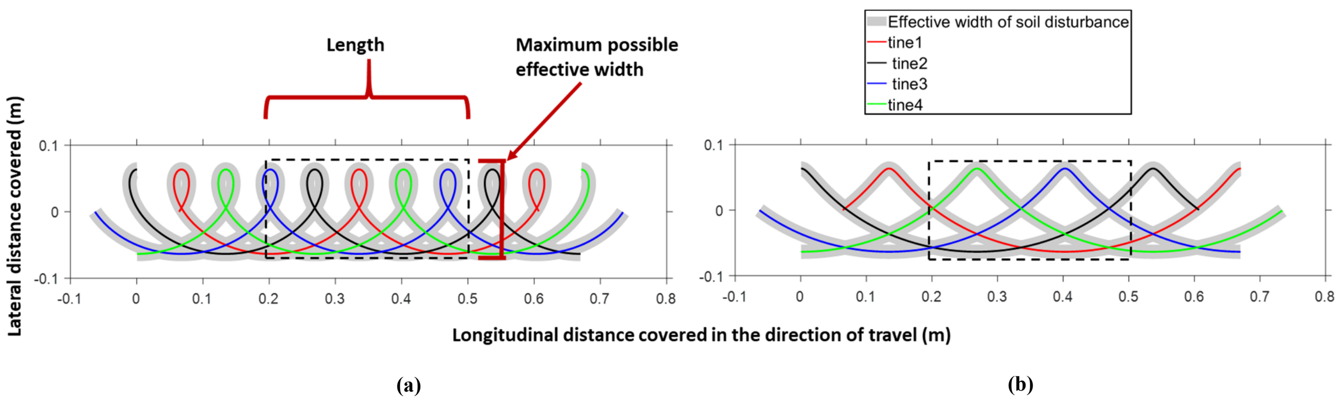


Figure 5. Simulation resulted in top view of paths of four tines of a rotating tine mechanism moving linearly at a speed of 0.45 m/s at rotational speed of 100 rpm (a), and 50 rpm (b). The rectangular window with dashed lines show the portion of the area covered by rotating tine mechanism used for image analysis.

DATA ANALYSIS

For the experiment with a single tine, 3-way ANOVA was conducted to investigate the effects of three experimental factors (tine size, soil working depth and tine speed) on soil disturbance. Specifically, two types of response variables were generated for the analysis. The first response variable was the soil disturbance width, which was obtained by counting total number of wooden cylinders classified as levels 2 to 5 in a row and multiplying it by the spacing between two adjacent cylinders (6.35 mm). This response variable represented soil disturbance due to soil failure and lateral movement of loose soil resulting in any small or large disruption of the wooden cylinders.

The weeding impact for a single tine interacting with soil is likely to be more pronounced closer to the tine than at the lateral extremes of a soil failure. The weeds closer to the tine will have higher probability of being buried, uprooted or even cut. Therefore, a second response variable was generated termed count of highly impacted simulated weeds, which was used to determine the role of different factors in high weeding capability. This variable was generated by counting the total number of wooden cylinders classified as level 5 in a row.

A 2–way ANOVA was performed for the rotating weeder experiment to analyze the impact of two factors: working soil depth and rotational speed of the tine mechanism on weeding performance. The response variable used in this analysis was the count of highly impacted simulated weeds. For the experiment with rotating tine mechanism, highly impacted simulated weeds were those either dislodged or displaced and tilted, and thus the response variable for this analysis was the count of wooden cylinders in a row that were classified as levels 4 and 5. A 5% probability level was used for all the analyses.

The methods used in this study could be used to determine operational parameters to achieve different weeding criteria such as higher weed plant mortality, reduced crop plant damage or a combination of both. Since the weeding criteria may change based on species of weeds and crop or vegetable plant, the analysis could be adjusted accordingly to find optimum parameters. Wooden cylinders are a lower fidelity representation of young weed plants, and methods for better modelling and simulating young weed plants biologically is a needed line of future research.

RESULTS AND DISCUSSION

SINGLE TINE SOIL DISTURBANCE WIDTH AND COUNT OF HIGHLY IMPACTED SIMULATED WEEDS

The ANOVA analysis for soil disturbance width showed that tine diameter, working soil depth and their interaction had significant effects on soil disturbance width ($p < 0.0001$). The p-value for tine speed was higher than the 5% significance level ($p = 0.098$), and thus there was no evidence to support a speed effect on the disruption of the soil in the 0.23 to 0.45 m/s range. The depth and width effects on the width of soil disturbance was consistent with the studies conducted by several soil dynamics researchers. Their work focused on the development of soil force prediction models for narrow tillage tools and tines in which soil disturbance width for was dependent on soil properties and the geometry of the tine, but independent of tine speeds (Godwin and Spoor, 1977; Perumpral et al., 1983; McKyes and Ali 1985).

The significant interaction between tine diameter and working soil depth suggested that soil disturbance width was affected by combinations of different levels of the two factors. The lowest soil disturbance width occurred when the 6.35 mm diameter tine was inserted into the soil at the 25.4 mm depth and was, as a mean value, 27.5 mm. The highest mean width of soil disturbance was 69.6 mm for a 9.53 mm tine at the 76.2 mm soil depth (fig. 6). These results showed that the mean width of soil disturbance increased with increases in tine diameter at all three soil depths used in the experiments. Similarly, the increase in working depth also increased the mean soil disturbance width.

The trend in this experiment of changes in the soil disturbance width due to tine diameter and soil depth was consistent with the work conducted by Godwin and Spoor (1977). In their work, they showed that the ratio of forward rupture distance to tine width increases with increasing aspect ratio (soil depth/tine width) for different rake angles. Assuming soil rupture for a cylindrical tine is similar forward and sideways, the width of soil disturbance for the single tine would be about two times the forward rupture distance. Using this association between soil disturbance and forward rupture distance and the relationship between two ratios, the widths of soil disturbance would increase for the increases in depths and diameters used in the experiment based on Godwin and Spoor's work. The experimental results were consistent with their prior work. However, it was observed that mean width did not change much for the tine with the 6.35 mm diameter at depths of 50.8 mm and 76.2 mm probably because the soil depth of 76.2 mm was greater than the critical depth for the 6.35 mm tine under the test soil conditions. For depths greater than the critical depth, the soil failure mechanism changes and any increase in depth does not considerably increase the forward rupture distance or soil disturbance width (Godwin and Spoor, 1977; Godwin, 2007).

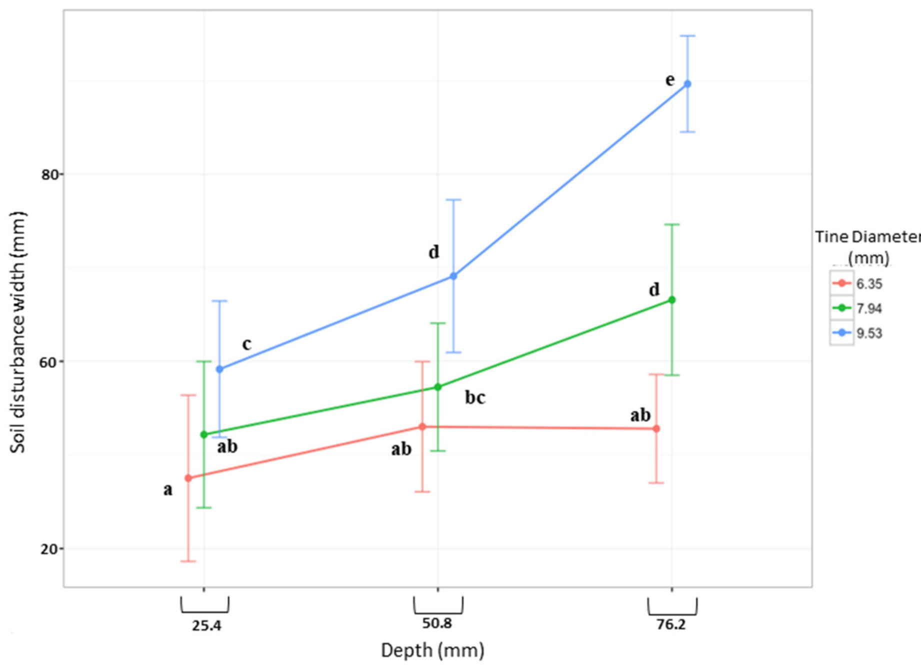


Figure 6. The interaction effect of tine diameters and soil working depths on the width of soil disturbance. Solid dots and error bars denote means and standard deviations respectively. The mean sharing same letters are not significantly different at p<0.05 using Tukey's adjusted comparisons.

Diameter, depth and speed all had a significant effect on highly impacted simulated weeds count ($P < 0.0001$). The mean values of count of highly impacted simulated weeds increased as the depth increased for all three tine diameters and at both tine speeds (fig. 7). Mean counts increased with increasing tine diameters at all soil depths except at the 25.4 mm depth. At a soil depth of 25.4 mm, the 7.94 mm and 9.53 mm diameter tines had almost same mean count, possibly due to higher variation of the data for 7.94 mm at this depth. For a typical soil failure profile of a single tine, soil disruption will be high closer to the tine and gradually decrease laterally. The section of the soil failure profile, close to the tine, where disruption of soil is higher and with higher weeding impact was called the effective weeding zone (fig. 3). This zone increased as the width of the soil disturbance increases. Because the soil disturbance increased with increasing tine diameters and soil depths in the experiment, the effective weeding zone also increased correspondingly resulting in a relatively higher count of substantially affected simulated weeds for the two factors.

Similarly, the mean count was higher for the faster tine speed of 0.45 m/s at all three soil depths and for all three diameters of the tine. At the higher speed of 0.45 m/s, the disrupted loose soil probably gained momentum due to the fast-moving tine and thus, moved vigorously and farther away from the tine. Consequently, more simulated weeds may have been dislodged for the speed of 0.45 m/s. Interestingly, the mean count of highly impacted simulated weeds was zero for the 6.35 mm diameter tine at a depth of 25.4 mm and a speed of 0.23 m/s, although the center simulated weed was in the path of line of action of the tine and should have been dislodged. This is probably because the loose soil that was disrupted all around the tine pushed the middle simulated weed away from the line of action of the tine as it moved. Furthermore, the soil motion was probably too slow to completely dislodge any simulated weeds.

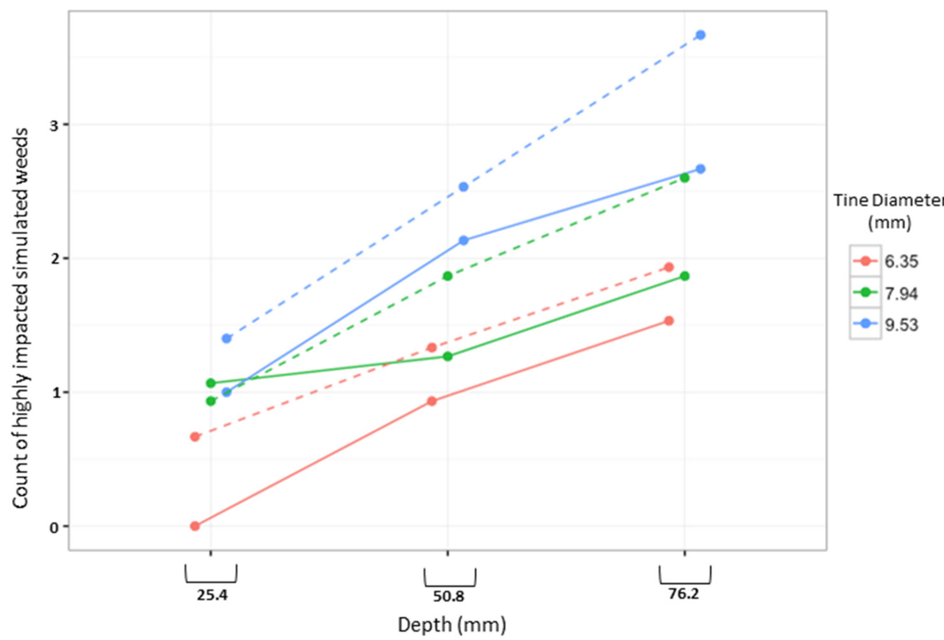


Figure 7. The interaction effect of tine diameters and working soil depths on the count of highly impacted simulated weeds for speeds of 0.23 m/s (solid line) and 0.45 m/s (dashed line).

ROTATING WEEDING TINE MECHANISM EFFECTIVE WEEDING WIDTH

The ANOVA analysis showed the working soil depths, tine mechanism rotational speed, and their interactions all had a significant effect on the count of highly impacted simulated weeds ($P < 0.05$). The count of highly impacted simulated weeds was found to increase with the increases in working soil depth and rotational speed of the tine mechanism (fig. 8). The count was lowest when the tine mechanism was rotated at the slowest speed of 25 rpm and the shallowest depth of 25.4 mm. The mean count of highly impacted weeds for these treatments was 4.2. The largest mean count of highly impacted simulated weeds was 11.9, which was observed at the speed of 100 rpm and depth of 76.2 mm.

Since the rotating mechanism consisted of four 7.53 mm diameter cylindrical tines, the soil disturbance pattern for each tine would be similar to that of a narrow tine and the width of soil disturbance would increase if the tines are inserted at greater soil depths. Because the effective weeding width also increases with the increase in width of soil disturbance, as discussed in single tine experiment, higher numbers of simulated weeds were found to be impacted at greater soil depths for all three rotational speeds.

The count of highly impacted weeds was also observed to increase for higher rotational speeds of the tine mechanism. The mean count varied marginally for rotational speeds of 25 and 50 rpm at both the soil depths; however, the variations were considerably higher when compared to the mean count caused by the rotational speed of 100 rpm at the corresponding depths. This result suggests larger rotational speeds of the tine mechanism causes a more substantial weeding effect.

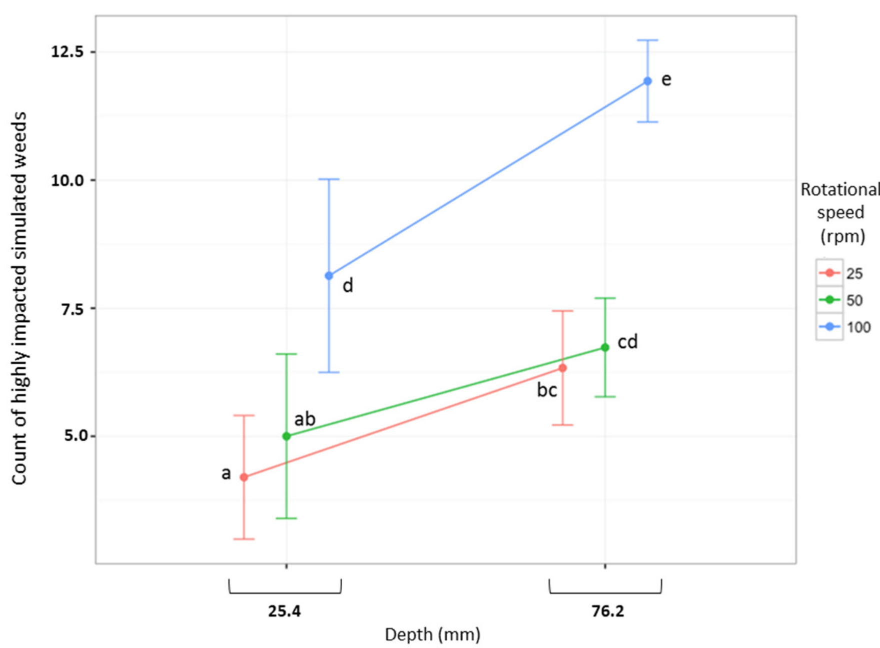


Figure 8. The interaction effect of soil working depths and rotational speeds of rotational tine mechanism on the count of highly impacted simulated weeds. Solid dots and error bars denote means and standard deviations respectively. The mean sharing same letters are not significantly different at p<0.05 using Tukey's adjusted comparisons.

The increase in the count of highly impacted simulated weeds for higher rotational speeds was because the tine paths were closer to each other (fig. 5(a)) when the mechanism was rotated at higher speeds, and therefore the mechanism disturbed a larger area of soil within the overall path of the mechanism. On the contrary, at lower rotational speeds, the tine paths were farther apart, and therefore, considerably lower numbers of simulated weeds were impacted due to a smaller soil disturbance area along the mechanism's path of travel (fig. 5(b)).

Analyzing the images from simulation results showed that the percentage of maximum possible effective area of soil disturbance for all the treatments were 25.6%, 27.1% and 37.7% at 25.4 mm soil depths and 51.6%, 52.5% and 68% at 76.2 mm soil depths for the rotational speed of 25, 50 and 100 rpm respectively (fig. 9). These values were calculated based on 9.3 mm and 21.6 mm effective soil disturbance width obtained for the 6.35 mm tine at 25.4 mm and 76.2 mm soil depths respectively in the single tine experiments. The experimental results from the rotating tine mechanism showed that the percentage of highly impacted simulated weeds over total number of simulated weeds within the effective width were 35 %, 41.7 % and 67.8 % at a 25.4 mm tine depth of and 52.8 %, 56.1 % and 99.4 % at a 76.2 mm tine depth for the rotational speeds of 25, 50 and 100 rpm respectively (fig. 9).

At each soil depth level used in the test, the percentages increased with increasing rotational speed of the rotating tine mechanism for both cases, which suggest that the impact on the simulated weeds have direct correlation to the area of soil disturbed due to different rotating speed of the tine mechanism. Although, there is similarity in the trends of percentage at each soil depth, the difference in the values of area percentage from the simulation did not correspond well with the count percentage from the experiments. This effect may be due to the simulation not accounting for increased kinetic energy transferred to soil particles at the higher rotation speeds. The simulation only used effective soil disturbance width around each tine path to estimate effective soil disturbance area.

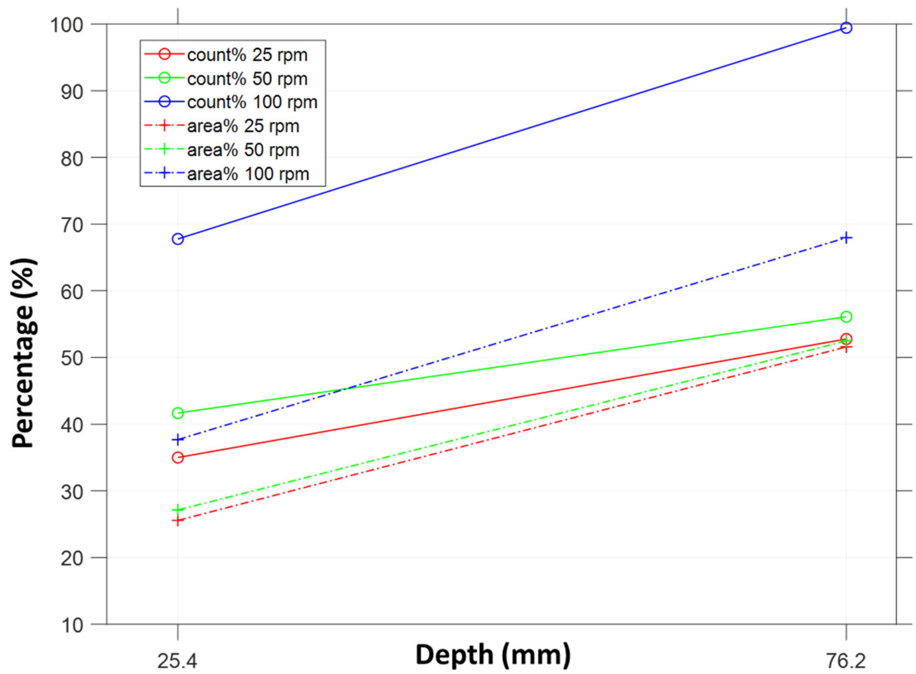


Figure 9. Simulation results show the percentage of soil disturbance area in the maximum possible area for all the treatments, labeled area% and represented by dashed lines, compared with the percentage of possible highly impacted simulated weeds for each treatment, labeled count% and represented by solid lines, for rotational speed of 25, 50 and 100 rpm and at soil depths of 25.4 mm and 76.2 mm.

Conclusions

A controlled experimental set up and simulated weed plants was used to study the interaction between soil and a mechanical weeding tool and its potential impact on weeding performance. Based on the experiments performed in a soil bin in a controlled lab setting with simulated weed plants, following conclusions were drawn:

- The width of soil disturbance due to single narrow tine increases with increases in tine diameter and soil depth. The two speeds 0.25 m/s and 0.45 m/s used in the test had no significant effect on the width of soil disturbance. Overall, it is likely that higher percentage of weed plants would be damaged in a given area for higher tine diameter, soil depths and tine speeds.
- For rotating tine mechanism, a higher percentage of weed plants would be damaged in a given area for higher soil depths and rotational speeds.
- The effective area of soil disturbance estimated using the simulation study showed similar trends in counts of highly impacted weeds, which suggested the number of weeds damaged due to a rotating tine mechanism can also be estimated through simulation.

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