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Intrarow Weed Removal in Broccoli and Transplanted Lettuce with an Intelligent Cultivator

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The performance of the Robovator (F. Poulsen Engineering ApS, Hvalsø, Denmark), a commercial robotic intrarow cultivator, was evaluated in direct-seeded broccoli and transplanted lettuce during 2014 and 2015 in Salinas, CA, and Yuma, AZ. The main objective was to evaluate the crop stand after cultivation, crop yield, and weed control efficacy of the Robovator compared with a standard cultivator. A second objective was to compare hand weeding time after cultivation within a complete integrated weed management (IWM) system. Herbicides were included as a component of the IWM system. The Robovator did not reduce crop stand or marketable yield compared with the standard cultivator. The Robovator removed 18 to 41% more weeds at moderate to high weed densities and reduced hand-weeding times by 20 to 45% compared with the standard cultivator. At low weed densities there was little difference between the cultivators in terms of weed control and hand-weeding times. The lower-hand weeding time with the Robovator treatments suggest that robotic intrarow cultivators can reduce dependency on hand weeding compared with standard cultivators. Technological advancements and price reductions of these types of machines will likely improve their weed removal efficacy and the long-term viability of IWM programs that will use them.

Nomenclature: Broccoli**,** *Brassica oleracea* L. 'Marathon'; lettuce, *Lactuca sativa* L. 'Sunbelt'.

Key words: Automation, broccoli, cultivator, DCPA, integrated weed management, intrarow weed control, lettuce, pronamide, robotic weeding, vegetable.

El desempeño del Robovator (F. Poulsen Engineering ApS, Hvalsø, Denmark), un cultivador robótico comercial para uso dentro de las hileras de siembra, fue evaluado en brócoli de siembra directa y lechuga trasplantada durante 2014 y 2015 en Salinas, California y Yuma, Arizona. El objetivo principal fue evaluar el cultivo establecido después de la labranza, el rendimiento del cultivo, y la eficacia para el control de malezas del Robovator, al compararse con un cultivador estándar. Un segundo objetivo fue comparar el tiempo de deshierba manual después de la labranza dentro de un sistema de manejo integrado de malezas (IWM) completo. Se incluyó herbicidas como un componente del sistema IWM. El Robovator no redujo el número de plantas del cultivo establecidas ni el rendimiento comercializable al compararse con el cultivador estándar. El Robovator eliminó 18 a 41% más malezas en densidades de moderadas a altas y redujo el tiempo de deshierba manual en 30 a 45% al compararse con el cultivador estándar. A bajas densidades hubo pocas diferencias entre los cultivadores en términos de control de malezas y tiempos de deshierba manual. El mejor tiempo de deshierba manual con los tratamientos con Robovator sugiere que cultivadores robóticos para uso dentro de las hileras de siembra pueden reducir la dependencia en la deshierba manual en comparación con cultivadores estándar. Los avances tecnológicos y las reducciones en precio de este tipo de máquinas probablemente mejorará la eficacia en la remoción de malezas y la viabilidad en el largo plazo de los programas IWM que los usen.

Arizona and California produce more than 95% of the broccoli and lettuce in the United States, with a gross farm value of $3.1 billion (NASS 2014). Broccoli and lettuce are highly sensitive to weed competition (Fennimore et al. 2010). Roberts et al. (1977) found that 4 wk of weed competition can reduce lettuce yields by 23%. In broccoli, ryegrass (*Lolium* spp.) at 600 plants m^{-2} within the row resulted in complete yield loss (Bell 1995). Uncontrolled weeds can also decrease harvest efficiency and damage crop quality, as well as be a host for insect pests (Shem-Tov et al. 2006). Because vegetables are high-value crops and total production value can reach $19,385 ha^{-1}, it is essential to control weeds effectively to ensure profitability (Smith et al. 2007a).

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Integrated weed management (IWM) systems are used in broccoli and lettuce production. IWM systems commonly incorporate cultural, physical, and chemical weed control tools. However, these IWM systems have major deficiencies, such as the limited number of herbicides registered for use with broccoli and lettuce crops, and most of these products provide only partial weed control (Fennimore et al. 2010; Slaughter et al. 2008). Additionally, two herbicides commonly used in broccoli and lettuce, DCPA and pronamide, respectively, have been found to contaminate groundwater (Bruggeman et al. 1995; MDCH 2003). These herbicides either have been or in the future could be subject to regulatory actions that severely restrict or cancel their use (Fennimore and Doohan 2008; Mou 2011). Because of the small market size for vegetables, the agrichemical industry has no incentive in developing new herbicides to fill in the voids created by the loss of old vegetable herbicides (Fennimore and Doohan 2008; Gast 2008).

Physical weed control tactics such as cultivators are key components in broccoli and lettuce IWM systems (Fennimore et al. 2010; Smith et al. 2007b). However, the standard cultivators are limited because they remove only the interrow weeds (Van der Weide et al. 2008). The available tools for intrarow cultivation, such as the finger and torsion weeders, are effective at removing only small weeds and can damage the crop (Cloutier et al. 2007). For these reasons, broccoli and lettuce growers have become highly dependent on hand-weeding for commercially acceptable weed control (Fennimore et al. 2014).The cost of hand weeding ranges from \$250 to \$450 ha^{-1}, but growers must choose between high weeding expense or possible rejection of their crop because of weed contamination (Fennimore and Doohan 2008). Labor shortages have been reported, and labor costs increased by 64% over a 10-yr period (Goodhue and Martin 2014; Taylor et al. 2012). Furthermore, performing hand weeding for long periods is a physically demanding task that can result in serious health problems for workers (Perez-Ruiz et al. 2014). It is essential for broccoli and lettuce producers to adopt alternative weed control tactics that will reduce the need for hand weeding and be economically sustainable in the long run.

A potential solution to this problem that is compatible with current vegetable IWM practices is the use of advanced intelligent cultivators (ICs) and co-robotic control systems (Perez-Ruiz et al. 2014; Rasmussen et al. 2012). ICs are robotic image-based machines designed to remove weeds automatically from within the crop row. The co-robotic systems perform a similar weed removal operation; however, the crop location is initially detected by a human operator rather than automatically by the machine (Perez-Ruiz et al. 2014). The first generation of commercially available ICs was the Robocrop in-row cultivator designed and developed in England by Tillett and Hague Technology Ltd. (Tillett et al. 2008). The *Robocrop* utilizes a machine vision system to detect plant location and disc blades that rotate away to avoid contacting the crop plants during weeding. The Robocrop was evaluated by Fennimore et al. (2014) in lettuce, bok choy, celery, and radicchio. They found the Robocrop can reduce weed densities in transplanted crops by 85%, and correspondingly, hand weeding time by 25%. For direct-seeded crops, the net return of the Robocrop-based treatments were lower than the standard cultivator treatments; the small distance between seedlings resulted in crop stand and yield reduction caused by the disc blades. Therefore, the authors concluded that there was no justification to adopt these machines for direct-seeded crops like lettuce.

A new generation of IC technologies is available: The Robovator (F. Poulsen Engineering ApS, Hvalsø, Denmark), Steketee IC (Machinefabriek Steketee BV, Haringvliet, The Netherlands), and Remoweed (Ferrari Costruzioni Meccaniche, Guidizzolo, Italy) (Melander et al. 2015; Siemens, 2014). These new ICs utilize pairs of knife blades controlled by machine vision guidance systems that move the knives in and out of the crop row to cultivate the intrarow weeds. The weed/crop classification algorithms are based on differentiating individual crop plants from weeds primarily via differences in plant size and the distance the plant is from the seed row. For these machines, wide spacing is preferable and successful weeding requires gaps between leaf edges of adjacent plants. The new ICs cultivate about 60% more surface area than standard cultivators (Hofstee and Nieuwenhuizen 2013) and are a new weed control tool available for vegetable production. However, the literature concerning the efficacy of these new ICs in vegetable crops is limited, and they have never been evaluated in Arizona and California vegetable production

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systems (Rasmussen et al. 2012). The objective of this study was to compare IC weed removal performance, crop safety, and crop yield to a standard cultivator. An additional objective was to compare hand-weeding time in IWM that is based on the new IC compared with a standard cultivator.

Material and Methods

Field Station Evaluations. Three experiments (exps.) with transplanted lettuce and two with directed-seeded broccoli were conducted during 2014 and 2015 at Salinas, CA, and at the University of Arizona Agricultural Center at Yuma, AZ (Table 1). Soil type at the Hartnell station in Salinas is an Antioch sandy loam soil, fine, smectitic, thermic Typic Natrixeralf (53% sand, 32% silt, and 15% clay) with pH 7.0 and an organic matter content of 2.1%. Soil type at the Spence station in Salinas is a Chualar loam, fine-loamy, mixed, thermic Typic Argixeroll (79% sand, 14% silt, and 7% clay) with pH 7.2 and an organic matter content of 1%. Soil type at Yuma is a Holtville clay loam (clayey over loamy, montmorillonitic [calcareous], hyperthermic Typic Torrifluvent, with 50% clay, 45% silt, and 5% sand). The broccoli variety 'Marathon' and the lettuce variety 'Sunbelt', a romaine type, were used.

Experimental Design and Herbicide Treatments. Experiments were established using a factorial design with two main factors, cultivator type (standard and IC), and herbicide application (with and without), arranged in a randomized complete block design with four replicates. Plots consisted of two raised beds 1 m (Salinas) and 1.1 m (Yuma) wide by 15 m long and 25 cm tall. Each bed had two plant lines 30 cm apart; the plants were spaced 23 cm within the plant line with the exception of 18-cm plant spacing at Yuma (exp. 3) and 30-cm spacing in exp. 4. The broccoli was direct-seeded, and the leaf lettuce was transplanted at the three to five true leaf stage (1 mo old). For the Salinas trials, a tractor-mounted transplanter (Mechanical Transplanter Co., Holland, MI 49423) was used for lettuce transplanting, and a tractor-mounted planter (Stanhay Webb Ltd., Bourne, UK) was used for broccoli seeding. For the Yuma trial, a Stanhay 785 vacuum planter tractor-mounted transplanter (Stanhay Webb Ltd.) was used for seeding. Overhead sprinkler irrigation and other common lettuce and broccoli cultural practices used were as described by Fennimore et al. (2010). Herbicides were applied with a CO_2-pressurized backpack sprayer equipped with 8002VS flat fan nozzles (Tee Jet Technologies, Wheaton, IL 60189) calibrated to deliver 337 L ha^{-1} at 290 kPa. Pronamide (Kerb 50W, Dow AgroSciences LLC, Indianapolis, IN 46268) was applied at 1.3 kg ha^{-1} 1 day after transplanting lettuce, and DCPA (Dacthal H 75W, Amvac Chemical Corporation, Los Angeles, CA 90023) was applied at 8.4 kg ha^{-1} 1 day after seeding broccoli. Five centimeters of water was applied by sprinkler irrigation immediately after treatment to activate the herbicides.

Cultivation and Weed Removal. Approximately 1 wk after lettuce transplanting or 3 to 5 wk after seeding broccoli, cultivation was performed using IC (Robovator intrarow weeder; Figure 1a), and by a standard cultivator tool bar equipped with two sets of cultivator knives; the cultivator shanks on the tool bar were adjusted to leave a 10.2-cm-wide noncultivated band centered over the seed line. The Robovator has fixed cultivating blades similar to that of a standard cultivator and pairs of moveable knives positioned over each crop row (Figure 1b). During operation, the knives move in and out of the crop row to cultivate intrarow weeds. Plant location is detected using a camera-based machine vision system. Crop plants are differentiated from

Table 1. Location, year, crop, herbicide, and planting, with cultivation, hand-weeding, and harvest dates for broccoli and leaf lettuce cultivator evaluations in the different experiments (Exp.) conducted at Hartnell and Spence (Salinas, CA) and Yuma (AZ).

Exp.	Location	Year	Crop	Herbicide	Planting	Cultivation	Hand weeding	Harvest[a]
1	Hartnell	2014	Lettuce	Pronamide	Jul. 2	Jul. 18	July 23	August 5
2	Spence	2014	Broccoli	DCPA	Sep. 25	Oct. 16	October 21	—
3	Yuma	2014/5	Broccoli	DCPA	Dec. 9	Jan. 12	January 16	March 26
4	Hartnell	2015	Broccoli	DCPA	Apr. 23	May 15	May 18	July 3, 8
5	Spence	2015	Lettuce	Pronamide	Jun. 8	Jun. 24	June 25	July 23

[a] Broccoli was not harvested in exp. 2 because of pests that destroyed the plants.

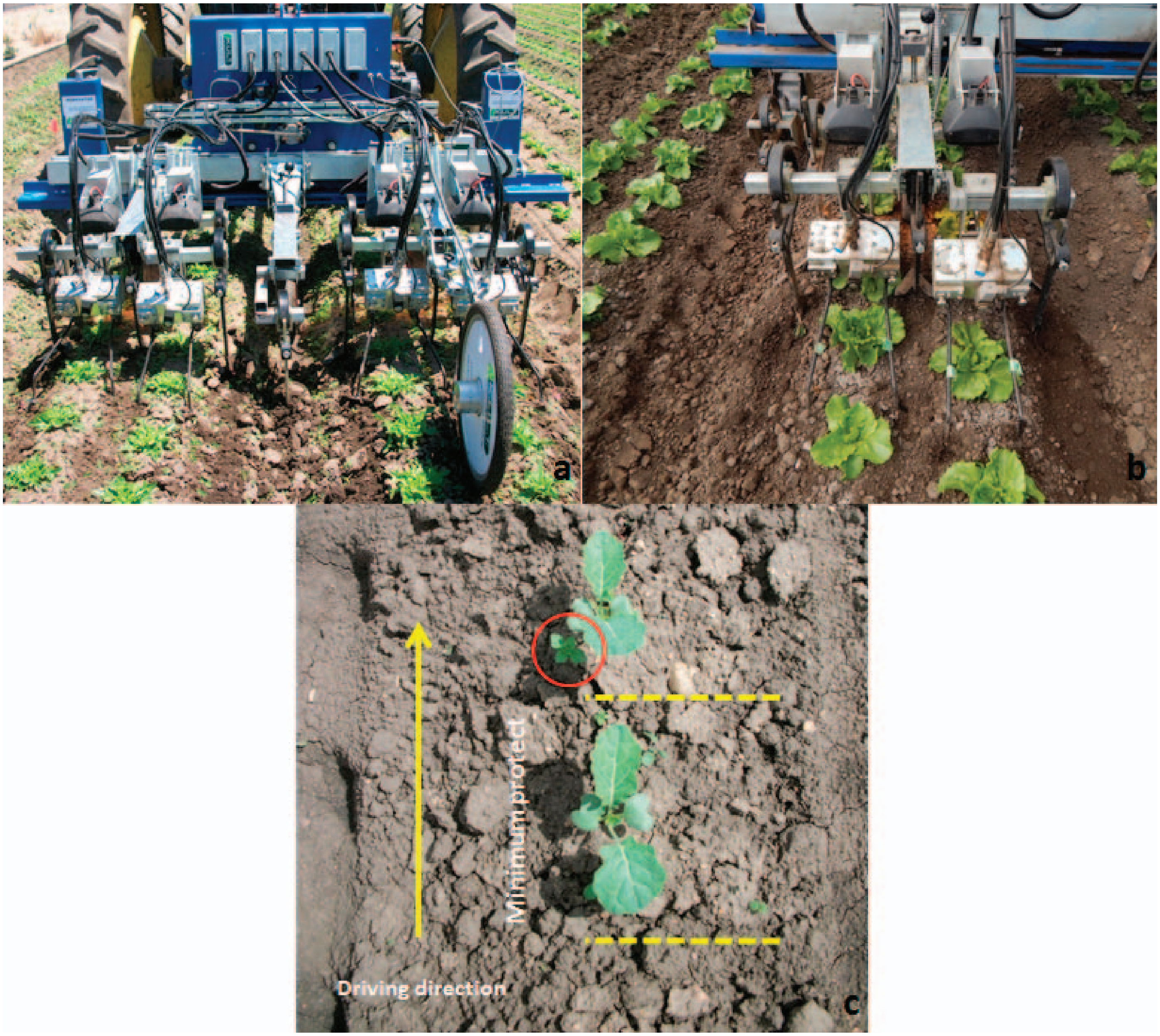

Figure 1. (a) An overview of the Robovator, (b) a close-up of the portable knife blades, and (c) a diagram illustrating the size threshold and minimum protect safety parameters (i.e., the noncultivated area around the crop plant). In the circle is a burning nettle (*Urtica urens* L.) plant; the significant size difference between the weed and the crop allow the machine to differentiate between small weeds and the crop. (Color for this figure is available in the online version of this article.)

weeds on the basis of size parameters entered by the user. The minimum protect parameter (Figure 1c) sets the distance between the knife "opening" timing (knife movement out of the crop row) and the crop edges. For more details about the Robovator crop safety parameters, see Melander et al. (2015). Parameters were calibrated in each trial before cultivation using extra beds that were located alongside the main trial plots. The calibration beds were treated similarly to the experimental beds. After cultivation, the remaining weeds were removed by hand weeding, as is the common practice in local IWM programs (Fennimore et al. 2014).

Evaluations. Before cultivation, weed densities were measured over the entire bed width in a 6-m-long sample area located in the center of the plot. One week after cultivation, weed density was measured from the same 6-m sample area, this time over 10-cm-width strips on the center of the seed line. Crop stand was evaluated over the entire two bed by 15-m-long plot area. Crop plants that did not show vigor (e.g., wilting or any growth inhibition) were not counted. Weed density reduction (WDR) was evaluated by

$$\mathrm{WDR} = 100 - \left[(I_{\mathrm{post}}/I_{\mathrm{pre}}) \times 100\right] \qquad [1]$$

where I_{pre} and I_{post} are the number of weeds before and after cultivation, respectively. The time required for a laborer to remove weeds using a hand hoe from the entire plot area was also measured 1 wk after cultivation. Broccoli and lettuce were harvested at maturity from a 3-m-long sample area in the center of the plot. Marketable plants were harvested and counted, and fresh weight was determined.

Data Analysis. The statistical analysis was conducted using SAS (Statistical Analysis Systems, version 9.3, SAS Institute Inc., Cary, NC 27513). Three-way ANOVA (Tukey–Kramer honestly significant difference [HSD] test, $P = 0.05$) was conducted using PROC MIX to evaluate the interaction between herbicide (herbicide, no herbicide; fixed effect), cultivation method (Robovator, standard; fixed effect), and location (exps. 1 to 5; random effect). Because the interaction was significant ($P = 0.0226$) each experiment was analyzed separately. Two-way ANOVA was conducted using PROC GLM to determine the interaction between cultivator type and herbicide on WDR, crop stand, crop yield, and weeding labor time.

Results and Discussion

Crop Stand and Yield. The Robovator was evaluated in direct-seeded broccoli and transplanted lettuce. Crop injury was evaluated using two parameters: postcultivation crop stand and marketable yield. Table 2 shows that the Robovator did not reduce broccoli or lettuce stand or yield. The only exception to this was in exp. 4, where the stand was reduced by roughly 12%. An explanation for this is that some of the broccoli plants were small and not recognized as crop plants by the machine vision system. As a consequence, the knife blades did not open when traveling by these plants and they were cultivated out. Despite the stand reduction, yield was not significantly affected ($P = 0.358$). These results indicate that when crop size is uniform the Robovator can reliably and safely control intrarow weeds without injury to the crop.

Intrarow cultivators, like the finger weeder, require strong crop rooting and small weeds to be effective; therefore, these machines can only be used during a short window of time when the crop is strong enough to tolerate the cultivation but the weeds are small enough to be controlled (Cloutier et al. 2007). The Robovator is a more flexible tool because it can be used safely over a much wider range of time. Broccoli was cultivated at the early second leaf stage (exp. 2) and the late fourth leaf stage, just before canopy closure (exp. 3). Neither experiment showed any indication of crop injury from the Robovator, with no reductions in the broccoli stand and yield. The Robovator can uproot both small and medium-sized weeds, allowing it to work over a longer window of time for effective cultivation (Perez-Ruiz et al. 2012; Van der Weide et al. 2008). Like any other cultivator, the Robovator requires adjustment to soil, crop, and weed conditions at the time of cultivation. For example, the presence of clods or soil crusts might not allow close cultivation to the crop. In contrast, smaller weeds and a much larger crop may allow close cultivation (Melander et al. 2015).

Weed Control and Hand-Weeding Time. In all experiments weed growth stage was not uniform and ranged between the second and the eighth leaf stage; common purslane (*Portulaca oleracea* L.) plants reached the 12th leaf stage. Weed densities observed were high in exps. 1 and 4 (> 350 weeds m^{-2}), medium in exps. 2 and 5 (> 100 weeds m^{-2}), and low in exp. 3 (< 15 weeds m^{-2}) (Table 3). In three experiments with high and medium weed densities (exps. 1, 2, and 4), the Robovator was found to remove significantly more weeds than the standard cultivator (Table 3). Correspondingly, hand-weeding times were lower than the standard cultivator in these experiments, with $P < 0.0129$ for the cultivator main effect (Table 4). The greatest difference between the cultivation methods was observed in exp. 4. The Robovator removed 39% more weeds than the standard cultivator (Table 3), and hand-weeding times were 11 and 6 s m^{-1} for the standard cultivator and the Robovator, respectively (Table 4). We did not observe reduction in the Robovator control efficacy from specific weed

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Table 2. Crop stand and marketable yield (fresh weight) resulting from cultivation with standard and Robovator cultivators, with and without herbicides, in the different experiments (Exp.), which were conducted in direct-seeded broccoli (exps. 2, 3, and 4) and transplanted leaf lettuce (exps. 1 and 5).

Main effect	Crop stand[a]					Marketable yield[a,b]			
	Exp. 1	Exp. 2	Exp. 3	Exp. 4[d]	Exp. 5[d]	Exp. 1	Exp. 3	Exp. 4	Exp. 5
	$1000\ ha^{-1}$					$kg\ ha^{-1}$			
Cultivator									
Robovator	105 a	116 a	134 a	75 b	83 a	21,380 a	13,180 a	17,990 a	38,100 a
Standard	120 a	134 a	133 a	85 a	81 a	19,190 a	13,210 a	17,050 a	35,800 a
Herbicide									
With[c]	107 a	124 a	135 a	84 a	82 a	19,970 a	12,950 a	18,110 a	34,970 a
Without	119 a	125 a	133 a	77 a	82 a	20,590 a	13,430 a	16,910 a	38,930 a
ANOVA									
Cultivator (C)	0.299	0.156	0.846	0.025	0.398	0.412	0.977	0.358	0.522
Herbicide (H)	0.355	0.678	0.982	0.053	0.895	0.813	0.713	0.245	0.2776
C × H	0.308	0.982	0.683	0.301	0.557	0.471	0.908	0.166	0.7463

[a] Means with the same letter within columns are not significantly different according to Tukey–Kramer honestly significant difference (HSD) test $P = 0.05$.

[b] Yield was not harvested in exp. 2 because of pests that destroyed the plants.

[c] Herbicide for exps. 1 and 5 was pronamide at 1.3 kg ai ha^{-1}; herbicide for experiments 2, 3, and 4 was DCPA at 8.4 kg ai ha^{-1}.

[d] Low crop stand was observed because of large crop spacing (exp. 4) and soil-borne wilting disease (exp. 5).

species or growth stage, and most weeds that were not controlled were next to the crop canopy in the noncultivated areas (i.e., the minimum protect area) (Figure 1c). These results demonstrate the potential contribution of the Robovator toward improvement of vegetable IWM systems; the Robovator can increase weed removal capacities and reduce hand-weeding time and cost.

Table 3. The effect of integrated weed management (IWM) cultivator and herbicide components on weed density before (pre) and after (post) cultivation in five experiments (Exp.) conducted in direct-seeded broccoli (exps. 2, 3, and 4) and transplanted leaf lettuce (exps. 1 and 5). IWM included standard and Robovator cultivators, with and without herbicides.

Main effect	Weed density[a,b]									
	Exp. 1		Exp.2		Exp. 3		Exp. 4		Exp. 5	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	$No.\ m^{-2}$									
Cultivator										
Robovator	269 a	44 b	122 a	13 b	7 a	2 a	238 a	76 b	58 a	8 a
Standard	249 a	156 a	98 a	43 a	6 a	3 a	219 a	160 a	53 a	19 a
Herbicide										
With[c]	62 b	11 b	66 b	10 b	0.3 b	0.2 b	89 b	40 b	9 b	2 b
Without	457 a	195 a	153 a	46 a	12 a	5 a	358 a	207 a	103 a	24 a
ANOVA										
Cultivator (C)	0.7230	0.0013	0.2015	0.0007	0.6462	0.4097	0.3153	0.0095	0.8521	0.0871
Herbicide (H)	< 0.001	< 0.001	0.003	0.002	0.0008	0.0009	0.0041	0.0011	0.0008	0.0012
C × H	0.5532	0.1223	0.6710	0.0531	0.7097	0.4733	0.6430	0.1218	0.8968	0.0574

[a] Means with the same letter within columns are not significantly different according to Tukey–Kramer honestly significant difference (HSD) test $P = 0.05$.

[b] Main weeds by percentage were: 65% burning nettle and 30% common purslane in exp. 1; 62% common purslane, 24% shepherd's-purse, and 11% hairy nightshade in exp. 2; 95% annual sowthistle (*Sonchus oleraceus* L.) in exp. 3; 55% burning nettle and 35% common purslane in exp. 4; 47% common purslane, 22% hairy nightshade, 12% common groundsel, and 12% burning nettle in exp. 5.

[c] Herbicide for exps. 1 and 5 was pronamide at 1.3 kg ai ha^{-1}; herbicide for exps. 2, 3, and 4 was DCPA at 8.4 kg ai ha^{-1}.

Table 4. Effect of cultivator type and herbicide on hand-weeding time in five experiments (Exp.) in direct-seeded broccoli (exps. 2, 3, and 4) and transplanted lettuce (exps. 1 and 5).

	Hand-weeding time[a]				
Main effect	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
	$s\ m^{-1}$				
Cultivator					
Robovator	12 b	4 b	4 a	6 b	4 a
Standard	17 a	6 a	5 a	11 a	5 a
Herbicide					
With[b]	5 b	3 b	4 b	3 b	4 b
Without	24 a	7 a	5 a	14 a	7 a
ANOVA					
Cultivator (C)	0.0079	0.0004	0.549	0.0129	0.148
Herbicide (H)	< 0.0001	< 0.0001	0.0013	< 0.0001	0.0004
C × H	0.1023	0.5857	0.3947	0.2129	0.1305

[a] Means with the same letter within columns are not significantly different according to Tukey–Kramer honestly significant difference (HSD) test $P = 0.05$.

[b] Herbicide for exps. 1 and 5 was pronamide at 1.3 kg ai ha^{-1}; herbicide for exps. 2, 3, and 4 was DCPA at 8.4 kg ai ha^{-1}.

In exp. 3, weed infestation was significantly lower than in the other experiments. Consequently, the Robovator did not reduce weed density and hand-weeding time compared with standard cultivation. Cultivation method main effect P values in exp. 3 were 0.409 and 0.549 for postcultivation weed density and hand-weeding time, respectively (Tables 3 and 4). Although exps. 5 and 2 had similar weed density in the no-herbicide treatments, lower weed densities in the herbicide-treated plots indicate that better weed control resulted from pronamide compared with DCPA, at 9 and 66 weeds m^{-2}, respectively (Table 3). DCPA did not adequately control 35% of the weeds in exp. 2 (shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] and hairy nightshade [*Solanum physalifolium* Rusby]) (Anonymous 2015a), whereas pronamide did not control 12% of the weeds (common groundsel [*Senecio vulgaris* L.]) (Anonymous 2015b). The contribution of selective herbicides for IWM is affected by the weed community in a specific area. Because pronamide effectively controlled the weeds in exp. 5, there was no advantage to the Robovator over the standard cultivator to reduce hand-weeding time. In an IWM program, the farmer can decide when and where to use the Robovator for vegetables**.** Where the herbicide is effective, less cultivation will be needed, but where weeds are missed, the Robovator provides a means for cost-effective weed control.

Arizona and California vegetable production integrates several tactics to control weeds, which include crop rotation, herbicides, cultivation, hand weeding, and use of stale seedbeds (Fennimore et al. 2014; Shem-Tov et al. 2006). The Robovator was evaluated as part of an IWM program, and the experimental design aimed to isolate the effect of each component in the system. Our objective was to evaluate the value of each component, and the results show that under moderate and high weed densities, each part of the system contributed toward commercially acceptable weed control levels, > 95%. The results also show that under these conditions the Robovator removed more weeds than the standard cultivator and therefore increased the effectiveness of the overall system. Integrating the Robovator into an ongoing IWM system can reduce hand-weeding times and, consequently, the high dependency of growers on human labor.

It can be assumed that weed removal capacity and hand-weeding time reduction of vegetable IWM systems that will use the new ICs can be further improved by better weed detection systems, more precise planting, and multiple IC passes per crop. We performed only a single cultivation per crop, whereas broccoli and lettuce growth cycles range from 60 to 90 days and can experience more than one weed emergence flush. The Robovator can be used multiple times per growth cycle; therefore, reduction in weeding time may be higher than reported here. This study was conducted on narrow beds with two crop rows per bed. Weeding wide beds, with five to six crop rows per bed, is more

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time consuming on a per hectare basis because the center rows are difficult to reach. The Robovator can be adjusted and used on different row numbers, widths, and seed line spacing. On the other hand, we observed that the performance of the Robovator at high weed densities, delayed application timings, or both was less than where there was good separation between the crop and weed plants. Under conditions where the crop and weed canopies overlapped, the detection algorithm could not differentiate weeds from the crop, and crop damage or poor weed control resulted. Most escaped weeds were located next to the crop plants. Operating the cultivator at an earlier stage of crop growth might have improved the results.

Integration of the new robotic intrarow cultivators into vegetable IWM systems can reduce growers' dependency on human labor and reduce the risks for unpredicted and costly hand-weeding expenses. Moreover, the Robovator can reduce the high dependency of vegetable growers on herbicides that might be subjected to regulatory actions, such as the loss of pronamide registration from 2009 to 2016 for leaf lettuce (Brett B, Dow AgroSciences, personal communication; Fennimore and Doohan 2008; Mou 2011).

The Robovator, did not by itself control all weeds for broccoli and lettuce and still needs to be used as a component within an IWM system in combination with hand weeding, herbicides, and effective cultural practices. However, results from this study, and others, demonstrate several advantages to this machine over standard cultivators and other intrarow weeding options: better weed removal capacity under moderate and high weed pressures, higher operation speed, wider operation time window, and need for only a single operator (Fennimore et al. 2014; Melander et al. 2015; Perez-Ruiz et al. 2014). Furthermore, ICs are compatible with other technological advances in the vegetable production system, such as automated thinners and transplanters (Fennimore et al. 2013; Smith 2015); all are aimed to reduce dependency on human labor and improve production efficiency. It is logical to think that the Robovator and other IC cultivator technology will continue to improve, and gains in efficacy and productivity will be made. As a result, increased labor savings and cost reductions would be realized, and the potential for economical use in commercial farm operations expanded (Fennimore et al. 2010, 2014).

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