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An Evaluation of Two Novel Cultivation Tools

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Cultivation is a critical component of organic weed management and has relevance in conventional farming. Limitations with current cultivation tools include high costs, limited efficacy, and marginal applicability across a range of crops, soil types, soil moisture conditions, and weed growth stages. The objectives of this research were to compare the weed control potential of two novel tools, a block cultivator and a stirrup cultivator, with that of a conventional S-tine cultivator, and to evaluate crop response when each tool was used in pepper and broccoli. Block and stirrup cultivators were mounted on a toolbar with an S-tine sweep. In 2008, the tripart cultivator was tested in 20 independently replicated noncrop field events. Weed survival and reemergence data were collected from the cultivated area of each of the three tools. Environmental data were also collected. A multivariable model was created to assess the importance of cultivator design and environmental and operational variables on postcultivation weed survival. Additional trials in 2009 evaluated the yield response of pepper and broccoli to interrow cultivations with each tool. Cultivator design significantly influenced postcultivation weed survival ($P < 0.0001$). When weed survival was viewed collectively across all 20 cultivations, both novel cultivators significantly increased control. Relative to the S-tine sweep, the stirrup cultivator reduced weed survival by about one-third and the block cultivator reduced weed survival by greater than two-thirds. Of the 11 individually assessed environmental and operational parameters, 7 had significant implications for weed control with the sweep; 5 impacted control with the stirrup cultivator, and only 1 (surface weed cover at the time of cultivation) influenced control with the block cultivator. Crop response to each cultivator was identical. The block cultivator, because of its increased effectiveness and operational flexibility, has the potential to improve interrow mechanical weed management.

Nomenclature: Broccoli, *Brassica oeracea* L.; pepper, *Capsicum annuum* L.
Key words: Block cultivator, cultivation, interrow weed control, mechanical weed control, stirrup cultivator, S-tine sweep.

La labranza es un componente crítico del manejo orgánico de malezas y tiene relevancia en la agricultura convencional. Las limitaciones de las herramientas de labranza actuales incluyen: altos costos, eficacia limitada y aplicabilidad marginal entre una variedad de cultivos, tipos y condiciones de humedad del suelo y las etapas de crecimiento de las malezas. Los objetivos de esta investigación fueron: 1) comparar el control potencial de malezas de dos nuevas herramientas (un cultivador de bloque y un cultivador de estribo), con un cultivador convencional de dientes pequeños y 2) evaluar la respuesta del cultivo cuando cada herramienta fue usada en pimiento y brócoli. Cultivadores de bloque y de estribo se instalaron en una barra de herramientas con una barredora de dientes pequeños. En 2008, este cultivador de tres partes se probó en campos sin cultivo, con 20 eventos/réplicas independientes. Los datos de supervivencia y re-emergencia de la maleza se recolectaron para cada una de las tres herramientas y también se recolectó información ambiental. Se creó un modelo multivariado para evaluar la importancia del diseño del cultivador, así como las variables ambientales y operacionales, en la supervivencia de las malezas después de la labranza. Ensayos adicionales en 2009 evaluaron la respuesta del rendimiento del pimiento y brócoli a la labranza entre-líneas con cada herramienta. El diseño de la herramienta de labranza impactó significativamente la supervivencia de la maleza ($P<0.0001$). Cuando la supervivencia de la maleza fue observada colectivamente entre todos los 20 eventos, los dos nuevos cultivadores mejoraron significativamente el control. En comparación con la barredora de dientes pequeños, el cultivador de estribo redujo la supervivencia de la maleza en cerca de un tercio, y el de bloque, redujo la supervivencia de las malezas en más de dos tercios. De los once parámetros ambientales y operacionales evaluados individualmente, siete tuvieron implicaciones significativas para el control de malezas con el barrido; cinco impactaron el control con el cultivador de estribo, y solamente uno (cobertura de la superficie con malezas al momento del cultivo), influyó en el control con el cultivador de bloque. La respuesta del cultivo a cada cultivador fue idéntica. Debido al aumento en la eficacia y flexibilidad operativa, el cultivador de bloque tiene potencial para mejorar el manejo mecánico de malezas entre líneas.

Cultivation can effectively manage weeds, and is a mainstay of many organic weed management programs (Ryan et al. 2007). Cultivation has also been successfully integrated with the use of herbicides on conventional farms. Weeds are controlled by burial, uprooting, root desiccation, and/or a physical separation or crushing of plant parts (Toukura et al. 2006). A number of papers have been published regarding the use of various cultivation implements within a wide range of cropping systems (Colquhoun et al. 1999; Mohler 2001; Pullen and Cowell 1997; Rasmussen 1992).

Limitations with current cultivation tools include high purchase and maintenance costs; marginal efficacy; excessive soil disturbance; stimulation of latent weed seed germination; and narrow applicability across a range of soil types, soil moisture conditions, and weed growth stages. There is a need for a cultivation implement that can address some of the limitations of current tools. The objective of this research was to evaluate whether two new tool designs (block and stirrup cultivators. G. Evans, Cornell University, Ithaca, NY 14853)

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could address some of the aforementioned limitations and have adequate crop safety.

Validating a new cultivator design requires assessment of a range of operational, environmental, and efficacy criteria. A new cultivator should require a minimum of force (energy) to be moved through the soil. The type and size of an implement can dictate operational speed, power, and fuel requirements (Michel et al. 1985). Draft is dependent upon the operating depth and the specific arrangement of the tool (Upadhyaya et al. 1984). A cultivator that operates at a reduced depth and allows soil to pass through (i.e., free flow through the implement), rather than one that attempts to push or pulverize the soil, should decrease draft. If a novel cultivation tool lowered operational draft power requirements, relative to a conventional cultivation tool, it would decrease the tractor horsepower requirement and permit increased fuel economy during cultivation.

A mechanical weed control implement needs to be economically viable. A cultivator should not be cost prohibitive for small-to-medium acreage growers. Replaceable parts should be relatively inexpensive and easy to change. For instance, the Baertschi brush hoe, despite its weed control effectiveness, is expensive to purchase, time consuming to modify to different row spacings, and requires a second operator behind the tractor to steer the tool (Colquhoun and Bellinder 1997). A structurally simple cultivator would limit undue expense during manufacture and would minimize the potential for complicated components to break or function poorly.

Cultivation tools for small and medium-acreage vegetable growers are often used in multiple crops grown with a wide range of between-row spacings. A flexible implement that could be readily adjusted to different row widths (e.g., 38 to 72 cm) would be useable in multiple cropping systems. A classic example of an adaptable design is a sweep mounted on an S-tine or fixed shank. This design has existed for centuries, yet remains a farm favorite even today due to its ease of use, adjustability, low purchase cost, and low maintenance costs (Currie 1916; Parker 2008).

Soil conditions impact cultivator performance. Kurstjens and Perdok (2000) noted that to facilitate a broader acceptance of mechanical weed control in agriculture we must expand the range of weather conditions under which soils remain workable by cultivation. High soil moisture during and after a cultivation can reduce efficacy (Bond et al. 2007). Terpstra and Kouwenhoven (1981) found that weed kill with a duckfoot sweep declined from 90% when the soil remained dry postcultivation, to 78% when the soil was wet postcultivation. Some implements perform poorly in certain soil types and/or conditions. For example, basket weeders are generally ineffective in stony or compacted soil because the stones clog the baskets or the baskets fail to cut through a crusted soil surface (Bowman 1997). Weed control with a harrow is more effective in sandy soils than in clay soils (Van der Weide and Kurstjens 1996). Ideally, a new cultivation tool would perform satisfactorily across a range of soil moistures, as well as variations in soil texture, structure, and other soil characteristics (e.g., organic matter content, clay content, degree of stoniness, and size of stones).

Weed species, size, and density influence cultivation efficacy. Some cultivators will control weeds within only a narrow size range. Flex-tine weeders are best suited for control of weeds in the white-thread to cotyledon stage (Bond et al. 2007). High weed densities clog rotary hoes and spider wheels. Weeds with tenacious or deep root systems escape cultivation implements that operate primarily by uprooting. The performance of cultivation tools that bury weeds will generally decline as weed size increases. As weeds grow older, they are less likely to be fully covered by soil, and are more prone to break through a covering of soil (Kurstjens and Perdok 2000). An ideal cultivator would provide high levels of weed control across a broad range of weed species, sizes, and densities.

Speed of cultivation not only influences the time it takes to cultivate a field, but efficacy as well. Pullen and Cowell (1997) evaluated a harrow, sweep, brush hoe, and rototiller, and found that increased travel speed did not equally improve the performance of each implement. Increasing travel speed with a sweep cultivator has been shown to increase soil covering of weeds and thereby reduce weed survival (Kouwenhoven and Terpstra 1979). Pullen and Cowell (1997) suggested that a 5–km hr^{-1} travel speed is common with existing interrow cultivators. One effective cultivation tool, a combination of intrarow rotating horizontal disks and interrow sweeps, operates at a 1.8–km hr^{-1} travel speed (Tillet et al. 2007). Such a slow speed severely limits the amount of field area that can be cultivated in a given time frame.

In cultivation of some row crops, speed is dictated by the sensitivity of the crop, size of the crop and weeds, and operator skill. Cultivation can be carried out at relatively high speeds when the crop is of an optimal size, resilient in nature, and/or the soil conditions are ideal. Narrow row spacing, the presence of large stones or soil clods, and/or high crop sensitivity necessitates precise cultivation, and thus a slower cultivation speed. An ideal implement would provide consistently high levels of weed control across a wide range of speeds.

The usefulness of a cultivation implement is ultimately determined by its ability to control weeds. Cultivation efficacy is strongly dependent on many of the aforementioned factors: soil conditions, weed variability, and travel speed. The inherent weed control potential of different tool designs is directly proportional to their flexibility to perform across a wide range of environmental and operational variables. Increased weed control with a single cultivation pass could reduce the need to make multiple passes. Minimizing repeated tractor field operations could result in time and energy savings, as well as reduce the potential for soil compaction (Ball 2006). All cultivation events have the potential to stimulate latent weed seed germination. Seeds of many weed species need light exposure to germinate (Milberg et al. 1996; Pons 1992). Cultivation events that minimize postcultivation weed seed germination could decrease the need for later cultivations.

The objective of this research was to evaluate two unique interrow cultivation tools that might address some of the shortcomings of current cultivators. Specifically, the objectives were to compare the weed control potential of both novel

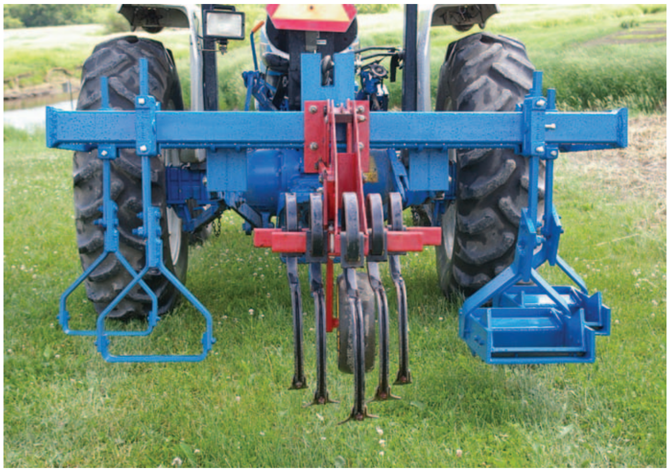

Figure 1. Rear view of the toolbar and the three different cultivator designs. Left to right: stirrup, sweep, and block cultivators.

tools directly to that of a conventional S-tine cultivator, and to evaluate the potential for crop injury in transplanted bell pepper and broccoli.

Material and Methods

Determining the Weed Control Potential of New Cultivation Tools. Both the block and stirrup cultivator were mounted onto a single toolbar alongside a traditional S-tine sweep, so that the novel tools could be compared directly with this common grower standard (Figure 1). The S-tine sweep setup was removed from a currently manufactured interrow cultivator (I & J two-row cultivator, I & J Manufacturing, 5302 Amish Road, Gap, PA 17527). Placing all three tools on the same toolbar minimized the potential for variances incurred by using each tool as a separate entity, where different toolbars, separate time frames of cultivation, and/or the necessity for larger field distances between cultivated areas, would confound findings.

Field trials to assess the weed control potential of each cultivator were conducted in 2008 at the H. C. Thompson Vegetable Research Farm in Freeville, NY. The tri-part cultivator was evaluated in 20 independently replicated non-crop field events. Trials were block designs with four replicated cultivations at 2, 6, and 10 km hr^{-1}. Cultivation speed was the whole plot factor (randomized) and cultivator type was the split-plot factor. Plots measured 3 m wide by 7.6 m long. Each plot accommodated a 0.6-m-wide swath of each of the three cultivator types and a similarly sized swath of uncultivated soil, the weedy check.

Cultivators were held in fixed positions on the toolbar for the duration of the trial. The potential for tractor tire effects on cultivation efficacy was considered. Postcultivation, but prior to collection of weed control data, weed counts in the two novel cultivator areas situated directly behind the tire tracks were compared directly to portions outside these tire tracks. With the block cultivator, there was never a measurable difference in weed number between tire-track and non–tire-track areas. With the stirrup cultivator, weed control in moist silt loam fields was generally higher in the cultivated area within the tire track as opposed to outside the tire track. In these instances, weed control data were collected solely from the cultivated area outside the tire track.

Half of the trials were conducted on field sites with an Eel silt loam soil (ESL; fine–loamy aquatic mixed mesic Udifleuvant), the other half on sites with a Howard gravel loam soil (HGL; loamy–skeletal mixed mesic Glossoboric Hapludalf). All field sites were moldboard plowed, disked, and field cultivated, and then natural weed populations were allowed to emerge. Trials were established in field areas where weed populations were relatively uniform. There were over 10 weed species present across all trials, with the most prevalent being: hairy galinsoga (*Galinsoga quadriradiata* Cav.), shepherd's purse (*Capsella bursa-pastoris* L. Medic.), purslane (*Portulaca oleracea* L.), common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and large crabgrass (*Digitaria sanguinalis* L. Scop.).

Table 1 outlines the environmental variables collected from each cultivation event. Table 1 also includes, where applicable, the range of data collected for each parameter, across all cultivations. One day postcultivation, a single permanent 0.25-m^2 quadrat was established in the center of each of the three cultivated swaths in each plot. Thus, in each cultivation event there were 12 quadrats total for each cultivator: 4 at each of the three tested speeds. Four additional 0.25-m^2 quadrats were randomly established in the weedy check areas of each trial. The number of surviving weeds were individually tallied for each quadrat. Then, all surviving weeds in each quadrat were cut at their base (to minimize soil disturbance) and discarded. All quadrats were revisited 14 d after cultivation. At this time, newly emerged weeds were counted, as well as weed escapes; i.e., those weeds that had appeared controlled at 1 d postcultivation but had managed to regrow.

An assessment of the mechanisms of weed mortality was made 1 d after cultivation, in 0.25-m^2 quadrats (four per cultivator type, from plots cultivated at 6 km hr^{-1}). These areas were separate from those that had been monitored for postcultivation weed survival. The soil in each cultivated area was carefully examined and sifted to identify the mechanism of weed death for each weed. Weed mortality was classified as due to desiccation, cutting/slicing, or burial. Recovery of all weeds controlled via burial was difficult. Therefore, the number of weeds killed by burial was determined by the number of unclassified weeds, relative to the base weed population per 0.25 m^2, after subtracting for weed survivors and weeds that had been killed via desiccation or cutting/slicing.

One day after cultivation, digital photographs were taken in each 6–km hr^{-1} cultivation tool swath, and in four random weedy areas. The camera was held approximately 1 m from the soil surface with a zero degree camera angle relative to the ground. Photos were uploaded into image analysis software (Imaging Crop Response Analyser, http://www.imaging-crops.dk) that took the multicolored images and converted them into binary images where green plant leaves were distinguished from the soil surface, dead plant residues, shadows, and stones (per work done by Rasmussen et al. 2007). Software output provided a percentage of weed ground

Table 1. A description of the assessed environmental and operation parameters, and the range of variability present within the collected data.

	Description	Range
Operation parameters		
Cultivator design	Block, stirrup, or sweep cultivator	–
Cultivation event	20 independently replicated cultivation trials	–
Cultivation speed	2, 6, or 10 km hr^{-1}	–
Soil-specific parameters		
Soil type	Silt or gravel loam	–
Soil moisture content	Gravimetric analysis was used to obtain a percent moisture at the time of each cultivation (7-cm-deep by 7-cm-wide cored samples, four per cultivation event)	7–22%
Surface stoniness	Visual assessment of the percent of the soil surface covered by stone	0–70%
Surface clod size	Average clod size, categorized as small (less than 2 cm diameter), medium (between 2 and 6 cm) or large (> 6 cm diameter)	Small to large
Surface levelness	A measurement of undulations, or unevenness, in the field surface prior to cultivation. Assessed as the vertical distance between the highest and lowest points of the soil surface (cm), within a square meter.	3–10 cm
Weed-specific parameters		
Base weed population	Mean number of weeds present in a 0.25-m^2 area	20–342 weeds 0.25m^{-2}
Mean weed size	Average weed size across the dominate weed species present (height in cm)	0.5–20 cm
Percent surface weed cover	Digital photo analysis of weedy areas; provided a quantitative percentage of ground cover at the time of cultivation	0.1–83%
Precipitation parameters		
Rainfall amount, on the day of cultivation	Rainfall volume on the day of cultivation (cm)	0–0.76 cm
Rainfall amount, in the five days prior to cultivation	Rainfall sum for the 5 d precultivation (cm)	0–5.3 cm

cover remaining 1 d postcultivation with each cultivation tool, and the relative weed cover of uncultivated ground.

Data Analysis. Data were subjected to ANOVA. Fisher's protected LSD tests were utilized to compare cultivator performance in each independent cultivation event, with significance values set at $P \leq 0.10$. Then, a SAS statistical package (SAS 9.2, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513) was used to model how operational and environmental variability impacted postcultivation weed survival across all 20 cultivation events. The number of surviving weeds per 0.25 m^2 1 d after cultivation, was set as the response variable w. The relationship between w and selected environment and operational variables was modeled as: $g(E[w_i]) = \beta_0 + \beta_1X_1 + \beta_2X_2\ \dot{c}+ \beta_{12}X_{12}$, with $X_1,X_2\dot{c}X_{12}$ representing each variable listed in Table 1 (except cultivation event); $\beta_1,\beta_2\dot{c}\beta_{12}$ coefficients representing slopes for $X_1,X_2\dot{c}X_{12}$; g the log link function; and $E(w_i)$ the expected value of w. It was hypothesized that the two novel cultivators, relative to the S-tine sweep, would have greater flexibility to perform across a range of travel speeds and under diverse environmental conditions; that is, there would be a less significant relationship between these variables and weed survival.

A generalized linear mixed model was created with the use of the PROC GLIMMIX function in SAS with a Poisson link function. The GLIMMIX procedure fits statistical models to data with correlations, where the response is not necessarily normally distributed. The generalized linear mixed model assumes normal (Gaussian) random effects but allows for data to be distributed within any exponential family. A Poisson distribution is a discrete member of the exponential family that adequately reflected the distribution present in the postcultivation weed survival counts.

The generalized linear mixed model with the Poisson distribution was modeled with the use of a log-link function, with the model fit on the log-lambda scale. Data were retained in their original form for presentation in figures. Weed-density data from the weedy control areas were integrated into the statistical model as the variable base weed population (Table 1). Two-way interactions between cultivator design and selected environmental and operational variables were included in the model if they provided significant explanatory power. Step-by-step backward selection, based on the Type III test for fixed effects in the PROC GLIMMIX procedure, was used to eliminate nonsignificant parameters ($P \geq 0.10$) and to create a final, reduced model. To determine how each tool's performance was uniquely predicated on operational and environmental conditions, a separate multivariable model was produced for each cultivator.

Determining Crop Injury Potential. Field trials using the block, stirrup, and sweep cultivators were carried out in the summer of 2009 at the H. C. Thompson Vegetable Research Farm in Freeville, NY. Trials in transplanted bell pepper 'Lady Bell' and broccoli 'Premium Crop' were each conducted twice, at two different field sites. Soil at both sites was a Howard gravel loam (HGL ; loamy–skeletal mixed mesic Glossoboric Hapludalf). Trials were randomized block designs with four replications.

The sweep cultivator was utilized in its original two-row configuration. The novel cultivators were mounted on the same toolbar, with the stirrup cultivator on each side of one row, and the block cultivator on each side of the other row. Cultivations were carried out with all tools adjusted to leave either a 15- or 24-cm-wide uncultivated in-row band. In-row areas of all treatments were hand weeded as necessary. An uncultivated weedy check was included for comparison.

Table 2. The significance of environmental and operational parameters on weed survival 1 d postcultivation. Insignificant parameters were eliminated from the reduced model.

	Full model	Reduced model
	—Significance value (P)—	
Operational parameters		
Cultivator design	< .0001	< .0001
Cultivation speed	0.0778	0.0779
Soil-specific parameters		
Soil type	0.2008	0.1555
Soil moisture content	0.0481	0.0361
Surface gravel cover	0.7208	–
Surface clod size	0.2228	–
Surface levelness	0.0507	0.0819
Weed-specific parameters		
Base weed population	0.0367	0.0102
Mean weed height	0.9358	–
Percent weed cover, untreated	0.0158	0.0033
Precipitation parameters		
Rainfall amount, on the day of cultivation	0.0727	0.0411
Rainfall amount, in the 5 d prior to cultivation	0.0419	0.0312
Selected interactions		
Design × cultivation speed	< .0001	< .0001
Design × percent weed cover	< .0001	< .0001
Design × soil moisture content	0.0071	0.0219
Design × soil type	< .0001	< .0001
Design × surface levelness	< .0001	< .0001

All field sites were moldboard plowed, disked, fertilized, and field cultivated prior to transplanting. Each plot was 1.5 m wide and contained two 7.6-m-long crop rows. Transplants were mechanically transplanted 60 cm apart, in rows spaced 76 cm apart. Both broccoli trials were planted on April 20 and cultivations were made at 16 and 26 d after planting (DAP). Broccoli was harvested 51 DAP. Pepper trials were planted on June 1 and cultivations were made at 14, 38, and 46 DAP. All cultivations at 46 DAP occurred with the larger 24-cm-wide uncultivated area, necessitated by the increased plant size. Peppers were harvested at 65, 72, and 82 DAP. In all trials, weed control and crop yield data were collected. Data were subjected to ANOVA. Fisher's protected LSD tests were conducted to compare crop response to each cultivator, with significance values set at $P \leq 0.10$.

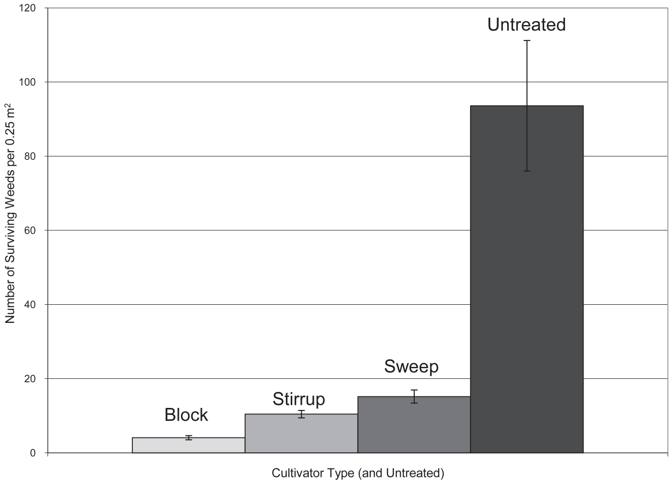

Figure 2. Weed survival, 1 d after cultivation with each tool and in the untreated area. Survival numbers were averaged across the 20 cultivation events and the three tested cultivation speeds. Standard error bars shown.

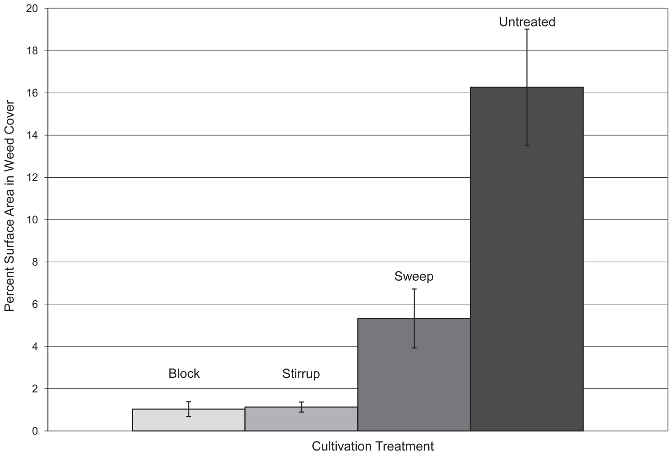

Figure 3. The percent weed cover, 1 d after cultivation with each tool and in the untreated area. Weed cover data was averaged across the 20 cultivation events and the three tested cultivation speeds. Standard error bars shown.

Results and Discussion

Cultivator Performance. Weed control varied by cultivator design. Full and reduced models of weed survival, as a function of operational and environmental parameters, are shown in Table 2. Notably, cultivator design was highly significant ($P < 0.0001$). Averaging across the three tested speeds, the block cultivator provided significantly greater weed control than the S-tine sweep in 17 of the 20 cultivation events ($P \leq 0.10$) and equivalent control in the other three cultivation events. The stirrup design, when compared with the S-tine sweep, significantly improved weed control in 6 of 20 cultivation events, provided equivalent control in 13

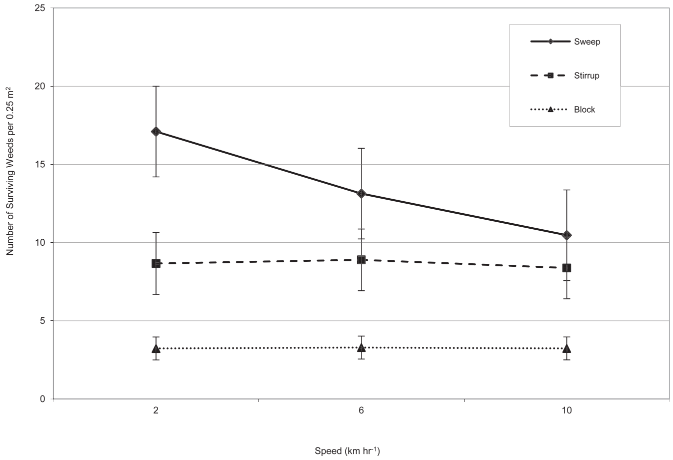

Figure 4. The impact of cultivation speed on weed survival, 1 d postcultivation. Standard error bars shown.

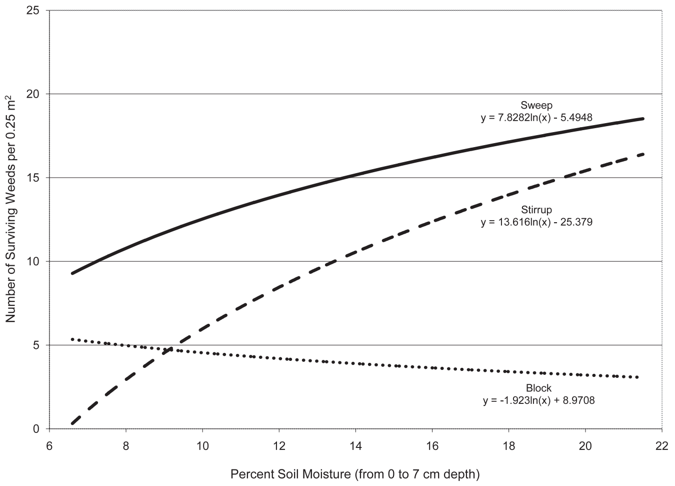

Figure 5. The impact of soil moisture on weed survival with each of the three cultivators, 1 d postcultivation.

events, and lowered control in 1 event (data not shown). When viewed collectively across all 20 cultivations, both novel cultivators significantly reduced weed survival compared to the S-tine sweep. The stirrup cultivator reduced weed survival by about one-third and the block cultivator reduced weed survival by greater than two-thirds (Figure 2). Similarly, when cultivator efficacy was measured by the percent surface area in weed cover 1 d postcultivation, the block and stirrup tools outperformed the sweep (Figure 3). There is 95% confidence that the average number of surviving weeds in a 0.25-m^2 quadrat, 1-d postcultivation with the block cultivator, will be between 3 and 5. In that same area, there would be between 8 and 13 weeds remaining after stirrup cultivation and between 11 and 19 weeds remaining after sweep cultivation. Thus, cultivation design was highly significant.

Performance increased with the sweep cultivator as speed increased from 2 to 10 km hr^{-1} (Figure 4). With harrowing, increased speed is associated with improved weed control (Kurstjens and Perdok 2000; Pullen and Cowell 1997). Sweeps function most effectively by throwing soil, contacting it at speeds where aggregate separation is maximized. Decreased soil particle size enhances separation of weed roots from soil and provides more complete burial of small weeds.

In contrast, weed control with the stirrup and block cultivators remained relatively constant across the range of tested speeds (Figure 4). Both tools caused minimal soil throw; they were primarily slicing into and through the soil, and in the case of the block cultivator, compacting the soil to force apart aggregates. Increased travel speed increased the rate of the slicing and compacting, but did not increase the degree of aggregate separation. Farmers will often cultivate at a range of travel speeds, depending on crop sensitivity and operator skill. The new cultivators provide a more consistent level of weed control across varying cultivation speeds.

Although some soil characteristics influenced cultivation, others were insignificant. Surface gravel cover and surface clod size did not measurably affect cultivation (Table 2). However, soil moisture at the time of cultivation remained an important variable (Table 2). Increased soil moisture correlated with increased weed survival with both the stirrup and sweep cultivators (Figure 5). In contrast, weed survival with the block cultivator remained constant throughout the observed moisture levels (7 to 22%, Table 3). Data collected on rainfall levels, on the day of cultivation and in the 5 d prior to cultivation, corroborates with the soil moisture data (Table 2).

Base weed populations were generally higher in cultivations where the soil moisture was higher. Thus, it is possible that the differences in cultivator efficacy attributed to soil moisture are a result of differences in the ability of each cultivator to control varying weed densities. The observed trends in Figure 5 could simply reflect that the block cultivator was able to control higher weed densities than ether the sweep or stirrup designs. Base weed population did have a significant impact on postcultivation weed survival with the sweep or stirrup, but was noninfluential with the block design (Table 3). Nevertheless, if we assume that weed numbers will

Table 3. The significance of environmental and operational variables on weed survival 1 d postcultivation, for each cultivator design. Variables that significantly impacted weed survival ($P \leq 0.10$) are shown in bold.

	Sweep	Stirrup	Block
	Significance value (P)		
Operational parameters			
Cultivation speed	**0.0027**	0.1469	0.9080
Soil-specific parameters			
Soil type	0.1587	0.6782	0.3813
Soil moisture content	**0.0436**	**0.1073**	0.1537
Surface stoniness	0.5450	0.9814	0.8982
Surface clod size	0.1153	0.3321	0.4680
Surface levelness	**0.0172**	0.4375	0.1358
Weed-specific parameters			
Base weed population	**0.0135**	**0.0875**	0.7594
Mean weed size	0.5219	0.3778	0.8810
Percent weed cover, untreated	**0.0184**	**0.0415**	**0.0583**
Precipitation parameters			
Rainfall amount, on the day of cultivation	**0.0624**	**0.0122**	0.9588
Rainfall amount, in the 5 d prior to cultivation	**0.0247**	**0.0812**	0.3701

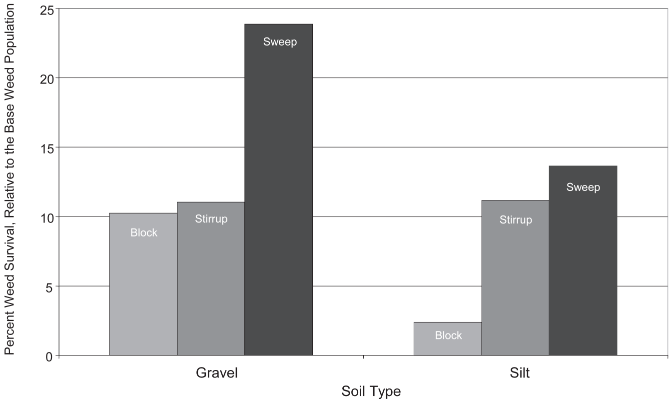

Figure 6. The proportion of surviving weeds in each soil type and with each cultivator (1 d after cultivation), as a percentage of the base weed population.

generally be higher in moist soil conditions, then the block cultivator appears more capable in such a situation.

Higher moisture levels reduced the capability of the sweep and the stirrup to separate soil aggregates. Mohler et al. (2000) noted that when soil clings to seedling roots there is a lower chance for weeds to be buried or weed roots to desiccate. In contrast, the block cultivator compacted aggregates prior to entering the soil, breaking apart more of these aggregates and separating more weeds from soil—despite the tendency of moist soil particles to cohere (visual observation). In soils that tend to become cloddy with increasing wetness, the downward pressure of the block cultivator provided a reliable means to break apart clods.

The sweep and stirrup also penetrate deeper into the soil than the block. Operational depth for the sweep was between 6 and 10 cm, between 2 and 8 cm for the stirrup, and between 1 and 5 cm for the block cultivator. Soil moisture levels rise with increasing soil depth. As the block cultivator operated at the shallowest depth, this design took advantage of the fact that the soil surface moisture was lower. The block cultivator has the potential to operate effectively over a wider range of soil moisture conditions compared to the other cultivators. However, the effectiveness of the block in moist soil conditions may be a reflection of its capability to control the higher densities of weeds that often persist in moist soils, rather than a direct corollary to the soil moisture level itself.

Soil-surface levelness was a unique attribute of the model, and provided some explanatory power (Tables 2 and 3). Fewer weeds survived with the sweep, and to a lesser extent, with the block cultivator, when the soil surface was uneven at the time of cultivation (data not shown). In contrast, stirrup cultivator efficacy was unaffected by differing degrees of soil-surface levelness (Table 3).

It is likely that soil-surface levelness was not the primary variable responsible for these observed differences; rather, soil-surface levelness could have been an indicator of the degree of soil compaction. Immediately after tillage operations (e.g.; harrowing, disking, or rototillering) soil is least compact, and the surface of this loosened soil is at its most uneven. The soil surface becomes more uniformly level, and the soil itself more compact, with both time (an effect known as age hardening) and an increasing number of wet-to-dry cycles (rain events) (Dexter et al. 1988; Horn 1993; Horn and Dexter, 1989). S-tine sweep entry into the soil was inhibited by compaction, and to a lesser degree this physical response occurred with the block cultivator. The stirrup cultivator had a comparatively lower penetration resistance and was less influenced by the degree of soil compaction. However, no compaction data was collected to verify this assessment. Mohler et al. (2000) found that weed control via mechanical cultivation was greater in a coarse seedbed that was chiseled and disked, compared to a fine seedbed that was chiseled, disked, and cultimulched. A cultimulcher increases soil compaction.

Soils that are high in clay, or low in organic matter, have a greater tendency toward compaction (Kooistra and Tovey 1994). A hard-setting soil has a structure that collapses after wetting, causing the soil to dry to a compacted mass (Dexter 2004; Mullins et al. 1987). Two features of hard-setting soils are a low organic matter content and a high content of sand and silt with only a small percentage of clay. Such soil is challenging to cultivate until it has been rewetted. In the two soil types in these experiments, the gravel loam, with its low organic matter and 13 to 16% clay content, had the greatest tendency to exhibit hard setting. Thus, if compaction was a negative factor in cultivator efficacy, we would expect poorer weed control with cultivations on the gravel loam soil relative to cultivations on the silt loam.

The proportion of weed survival, relative to the existing weed population, was influenced by the interaction between cultivator design and soil type (Table 2). With the sweep cultivator, and to some degree, the block cultivator, there were proportionally more weeds surviving in the 10 trials conducted on gravel loam as compared to the 10 trials conducted on silt loam (Figure 6). In contrast, weed survival percentages between stirrup cultivations on both soil types were identical. It is possible that soil compaction, as indicated by soil surface levelness and soil type, influenced each cultivator differently. Sweep performance was negatively influenced by increasing soil compaction (increasing surface levelness), block performance was somewhat influenced, and the stirrup was largely unaffected (Table 3).

Weed population parameters affected cultivator performance. With all three cultivators, weed ground cover at the time of cultivation was a strong predictor as to the number of weeds surviving 1 d after cultivation (Table 3). There was not, however, a strong relationship between cultivator performance and mean weed size. For the sweep and stirrup, the greater the number of weeds present, the greater the number of weeds that survived (Table 3). It would stand to reason that, if a cultivator routinely controlled 90% of the weeds present, that weed survival in an area of 1,000 weeds (100) would be greater than that of a like area containing 100 weeds (10). Unlike the stirrup and sweep, performance of the block cultivator was not linked to weed population level ($P = 0.7594$). With the block cultivator, the high control levels observed across all weed populations may have overshadowed any population effects.

The percent weed ground cover, assessed 1 d after cultivation via image analysis, reflects an interaction between weed size and weed density (Figure 7). With increasing weed densities and/or increasing weed size, there was more surface

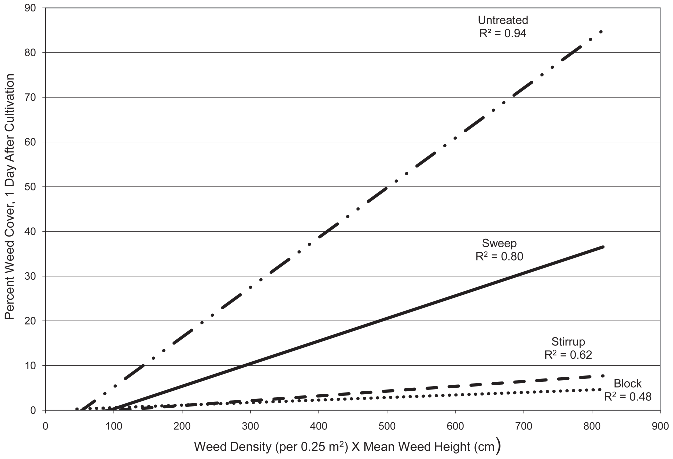

Figure 7. The impact of weed size and density on the percent of ground covered by weeds before and after cultivation.

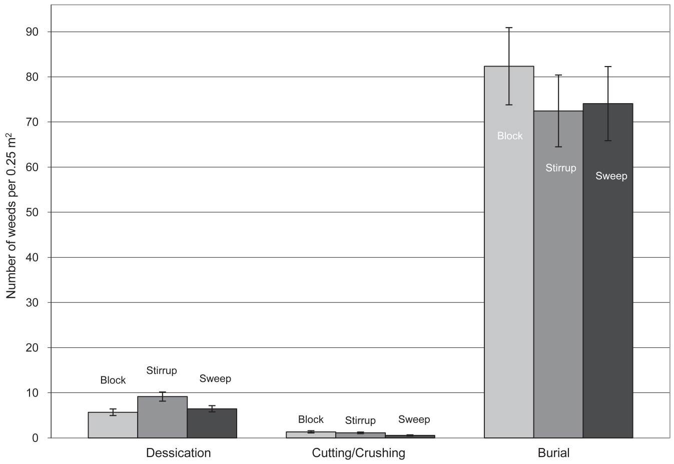

Figure 8. The distribution in the mechanisms of weed mortality with each of the three cultivators. Standard error bars shown.

weed cover remaining postcultivation. However, the strength of this relationship changed depending on which cultivator was being used. Sweep performance was the most dependent on weed population dynamics ($R^2 = 0.80$), whereas the block cultivator was the least dependent ($R^2 = 0.48$). Weed morphology, density, and size have all been reported to influence the efficacy of mechanical cultivation (Baerveldt and Ascard 1999; Bond et. al 2007; Rasmussen 1993). Although weed population parameters influenced control with all three cultivators, the block cultivator was the least affected.

The ability of each cultivator to control specific weed species was difficult to assess, because no single species was present in all 20 trials. The most common weed species was hairy galinsoga, which was present in 13 of the 20 trials. Average postcultivation survival of galinsoga was nine weeds per 0.25 m^2 with the sweep cultivator, seven with the stirrup, and two with the block. The range of variability in galinsoga survival also differed between tools. There were, on average, < 1 to 26 survivors per 0.25 m^2 with the sweep, < 1 to 21 survivors with the stirrup, and < 1 to 6 survivors with the block. With the block cultivator, galinsoga control increased, and the variability in the range of that control decreased, relative to the other tools.

Cultivator usefulness can be undermined by postcultivation weed escapes, and by the potential stimulation of weed germination. The number of weeds that appeared controlled at 1 d after cultivation, and yet regrew by 14 d after cultivation, averaged between one and two per 0.25 m^2. There were no striking differences between cultivator designs, although weed escapes were generally fewer with the new designs. All cultivation events have a tendency to trigger new weed germination (Milberg et al. 1996; Pons 1992). Implements can stimulate and redistribute weed seeds in different ways (Cousens and Moss 1990). In these experiments, at 2 wk after cultivation, there was an average of 41, 37, and 31 newly germinated weeds per 0.25 m^2 with the sweep, stirrup, and block cultivators respectively (data not shown). Differences in weed germination between the three tested implements were insignificant.

Most germinable weed seed lies in the upper few centimeters of the soil. Because all three cultivators disrupted this soil layer, the seeds were equally likely to germinate. With a single cultivation, it is unlikely that new weed germination will be influenced by the type of cultivator. However, with multiple cultivation passes across the same area, differences could appear. Soil disturbance with the block cultivator is shallower than that with the sweep or stirrup, and thus a smaller volume of soil is repeatedly being disturbed. With frequent shallow cultivation, there is the potential that new seed germination could be exhausted sooner, as the available pool of germinable seed becomes smaller and smaller (Roberts and Dawkins 1967). This could be an important factor in field operations where multiple cultivations are made in a single season.

Weed mortality with each of the three cultivators was largely a result of burial (Figure 8). Slight increases in the number of weeds killed via desiccation were observed with the stirrup cultivator. This may reflect the slicing motion of the tool, whereby soil is disturbed, but less overturned, than with either the sweep or block. As a consequence, more weeds would remain at the surface, with soil separated from roots, and become subject to desiccation. Increased performance with the block and stirrup cultivators was not due to novel mechanisms of mortality, but instead, reflected increased tool tolerance to operational and environmental inconsistencies.

It is likely that, with weed burial in particular, the mortality of a given weed may be due to a combination of factors. For example, a weed that is buried may also have sustained some degree of crushing of stems and leaves, and certainly had soil disturbance around the roots. These factors together would amplify the potential stress on a weed and minimize the likelihood of regrowth. Categorizing weed mortality by only the primary observable cause of weed death, as has been done in this research, limits interpretation of possible interactions between multiple mortality mechanisms.

Crop Response. Pepper and broccoli per-plant yields were comparable between plants cultivated with the new cultivator designs and those cultivated with the traditional S-tines (Figures 9 and 10). Plot yield and harvestable number of

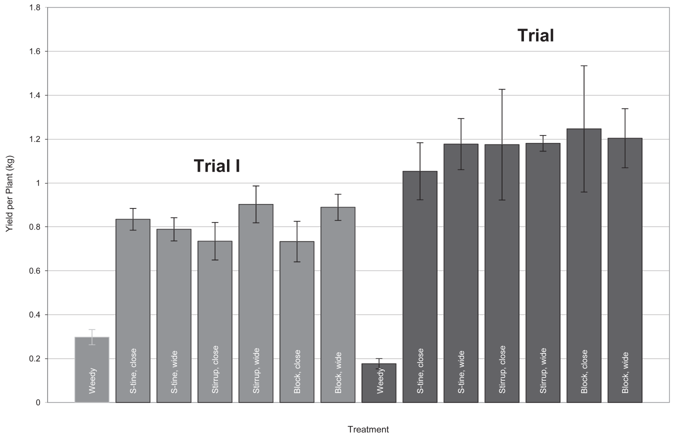

Figure 9. Pepper plant yield across cultivation treatments and trial locations. Standard error bars shown.

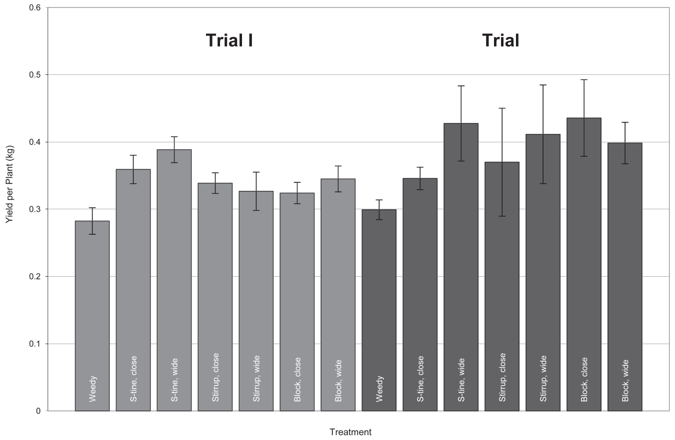

Figure 10. Broccoli per plant head weight across cultivation treatments and trial locations. Standard error bars shown.

heads (broccoli) or peppers did not differ significantly between treatments (data not shown). Close cultivation appears possible with all three tools. However, in some instances, particularly in pepper trial II, there was more yield variability with close than with wide cultivations. With close cultivation there was greater random occurrence of crop injury. Nevertheless, there was little difference in crop response between the three tools.

The directionality of soil flow with each cultivator influenced soil movement into the crop row. The flow-through passage of soil with the block and stirrup cultivators limited soil movement sideways into crop rows. In contrast, when the sweeps were operated at higher speeds, some soil was "thrown" into the crop row. With tough crops, such as broccoli, beans, or potato, soil movement into the crop row may be beneficial because it can bury and suppress small intrarow weeds. However, more sensitive crops like onion or carrot can be injured by this intrarow soil movement. In these trials, pepper and broccoli plants were not noticeably affected.

Practical Considerations. Purchase costs bear consideration with each type of cultivator. A two-row version of the tested S-tine sweep cultivator costs $1,400. The cost for a two-row version of the stirrup and block cultivators, based on the documented prices of materials and estimated labor, would be $1,300 and $1,500, respectively. It is likely that labor costs (time of production) would be reduced within an efficient production system. Because both novel cultivators make use of "shorts," small lengths of steel that are commonly sold as remnants of larger pieces, there is also a potential for material savings.

Operational efficiency needs to be considered. McKyes and Maswaure (1997) suggested that to minimize the draft requirement for a tillage tool, it should be designed to operate at a shallow depth and with a low rake angle. Both the stirrup and block cultivators operate at shallower depths than typical sweep setups. Blade angle is less than 30° with both tools. However, field experiences indicate that the draft requirement of all three tools is relatively small, as each can be pulled at low engine revolutions and at high speeds with little difficulty.

Draft differences between the tested tools may not be particularly relevant, as compared to the more extreme differences in draft requirements between primary tillage implements like plows and harrows. Nevertheless, cultivations with the sweep, stirrup, and block provide an energy savings relative to weed control with power-take off (PTO) operated equipment (e.g., a brush hoe or rototiller), as these alternatives require a higher engine speed and a slower travel speed. Because the block and stirrup cultivators provide higher levels of weed control with a single operation, it is possible that fewer cultivations would be needed to provide season-long control. Reducing the number of cultivations, or the need for multiple passes within a single cultivation event, would reduce on-farm fuel usage and operator time.

Weed control with the three cultivation tools was strongly dependent on the capability of each tool within the tested range of travel speeds, weed pressures, and soil parameters. The S-tine sweep was highly influenced by environmental conditions and the speed of cultivation. As a result, overall performance was lowered. In contrast, the block cultivator was minimally impacted by variations in environmental conditions or working speed and weed control was consistently highest with this tool. The stirrup cultivator was intermediate between the block and sweep cultivators. There were no distinct differences between postcultivation weed survival and new weed germination with any of the tested tools. Additionally, each design had a similar purchase cost and draft requirement.

Integration of either tool into the mechanical marketplace is dependent on piquing the interest of agricultural tool manufacturers who see fit to invest in these designs. By producing cultivation tools that are functionally independent of the uncontrollable variables, operational and environmental, that occur in agriculture, we can increase the consistency and reliability of cultivation as a weed management technique. The block cultivator, due to increased flexibility, has the potential to significantly improve interrow mechanical weed management.

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