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Stacking tools on a wheel hoe to improve weed control for small-scale farmers

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Research Article

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Abstract

Small-scale vegetable farmers rely on hand tools for weed management, including wheel hoes, stirrup hoes, and tine rakes. They also pull weeds by hand in crop rows, with costs increasing in proportion to weed density. The Terrateck double-wheel hoe offers improved efficiency by straddling the crop row and weeding both sides. We evaluated the effects of single tools and tool combinations or (stacking) with the Terrateck double-wheel hoe, measuring weed control efficacy and crop mortality. In 2 yr of field experiments, six single tools and all possible two- and three-tool combinations were tested. Tools included biodiscs, finger weeders, tine harrows, L-sweeps, precidiscs, and torsion weeders. Bush bean and table beet were used as test crops. Tool stacking improved weed control efficacy over single tools, but average benefits were modest, with gains of 12% and 13% over single tools in bush bean and table beet, respectively. Regression analysis and observation of treatment rankings indicated that L-sweeps were a critical tool for top-performing treatments. In bush bean, for example, four tool combinations with L-sweeps had an average efficacy of 69% ± 15% compared with 37% ± 11% efficacy for all other treatments. The combination of L-sweeps, tine harrows, and torsion weeders provided the greatest weed control efficacy in both bush bean and table beet. Tool stacking did not affect bush bean mortality, which ranged from 0.9 to 2.0 plants killed per 1.5 m of row. However, in one experiment, stacking increased table beet mortality from 4.1 plants per 1.5 m of row for single tools, to 6.9 plants per 1.5 m of row for combinations with two tools. Overall, the Terrateck double-wheel hoe provides small-scale farmers an opportunity to improve efficiency and, with the ability to stack tools, improve weed control efficacy.

Introduction

Weed control is the foremost production challenge for organic farmers (Snyder et al. 2022) and for those who grow vegetable crops for which few herbicide options are available (Pannacci et al. 2017). These farmers usually depend on cultivation, harrowing, hoeing, or a combination of these, also referred to as mechanical or physical weed control (PWC) (Gallandt 2014; Gallandt et al. 2018a). PWC efficacy can be effective in a large crop with small weeds, especially where soils are hot and dry (Mohler 2001). Unfortunately, suboptimal conditions often result poor PWC efficacy with high levels of crop injury (Gallandt et al. 2018b). This is especially a problem for small-scale vegetable farmers such as those who farm 2 hectares or fewer, who rely on manual labor, using hand tools and hand weeding after some form of tractor-based cultivation (Bond and Grundy 2001).

Common hand tools used on small-scale farms include wheel hoes, long-handled hoes, and short-handled tools. Weeding labor can make up a large percentage of a small farm's operational costs (Brown et al. 2018). Working rates for using hand tools and to pull weeds by hand are density-dependent, increasing proportionally with weed density, a problem given the high weed seedbank densities that exist on organic farms (Jabbour et al. 2014). Labor costs can reach US \$6,000 ha^{-1} for some crops, with at least 600 h ha^{-1} spent weeding (Sørensen et al. 2005). Reducing labor costs associated with hand-weeding has the potential to improve the profitability of small-scale vegetable farms.

Weeding costs could be reduced if PWC efficacy were improved. Brown and Gallandt (2018) found that PWC tool "stacking"; that is, using more than one cultivation tool at a time, generally resulted in an additive increase in efficacy. In one notable tool sequence there was evidence of synergy. Stacking torsion, finger, and tine weeders resulted in 75% efficacy, exceeding the expected value of 57%. The varying performance of individual tools and particular sequences was believed to reflect varying PWC mechanisms, including severing, uprooting and desiccation, and burial (Mohler 2001).

The double-wheel hoe manufactured by Terrateck (Lestrem, France) is a unique hand tool that can accommodate tool stacking, making this strategy available to small-scale farms (Figure 1). Wheels straddle the crop row so both sides of the crop row are cultivated, and a variety of tools, including cut-away and hilling discs, finger weeders, tine harrows, sweeps, and torsion weeders, are then used for weeding purposes (Figure 2). Tools are attached and adjusted along two notched tool bars. The objective of this research was to test PWC tool stacking using

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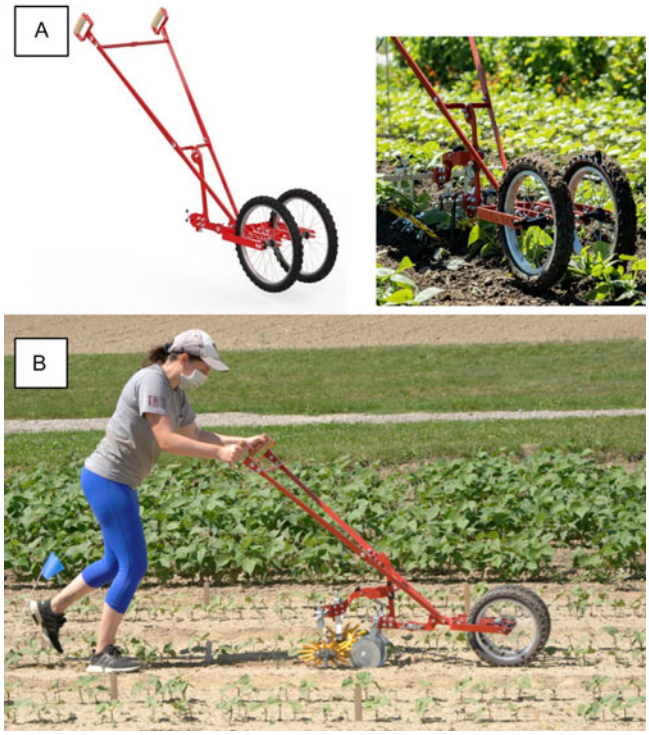


Figure 1. Terrateck double-wheel hoe used for experiments with individual and stacked tools showing how wheels straddle the crop row to permit cultivating on both sides of the crop row (A). Tools are attached to either of two notched tool bars. The stacked tool example shown (B) includes precidiscs on the front toolbar, with finger weeders and tine harrows on the rear toolbar. Photos: (A) Terrateck, Lestrem, France, used with permission; and (B) E. Gallandt.

hand tools to confirm whether performance would be improved over the use of tractor-mounted tools (Brown and Gallandt 2018).

In this study, we tested single tools and tool stacking using the Terrateck double-wheel hoe, examining weed control efficacy and crop mortality. Field experiments were conducted over 2 yr with bush bean and table beet crops, which were chosen to represent large- and small-seeded crops, respectively. We hypothesized that 1) stacking the use of two or three tools would increase weed control efficacy compared with using single tools; and 2) tool stacking would result in greater crop mortality.

Materials and Methods

Site Description

Six field experiments (Table 1) were conducted at the University of Maine Rogers Farm in Old Town (44.926°N, 68.696°W). The site is in Plant Hardiness Zone 4b, with an average annual high/low temperature of 20/−7 C, and average annual precipitation of 1,023 mm. In 2019, experiments with bush bean were performed in two fields: Run 1 occurred on a fine sandy loam with 3.0% soil organic matter; Run 2 on a very fine sandy loam with 3.5% organic matter (Table 1). In 2020, experiments included bush bean and table beet with two runs for each experiment on a silt loam soil with 3.2% organic matter (Table 1).

Fields were disked and preplant nitrogen was applied as Nutri-wave 4-3-2 (Northeast Agricultural Sales Inc., Detroit, ME) at 60 kg ha^{-1} plant-available nitrogen and incorporated with a Perfecta field cultivator (Unverferth Manufacturing Company Inc., Kalida, OH). Plots were firmed using a Brillion cultipacker (Landoll

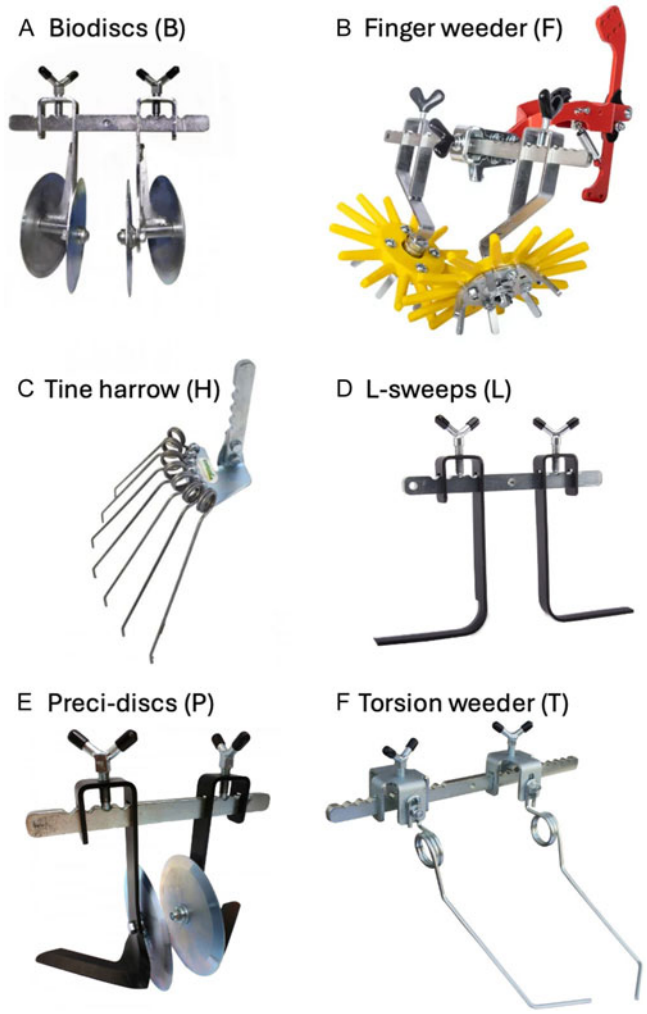


Figure 2. Terrateck weeding tools available for the double-wheel hoe: biodiscs (A), finger weeders (B), tine harrow (C), L-sweeps (D), precidiscs (E), and torsion weeder (F). Photos: Terrateck, Lestrem, France. Used with permission.

Corporation, Marysville, KS); bush bean variety Provider and table beet variety Chioggia Guardsmark were planted using a Wizard vacuum seeder (Sutton Agricultural Enterprises, Inc., Salinas, CA) on 50-cm rows with two rows per bed. In each experiment, condiment mustard (*Brassica juncea* 'Pacific Gold') was sown as a surrogate weed (Kolb et al. 2012; Melander and McCollough 2020). Mustard was broadcast with a Brillion seeder (Landoll) at 8 kg ha^{-1} 10 d prior to cultivation in each crop. Efficacy data include either ambient or surrogate weeds (Table 1) depending on their abundance and satisfactory precultivation densities as discussed below.

Experimental Design and Treatments

Six tools (Figure 2), used alone and in combination, were chosen for field testing. Tool combinations were chosen by setting up all possibilities and eliminating those with obvious tool interference. Tools were initially set up and tested on at least 50 m of crop row in practice areas prior to use in experimental plots. Each tool was first tested at a setting that did not cause any visible crop injury and then moved closer to the crop row for a more aggressive setting that caused an unacceptable level of crop injury (e.g., >10% loss of stand). Once these extremes were established, a mid-point setting was chosen as being optimal for each treatment. Settings were the

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Table 1. Metadata for Terrateck tool stacking field experiments conducted in 2019 and 2020.[a]

Year	Crop	Run	Soil texture	Soil organic matter	Precipitation preceding cultivation[b]	Date cultivated	Soil moisture[c]	Average daily temperature[d]	Surrogate or ambient weeds
				%	mm		%	C	
2019	Bean	1	Fine sandy loam	3.0	0.0	August 7	n/a	19.2	Ambient
2019	Bean	2	Very fine sandy loam	3.5	1.3 (−5 d), 0.3 (−4 d)	September 19	n/a	12.4	Surrogate
2020	Bean	1	Silt loam	3.2	2.0 (−5 d)	June 19	12.8	21.8	Surrogate
2020	Beet	1	Silt loam	3.2	0.0	June 25	12.8	20.3	Ambient
2020	Bean	2	Silt loam	3.2	0.3 (−4 d), 10.4 (−2 d)	August 6	13.5	20.4	Surrogate
2020	Beet	2	Silt loam	3.2	0.51 (−3 d), 1.0 (2 d)	August 12	12.5	23.2	n/a

[a]n/a indicates data were not available.
[b]Precipitation during the 5 d preceding cultivation events (0 d). For example, −4 d indicates precipitation 4 d prior to cultivation.
[c]Volumetric soil moisture was measured to a depth of 8 cm. Values are averages for all plots within an experiment due to lack of significant block or treatment effects.
[d]Average daily air temperature for the 5 d centered on the date of cultivation (e.g., 2 d prior to cultivation, the day of cultivation, and 2 d after).

Table 2. Terrateck double-wheel hoe tools and settings used in 2019 and 2020 field experiments.[a,b]

Tool combination	Tool, toolbar location, and adjustment notch number[c]	Distance between tools at their closest point[d]	Working width[e]
		cm	cm
Single tools			
	B, front, 2	5.0	20
	F, back, 8	5.0	18
	H, back, 5[f]	2.5	38
	L, front, 2	7.6	30
	P, front, 3	7.6	33
	T, front, 4[f]	2.5	15
Two-stacked tools			
	B, front, 2; F, back, 12	5.0; 10.2	25
	B, front inside, 2; H, front outside, 6	5.0; 12.7	38
	H, outside front, 10; T, inside front, 4	12.7; 2.5	51
	T, front, 4; H, back, 8	2.5; 10.2	46
	L, front, 2; B, back, 2	7.6; 5.0	30
	L, front, 2; F, back, 8	7.6; 5.0	30
	L, front, 2; H, back, 5	7.6; 2.5	38
	L, front, 2; T, back, 4	7.6; 2.5	30
	T, front, 4; H, back, 8	2.5; 10.2	51
	P, front, 3; F, back, 8	7.6; 5.0	18
	P, front, 3; H, back, 5	7.6; 2.5	38
Three-stacked tools			
	L, front, 4; H, front, 10; T, back, 4	15.2; 15.2; 2.5	51
	P, front, 3; F, back, 8; H, back, 16	7.6; 5.0; 30.5	51
	P, front, 3; H, front, 8; T, back, 4	7.6; 10.2; 2.5	46

[a]Abbreviations: B, biodisc; F, finger weeder; H, tine harrow; L, L-sweep; P, precidisc; T, torsion weeder.
[b]Toolbars are available in four widths, 25, 40, 60, and 80 cm. These experiments were conducted using both 40- and 60-cm width bars. Notched spacings for adjusting tools are standard on all bars.
[c]Adjustment notch numbers are counted from the toolbar center.
[d]Measured at parts of tools closest to the crop row, the narrowest point of each single tool or stacked tool combinations at their optimal setting.
[e]Working width was determined by measuring across the widest point of each single tool or stacked tool combination at their optimal setting.
[f]Tool settings were the same for most tools when used with both bush bean and table beets, except for torsion weeders and harrows, which were moved away from the crop row center by one notch on the toolbar.

same for most tools (B for biodisc, F for finger weeder, L for L-sweep, and P for precidisc) when used on both bush bean and table beet crops, but two tools, tine harrows (H) and torsion weeders (T), were moved one notch away from the crop row center when table beets were being weeded (Table 2). In total, there were 20 treatments: 6 single tools, 11 two-stacked tool combinations, and 3 three-stacked tool combinations (Table 2). The distance between tools ranged from 2.5 cm for tine harrows and torsion weeders used singly, to 30.5 cm for tine harrows in the three-stacked precidisc, finger weeder, tine harrow (PFH) treatment. Working widths, based on the widest point of each tool treatment, ranged from 15 cm for torsion weeders, to 51 cm for several stacked combinations that included tine harrows (Table 2). Tools caused only very shallow soil disturbance (5 to 20 mm).

Given the uniformity of the field sites and lack of observed or anticipated gradients, experiments were established as a completely random design with three replications. Plots were 9.1 m long by 0.5 m wide with a single crop row. Tool treatments were randomly assigned to plots.

Bush bean was cultivated when the crop reached the 1-leaf stage, and table beet at the 1- to 2-leaf stage. At the time of cultivation, surrogate mustard was at the cotyledon to 1-leaf stage. One tool operator performed all treatments in all experimental runs to minimize operator error. Cultivating speed averaged 54 m s^{-1}.

Data Collection

Three permanent 0.25-m^2 sampling locations were randomly established in each plot and marked on each end by a wooden stake that was centered in the crop row. Quadrats, constructed 50 cm wide to match crop row spacing, were centered at the wooden stake over the crop row and precultivation crop density was recorded just prior to cultivation. Volumetric soil moisture was measured at three randomly selected intrarow locations in each plot using a Delta-T HH2 Moisture Meter with a Theta Probe (Delta-T Devices, Burwell, UK). Ambient and surrogate weed densities were also recorded for the 10-cm intrarow zone, marked with strings, and the outer interrow zones. Postcultivation crop, ambient, and surrogate weed densities were recorded approximately 24 h after cultivation to allow adequate time for weeds to desiccate.

Data Analysis

Efficacy was calculated using the following equation:

$$Efficacy = ([Pre - Post]/Pre)\text{x}100 \quad [1]$$

where *Pre* equaled the precultivation number of ambient or surrogate weeds, and *Post* equaled the postcultivation density of ambient or surrogate weeds. Efficacy was calculated at the sample

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level and then averaged ($n = 3$) prior to analyses. Because precultivation density of the 10-cm intrarow was very low, averaging 3.8 plants 500 cm^{-2} sampled area, intrarow, and interrow data were combined at the sample level to calculate efficacy.

Data were analyzed for analysis of variance using JMP software (v.14.0; SAS Institute Inc., Cary, NC). Model residuals were analyzed for normality using Shapiro-Wilk tests. Year and run were included as a random effect; tool was included as a fixed effect. Preplanned contrasts of tool number were conducted to test tool stacking effects. A regression tree analysis (Klimberg 2023) was constructed with JMP software using efficacy as the response variable. Data are presented using box plots to accurately show the variability within and among treatments.

Results and Discussion

Weed Control Efficacy

Data Sets Included in Analyses

Quadrat samples with a precultivation density of ≤10 ambient or surrogate weeds were excluded from analyses to avoid misleading estimates of efficacy based on low precultivation densities (Vanhala et al. 2004). Based on this criteria, four bush bean data set and one table beet data set were sufficient for subsequent analysis (Table 1), with ambient or surrogate precultivation weed densities at the sample level ranging from 10 to 74 plants 0.25 m^{-2} (average was 30 plants 0.25 m^{-2}).

Bush Bean

Tool treatment effects on efficacy in bush bean were consistent over both years (Year × Tool, $P = 0.180$) and runs (Run × Tool, $P = 0.198$). Analyses indicated no interaction between tool treatment and weed type (e.g., ambient vs. surrogate weeds; data not shown), so efficacy data were analyzed over year, run, and weed type (Figure 3). Consistent with the hypothesis that motivated this work, tool stacking increased efficacy from 38% for single tools to 50% with two-tool stacked combinations (1 vs. 2 tools, $P < 0.001$) (Figure 3). Adding a third tool improved efficacy by 5% (2 vs. 3 tools, $P = 0.037$), an effect driven by a single treatment, LHT (see Figure 3). Soil moisture, measured only in 2020, was poorly correlated with efficacy in both Run 1 ($P = 0.406$) and Run 2 ($P = 0.680$).

Table Beet

Heavy rain caused two table beet crop failures in 2019. Table beet crop stands were very good in 2020, but in Run 2, poor surrogate weed establishment and low ambient weed densities excluded this data set from our analyses (Table 1). Based on ambient weeds in Run 1, tool stacking benefits were evident in table beet crops (1 vs. 2 tools, $P < 0.001$; Figure 4), but without an advantage of adding a third tool (2 vs. 3 tools, $P = 0.147$). LHT, the top-performing stacked combination in bush bean (see Figure 3), was likewise a standout treatment in table beet (Figure 4). We were surprised to find that soil moisture was poorly correlated with efficacy in this experiment ($P = 0.731$). In other research, soil moisture was negatively correlated with efficacy (Brown and Gallandt 2018; Mohler et al. 2016), as higher soil moisture likely slows desiccation of uprooted weeds.

The LHT combination had the greatest weed control efficacy in both bush bean (Figure 3) and table beet (Figure 4). L-sweeps in particular, and not stacking per se, was driving this effect. Regression tree analysis (data not shown) in bush bean resulted

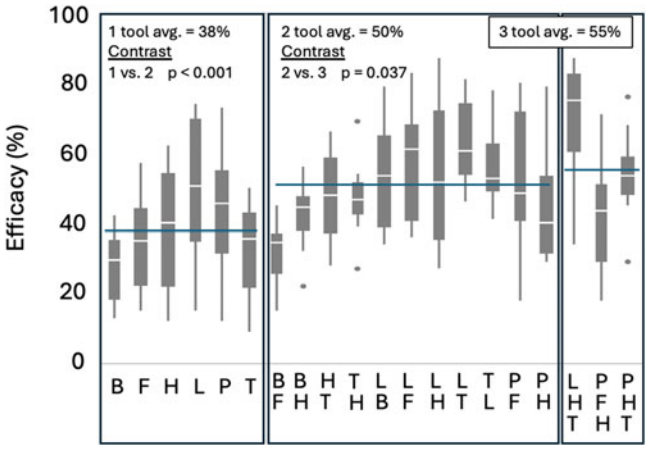


Figure 3. Weed control efficacy measured in four experiments conducted in bush bean in 2019 and 2020. Tool abbreviations include bio-discs (B), finger weeder (F), tine harrow (H), L-sweeps (L), precidiscs (P), and torsion weeders (T). Box plots show median center lines, upper and lower quartiles, with whiskers at 1.5× the interquartile; outliers are also shown. Horizontal blue lines in the three panels show mean values for single, two-stacked, and three-stacked tools.

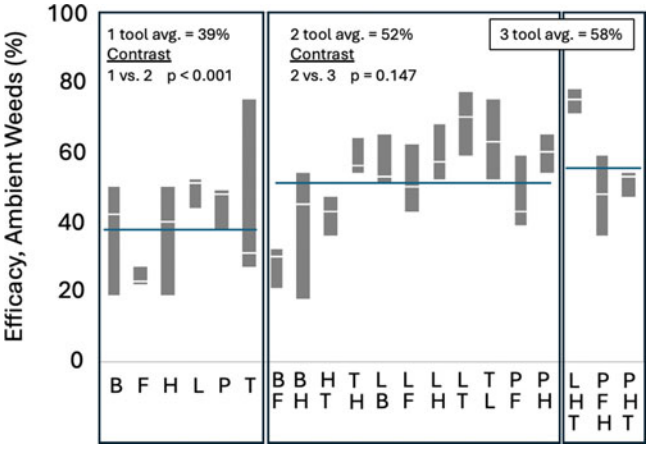


Figure 4. Weed control efficacy measured in table beet in 2020. Tools include bio-discs (B), finger weeders (F), tine harrows (H), L-sweeps (L), precidiscs (P), and torsion weeders (T). Box plots show median center lines, upper and lower quartiles, with whiskers at 1.5× the interquartile; outliers are also shown. Horizonal blue lines in the three panels show mean values for single, two-stacked, and three-stacked tools.

in a first split containing four treatments with L-sweeps (LF, LH, LT, and LHT) with an average efficacy of 69% ± 15% compared with 37% ± 11% for other tool treatments. Results in table beet were similar, with a first split including LH, LT, and LHT, with efficacy averaging 68% ± 9% compared with 41% ± 12% for other tool treatments. We speculate that the L-sweeps may have helped loosen soil and increased the effectiveness of the tool on the second toolbar. The stacking benefit of LHT could simply reflect a greater area of soil disturbance, 51 cm for this combination (Table 2). However, HT and TH treatments also had 51-cm working widths (Table 2), but offered poor efficacy compared with LHT. Thus, the L-sweep was pivotal to the success of the stacked treatments.

Crop Mortality

Bush bean mortality at the 1-leaf stage was not affected by tool treatment ($P = 0.231$); mortality averaged 0.9 to 2.0 plants killed

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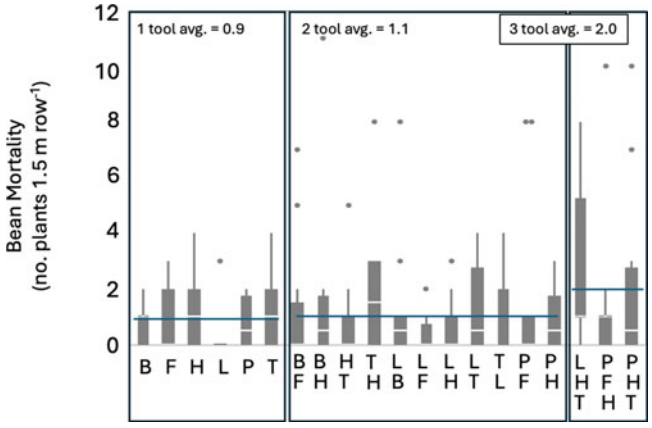


Figure 5. Bush bean mortality measured in four experiments conducted in bush bean in 2019 and 2020. Mortality includes the sum of all plants killed over three 0.5-m-long samples totaling 1.5 m of crop row. Tools include bio-discs (B), finger weeders (F), tine harrow (H), L-sweeps (L), precidiscs (P), and torsion weeders (T). Box plots show median center lines, upper and lower quartiles, with whiskers at 1.5× the interquartile; outliers are also shown. Horizonal blue lines in the three panels show mean values for single, two-stacked, and three-stacked tools.

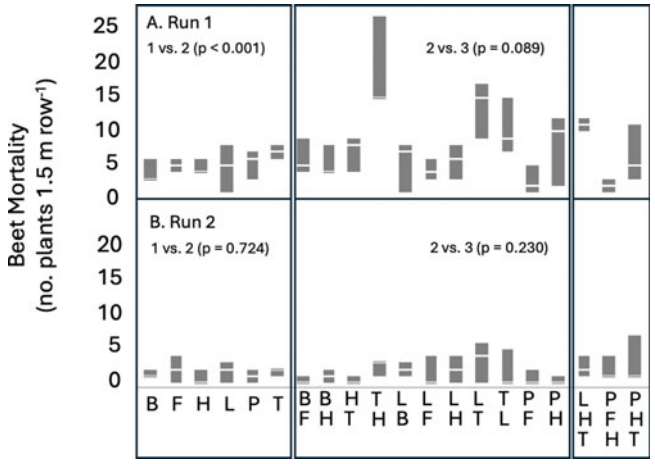


Figure 6. Table beet mortality measured in two experiments conducted in 2020. Mortality includes the sum of all plants killed over three 0.5-m-long samples totaling 1.5 m of crop row. Tools include bio-discs (B), finger weeders (F), tine harrows (H), L-sweeps (L), precidiscs (P), and torsion weeders (T). Box plots show median center lines, upper and lower quartiles, with whiskers at 1.5× the interquartile; outliers are also shown. Horizontal blue lines in the three panels show mean values for single, two-stacked, and three-stacked tools.

per 1.5 m of crop row cultivated (Figure 5). Although we expected higher mortality from tool stacking, bush bean seedlings were relatively large and well-anchored at the time of cultivation. Table beet mortality, on the other hand, was approximately 4-fold greater than bush bean, and increased with tool stacking in Run 1, averaging a loss of 4.1 and 6.9 plants per 1.5 m of row cultivated with single and two-tool treatments, respectively (Figure 6A). Table beet mortality was lower in Run 2 and not affected by tool treatment, averaging a loss of 1.6 plants per 1.5 m of row cultivated (Figure 6B). The LHT combination, which provided the greatest level of weed control in both bush bean (Figure 3) and table beet (Figure 4), also caused the greatest table beet mortality (Figure 6A), highlighting the challenge of selectivity in sensitive crops. In table beet, cultivation was performed at the 1 true-leaf stage due to high weed densities. While the timing was appropriate given the weeds present, the crop was too small, leading to high mortality. Van der Weide et al. (2008) recommended that directly cultivating the intrarow zone with tractor-mounted implements occur at the 3- to 4 true-leaf stage or greater to prevent high rates of injury.

The wide range of attachments for the Terrateck double-wheel hoe were assumed to include a diversity of physical modes of action that would cause weed mortality by uprooting, cutting, or covering (i.e., burying) (Terpstra and Kouwenhoven 1981). Based on observation of the tools used in our experiments (Figure 2), we expect that tools would vary in these effects; for example, uprooting would predominate over tine harrows, torsion, and finger weeders, although L-sweeps would still be important for cutting purposes. In a thorough review of physical weed control, Chicouene (2007) concluded that weeds were ultimately killed by one of three mechanisms: direct lethal injury, exhaustion of reserves, or withering. It is possible that the combination of L-sweeps, tine harrows, and torsion weeders resulted in the highest levels of weed control (Figures 3 and 4) by combining optimal weed-uprooting and burial effects. As a mechanism, uprooting has received considerable attention, with empirical studies related to crops and weeds (Fogelberg and Dock Gustavsson 1999; Fogelberg and Gustavsson 1998; Kurstjens et al. 2000), and modeling efforts to predict efficacy and selectivity (Kurstjens 2004; Kurstjens et al. 2004). Connors and Brainard (2025) recently adapted the anchorage force model presented by Kurstjens et al. (2004) to include burial as an additional mechanism. Their model predicted uprooting as being most important for removing broadleaf weeds, but greater predicted efficacy would occur with grass weeds using burial tools. In contrast to our previous empirical evidence supporting tool stacking (Brown and Gallandt 2018), the predicted efficacy of stacking had only a minimal effect on individual weed species, perhaps reflecting the complexities of tool, weed, crop, and soil interactions occurring in the field (Gallandt et al. 2018b).

In summary, weed control efficacy increased with tool stacking in fields of both bush bean and table beet, which supports our tool stacking hypothesis and is also supported by previous tool stacking results (Brown and Gallandt 2018; Hitchcock Tilton 2018). The LHT stacking resulted in greater efficacy and no difference in bush bean mortality, but this aggressive tool stacking treatment resulted in table beet mortality. Table beets need to be larger, likely the 2- to 3-leaf stage, when stacking tools are used to avoid a high level of crop mortality. Tool stacking can be applicable to hand tools such as the Terrateck and may help increase weed control efficacy, but crop growth stage and tool choice must be considered to prevent high crop mortality in small-seeded crops. Lastly, when stacking, the selection of tools and their sequence should be carefully considered and observed. Here we found L-sweeps to play a pivotal role in improving the performance of supporting tools.

Practical Implications

The Terrateck double-wheel hoe offers small-scale farmers access to individual and stacked tool combinations previously available only for larger, tractor-mounted applications. Stacking improved weed control efficacy in both a large-seeded, robust bush bean crop, and in a small-seeded, more tender crop of table beet. The average benefits of stacking were relatively modest, and perhaps not worth the trouble for many farmers. However, selected stacked combinations including L-sweeps consistently outperformed other tools, with an impressive 30% improvement in efficacy that could

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prove to be a significant improvement in weed control for many small-scale farmers.

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Competing Interests. The authors declare they have no competing interests.

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