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Weed Management—Techniques

Evaluation and Economics of a Machine-Vision Guided Cultivation Program in Broccoli and Lettuce

Steven A. Fennimore, Laura Tourte, John S. Rachuy, Richard F. Smith, and Christina George*

Machine-vision cultivator guidance systems are commercially available to growers, but little work has been done to determine if these guidance systems can improve integrated weed management systems in vegetable crops. Studies were conducted in 2005 and 2006 in broccoli and lettuce to evaluate band-applied DCPA or pronamide, respectively, and four noncultivated bands ranging from 5.1 to 12.7 cm. DCPA or pronamide were applied in bands centered on the seed line at 0, 7.6 or 12.7 cm wide. A commercial machine-vision system was used to guide a commercial cultivator. Generally, weed densities and hand-weeding times were less where the DCPA band in broccoli or the pronamide band in lettuce were 7.6 or 12.7 cm wide compared to no herbicide. Weed densities were lowest in both crops where the noncultivated band width was 5.1 cm compared to 12.7-cm noncultivated bands. For broccoli in both 2005 and 2006, net returns above production costs were generally higher in the 7.6- and 12.7-cm-wide DCPA bands compared with the no-herbicide band. In lettuce in both years, the no-pronamide treatment had higher net returns, when compared with the 7.6- and 12.7-cm pronamide bands. Lettuce yields and higher net returns in the no-pronamide treatment compared to the 7.6- and 12.7-cm pronamide bands may be due to slight yield reduction from pronamide. Results suggest that pronamide was not needed during the dry months of the year when weed management tools such as hand-weeding and cultivation work very well. However, in periods of rainy weather when cultivation and hand-weeding are not possible, then pronamide would likely provide the greatest economic benefit. Given the large impact of cultivation on vegetable weed management programs, the greatest potential benefit of machine-vision guided cultivators is if they facilitate more timely and effective cultivation.

Nomenclature: DCPA; pronamide; broccoli, *Brassica oleracea* L. var. *botrytus* L. 'Marathon'; lettuce, *Lactuca sativa* L. 'Sniper', 'PIC 714', and 'Darkland'.

Key words: machine-vision guidance, weed control, cultivation, head lettuce, broccoli, economics.

En el mercado para agricultores, varios sistemas automatizados de guía mecánica para el cultivo están disponibles, pero muy poca investigación ha sido llevada a cabo para determinar si estas guías pueden mejorar los sistemas de manejo integrado de maleza en los cultivos de vegetales. En 2005 y 2006 se llevaron a cabo estudios enfocados en brócoli y lechuga para evaluar DCPA aplicado en banda o el uso de pronamide, respectivamente. Como testigo, se incluyeron cuatro bandas no cultivadas de 5.1 a 12.7 cm. El DCPA o el pronamide se aplicaron en bandas en el lomo de los surcos en rangos de 0, 7.6 o 12.7 cm de ancho. Un sistema automatizado (Machine-Vision) fue utilizado para guiar el cultivador comercial. Generalmente, las densidades de maleza y el tiempo utilizado para el deshierbe manual fueron menores en donde la aplicación del DCPA en la línea de brócoli o el pronamide en la lechuga fue mediante bandas de 7.6 o 12.7 cm de ancho comparado con el testigo donde no se aplicó herbicida. Las densidades de maleza fueron menores en ambos cultivos donde el ancho de la banda no cultivada fue de 5.1 cm comparada con 12.7 cm de las bandas no cultivadas. Para el brócoli, tanto en 2005 como en 2006, las utilidades sobre los costos de producción fueron generalmente más altas en las bandas DCPA de 7.6 y 12.7 cm de ancho, comparadas con los testigos sin herbicida. Con respecto a la lechuga, en ambos años, el tratamiento sin pronamide tuvo mayores utilidades, cuando se comparó con las bandas de 7.6 y 12.7 cm con pronamide. Los rendimientos y las mayores utilidades de la lechuga en los tratamientos sin pronamide comparados con la aplicación de pronamide en bandas de 7.6 y 12.7 cm podrían deberse a una leve reducción en el volumen de la cosecha a partir del uso de pronamide. Los resultados sugieren que el uso de pronamide no fue necesario durante los meses secos del año cuando otros recursos para el manejo de maleza como el deshierbe manual y el barbecho funcionan muy bien. Sin embargo, en la temporada de lluvias cuando el barbecho y el deshierbe manual no son posibles, el uso del pronamide podría proporcionar el mayor beneficio económico. Tomando en cuenta el gran impacto que tienen los programas de manejo de maleza en el cultivo de vegetales, el mayor beneficio potencial de los cultivadores automatizados es que facilitan un manejo del cultivo oportuno y efectivo.

Weed control continues to be a significant portion of the overall cost of vegetable crop production. The availability of labor for weed control is decreasing, whereas the cost of labor, herbicides, fuel, and tractor maintenance expenses are increasing, often resulting in reduced net returns to growers. Broccoli and lettuce are sensitive to weed competition, but these crops have few herbicides and fumigants registered (Bell 1995; Roberts et al. 1977). Of those few herbicides and fumigants available, most provide only partial weed control (Haar and Fennimore 2003). DCPA and pronamide are typical vegetable herbicides. They were registered before 1975, some are potential groundwater contaminants (Bruggeman et al. 1995, MDCH

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* Extension Weed Specialist, University of California, Davis, Salinas, CA 93905; County Director/Farm Advisor, University of California, Santa Cruz County, Watsonville, CA 95076; Staff Research Associate, University of California, Davis, Salinas, CA 93905; Farm Advisor, University of California, Monterey County, Salinas, CA 93901, Former Graduate Research Assistant, University of California, Davis, CA 95616. Corresponding author's E-mail: safennimore@ucdavis.edu

2003), and they control only a fraction of the weeds infesting vegetable plantings (Shem-Tov et al. 2006). There are few new vegetable herbicides in development, as there is little incentive for industry to develop new ones, because of small hectarage and high potential liability for manufacturers (Gast 2008). Thus control of weeds in fresh market vegetable crops produced year-round requires an integrated use of cultivation, hand-weeding, and herbicides with an emphasis on the most cost-effective combination of these weed control tools. Potential labor shortages may impact the costs and supply of workers available for hand-weeding (Martin 2007); therefore, it is necessary to periodically revisit the mix of weed management tools available for vegetable growers as relative net returns above weed control input costs change periodically.

Uncontrolled weeds in vegetables results in lower yields, reduced quality, and decreased harvest efficiency, particularly in hand-harvested crops such as broccoli and lettuce. Broccoli is very susceptible to weed competition. Bell (1995) found that 4.9 ryegrass plants/m of broccoli row resulted in 3.6% yield loss, and 600 to 1,000 plants/m resulted in complete yield loss. Weed cover of 25% resulted in 20 to 40% yield loss in California lettuce, and greater than 25% weed cover resulted in complete yield loss (Lanini and LeStrange 1991). Previous studies have shown that, compared to no herbicide, pronamide reduced weed management expense in lettuce by $543 to $578/ha and bensulide reduced weeding expense by $206 to $333/ha (Haar and Fennimore 2003). However, pronamide can cause injury and yield loss in lettuce (Tickes and Kerns 1996). Therefore, pronamide use in lettuce is a tradeoff between use of a soil-active herbicide to prevent severe weed infestations and potential for crop injury.

Machine-guided cultivation has the potential to greatly increase the precision and speed of cultivation. Machine guidance controls the fine movements of the cultivator, thus allowing for more rapid and accurate operation. A typical machine, such as the Eco-Dan® cultivator guidance system, uses a digital camera that takes 25 pictures/s of the crop row, and in turn, these pictures are processed by a computer to establish the row centerline. As the row centerline shifts, the computer signals a control valve to shift a hydraulic cylinder right or left to keep the cultivator centered over the row. Machine-vision guidance systems differentiate between the crop row and random weed patterns, and their performance has been compared to human-guided cultivators (Slaughter et al. 1999). Error rates were higher in human-guided cultivation compared to machine-vision guidance systems.

In California's lettuce production regions, pronamide is typically applied as a 12.7-cm-wide band centered over each seed line, which in a 1-m-wide bed with two rows results in an herbicide cost of $118/ha (Haar and Fennimore 2003; Tourte and Smith 2001). Costs for a similar DCPA use pattern in broccoli were $111/ha. Labor costs for hand-weeding of $232 and $261/ha in broccoli and lettuce, respectively, and cultivation costs of $40 and $67/ha result in total weed control costs of $383 and $446/ha for broccoli and lettuce, respectively (Smith et al. 2004; Tourte and Smith 2001). If machine-vision guided cultivators would allow closer cultivation leaving fewer weeds, herbicide bands could be narrowed, resulting in reduced herbicide and hand-weeding costs. The objective of this research was to determine the herbicide band width and noncultivated band width that had the best weed control and highest net returns in broccoli and lettuce using a machine-vision guided cultivator.

Materials and Methods

Field Station Evaluations. All experiments were conducted at the U.S. Department of Agriculture Spence Research Station near Salinas, CA. The soil was classified as Chualar loam (fine-loamy, mixed, thermic Typic Argixeroll), 79% sand, 14% silt, and 7% clay (Cook 1978) with a pH of 7.2 and organic matter content of 1%. The experiments were established using a split-plot design arranged in a randomized complete block. The main plot was herbicide band width and the subplot was noncultivated band width. Plots consisted of two 1-m-wide raised beds with two seed lines per bed by 12.2 m long. Seed lines were 30 cm apart. Each treatment was replicated four times. The broccoli variety was 'Marathon' and the lettuce variety was an iceberg (head) type 'Sniper'. Both crops were direct-seeded using a tractor-mounted Stanhay®[1] planter. Critical dates, such as those of planting, cultivation, thinning, hand-weeding, and harvest for the four experiments are listed in Table 1. The herbicide used in broccoli was DCPA[2] applied PRE at 8.4 kg/ha; in lettuce pronamide[3] was applied PRE at 1.35 kg/ha. Both herbicides were applied on 7.6- or 12.7-cm-wide bands at 1,169 L/ha at a pressure of 206.8 kPa using a boom mounted behind the planter with 4002E-SS[4] nozzles centered over each seed line to ensure correct placement. High application volumes were used in the simultaneous planting and spray operation because of the need for slow speed in the seeding operation. Nontreated controls were included in all trials. Sprinkler irrigation was applied the day after seeding and herbicide application, and plots were irrigated twice weekly for the remainder of the season.

About 3 to 4 wk after planting, cultivation was performed using the Eco-Dan®[5] machine-vision guidance system to control a commercial cultivator tool bar equipped with cultivator knives (Table 1). The cultivator shanks on the tool bar were adjusted to leave a 5.1-, 7.6-, 10.2-, or 12.7-cm-wide noncultivated band centered over the seed line.

Weed densities were measured on the bed top for the full length of the plot between the two seed lines (3.7 m^2) before and after cultivation. Pre- and postcultivation weed densities were measured for all trials except the 2005 broccoli trial where only postcultivation weed densities were measured just after cultivation. Time for a laborer to thin the crop to the desired stand and remove weeds was measured with a stopwatch. About 2 to 3 wk after thinning, the plots were hand-weeded and the laborer was again timed as was previously done during thinning. Thinning for the 2005 lettuce trial was timed but hand-weeding was not timed. Broccoli and lettuce heads were harvested at maturity (Table 1). At each broccoli harvest date, individual counts and weights for both unmarketable and marketable heads were measured. For head lettuce, mature heads were harvested and sized, and head counts and weights recorded. Yields are presented in cartons per hectare, as is typical for fresh vegetable crops (Lauritzen 2005, 2006).

Commercial Evaluations. On-farm trials were conducted with cooperating growers in 2005 and 2006, and all treatments were

Table 1. Crop and planting, cultivation, crop-thinning, hand-weeding, and harvest dates for broccoli and lettuce cultivator evaluations at Salinas, CA.

Crop	Planting date	Cultivation	Thinning date	Hand-weeding date	Harvest dates	Herbicide
Field station evaluations						
Broccoli	September 15, 2005	October 12, 2005	October 13, 2005	October 26, 2005	January 6, 13, and 20, 2006	DCPA
Broccoli	August 3, 2006	August 25, 2006	August 25, 2006	September 20, 2006	October 26 and November 1, 2006	DCPA
Lettuce	June 30, 2005	July 26, 2005	July 27, 2005	—	September 6, 2005	Pronamide
Lettuce	August 3, 2006	August 28, 2006	August 29, 2006	September 20, 2006	October 13 and 18, 2006	Pronamide
Commercial evaluations						
Broccoli	July 25, 2005	August 24, 2005	—	August 24, 2005	November 4, 2005	DCPA
Broccoli	June 20, 2006	July 24, 2006	—	July 27, 2006	October 9 and 13, 2006	DCPA
Lettuce	July 2, 2005	July 28, 2005	July 28, 2005	—	September 14, 2005	Pronamide
Lettuce	July 15, 2006	August 12, 2006	August 14, 2006	—	September 19, 2006	Pronamide

applied using the grower's cultivator guided by the machine-vision guidance system (Table 1). The broccoli trials were conducted on 2-m-wide beds with four seed lines per raised bed. The trials were planted with the broccoli variety 'Marathon' and treated with DCPA at 8.4 kg/ha applied to a 15.2-cm-wide band over each seed line. Seed lines were 30 cm apart as for lettuce. Treatments were applied by adjusting the noncultivated band width to 7.6, 10.2, or 12.7 cm in 2005 and 5.1 or 10.2 cm in 2006; wider noncultivated bands were used in 2005 because of cloddy soil conditions. Each noncultivated band width was applied to one bed by the 300- to 400-m length of the field and was replicated three times. Weed densities were measured in a 15.2- by 2.0-m section of each plot before and after cultivation; hand-weeding times were measured in a 15.2- by 2.0-m sample area in each plot. Crop stand counts were measured in 15.2- and 30.5-m-long sample areas in 2005 and 2006, respectively. Commercial crews harvested the trials. The lettuce trials were conducted on 2.0-m-wide beds with five seed lines. Both lettuce trials utilized romaine lettuce varieties: 'PIC 714' in 2005 and 'Darkland' in 2006. Pronamide was applied at 1.35 kg ai/ha in a 15.2-cm-wide band centered over each seed line at planting. Treatments were applied by adjusting the noncultivated band width to 5.1 and 10.2 cm on the cooperating grower's equipment. Each cultivation treatment was applied to one bed by the length of the field and was replicated three times. Weed densities were measured in 15.2- by 2.0-m sample areas within each plot before and after cultivation; weeding time evaluations were made by recording the time to weed a 30.5- by 2.0-m sample area in each plot. Lettuce stand was measured in a 30.5-m-long sample area in each plot and the plots were harvested by commercial crews. Commercial harvests were not subjected to statistical analysis because the crew was not able to keep the replicates separate and therefore the data are not presented.

Data Analysis. All weed and crop assessment data were subjected to factorial ANOVA, and mean separation was performed using LSD ($P = 0.05$). ANOVA was conducted to determine the main effects of herbicide band width and noncultivated band width on weed densities, weeding labor and yield. Two-way ANOVA tests were used to compare the effect of herbicide band widths (0, 7.6, and 12.7 cm) and noncultivated band widths (5.1, 7.6, 10.2, and 12.7 cm) using PROC GLM in SAS®.[6] Analysis of covariance was performed using PROC GLM to test the effects of herbicide band width and noncultivation band width and the interaction on postcultivation weed densities. The precultivation weed densities were used as a covariate to analyze the postcultivation weed densities, except 2005 broccoli where only postcultivation weed densities were available. An economic analysis was performed for the trials using Budget Planner software.[7] The data were collected and reported as per hectare, and the cost of equipment use (machine labor, fuel, lubrication, repairs), herbicides, hand-thinning and weeding labor, and interest on operating capitol were entered into Budget Planner for analysis. Budget Planner generated production cost (partial budget) tables for each treatment combination. Partial budgets were calculated using the following: material costs: \$4.00/100 g DCPA and \$7.97/100 g pronamide; labor rates: \$13.97/h machine and \$11.81/h field; fuel costs: diesel \$0.66/L in 2005 and \$0.53/L in 2006; lubrication and repairs: by implement or machine and based on formulas from the American Society of Agricultural Engineers (Hahn and Rosentreter 1994). Net returns were then calculated by subtracting production costs from gross returns (experimental yield in cartons per hectare by price per carton; Lauritzen 2005, 2006).

Results and Discussion

Field Station Evaluations. The main effect of herbicide band width on weed densities was significant for all broccoli and lettuce experiments (Table 2). In broccoli and lettuce the weed density in the 7.6-cm-wide herbicide band was not different than in the 12.7-cm-wide herbicide band. Thinning and weeding times in the 7.6- and 12.7-cm-wide herbicide bands incurred similar hours in both broccoli trials and the 2005 lettuce trial. In the 2006 lettuce trial, thinning and weeding times were lower in the 12.7-cm herbicide band than in the 7.6-cm band. This suggests that it is possible to reduce the herbicide band width in broccoli yet maintain weed control without higher hand-weeding times. The results in lettuce were mixed with regard to the effects of reducing the herbicide band from 12.7 to 7.6 cm as weeding times were the same in 2005, but the 12.7-cm band width had lower thinning and weeding times in 2006 than the 7.6-cm band (Table 2). The main effect of noncultivated band width on final weed densities was significant in all experiments (Table 2). Final weed densities were lower in the 5.1-cm noncultivated band width than in the 12.7-cm noncultivated band in all experiments, and the 7.6- and 10.2-cm bands had final weed densities that were intermediate between the two extremes. The effect of noncultivated band width on thinning and weeding time was significant in the 2005 broccoli

Table 2. Effect of DCPA and pronamide band width and noncultivated band spacing on final weed densities after cultivation, but prior to thinning. Thinning and hand-weeding time is the time for a laborer to hand-thin and hand-weed the broccoli and lettuce.

	Broccoli		Lettuce		Broccoli		Lettuce	
	2005	2006	2005	2006	2005	2006	2005[a]	2006
	Density (no./m^2)				Thinning and weeding time (h/ha)			
Herbicide band width (cm)[b]								
0	20.3 a[c]	10.8 a	0.7 a	13.0 a	77.0 a	69.2 a	19.1 a	56.4 a
7.6	5.5 b	5.4 b	0.5 ab	5.8 b	48.6 b	46.4 b	17.2 b	50.5 b
12.7	3.5 b	6.2 b	0.4 b	6.1 b	47.6 b	47.7 b	17.8 b	45.4 c
Noncultivated band width (cm)								
5.1	5.2 b	6.1 b	0.4 b	4.3 c	51.7 c	51.4	18.2	47.6 b
7.6	6.5 b	4.5 b	0.4 b	7.7 b	56.2 bc	54.5	18.4	49.8 ab
10.2	9.7 b	8.1 ab	0.7 a	8.7 b	58.1 b	52.9	17.6	51.1 ab
12.7	17.6 a	11.0 a	0.7 a	12.5 a	64.9 a	59.0	18.0	54.6 a
	Analysis of covariance P values				ANOVA P values			
Herbicide band	< 0.0001	0.0037	0.0068	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Noncultivated band	< 0.0001	0.0040	0.0035	< 0.0001	0.0007	0.1155	0.3684	0.0431
Herbicide band × noncultivated band	0.0286	0.7290	0.2834	0.0093	0.5461	0.8995	0.6240	0.3502

[a] Thinning times only.

[b] DCPA was applied at 8.4 kg/ha in broccoli, and pronamide was applied at 1.35 kg/ha in lettuce.

[c] Means with the same letter within columns for a herbicide or noncultivated treatment are not significantly different according to Fisher's Protected LSD test (P = 0.05).

experiment where the 5.1-, 7.6-, and 10.2-cm noncultivated bands had lower times than the 12.7-cm noncultivated band and the 2006 lettuce trial that had lower times in the 5.1-cm than the 12.7-cm noncultivated band (Table 2). The herbicide band width by noncultivated band width interaction term was significant for weed densities in broccoli in 2005 and lettuce in 2006; however, those data were not critical to this paper and are not shown.

Commercial Evaluations. The on-farm trials were conducted to test the cultivation guidance system under commercial conditions of variable soil conditions and weed pressure. Weed densities in 2006 broccoli and 2005 lettuce were lower in the 5.1-cm noncultivated bands than in the 10.2-cm bands (Table 3). In broccoli in 2005 the 7.6- and 10.1-cm noncultivated bands had weed densities lower than the 12.7-cm noncultivated band. For broccoli and lettuce, weeding times were lower in the narrow noncultivated bands than in the wider noncultivated bands (Table 3). In 2006 broccoli and lettuce there were fewer plants per hectare in the 5.1-cm cultivation treatment, but commercial harvests do not indicate a reduction in yield (data not shown).

Table 3. Weed control, hand-weeding time, and broccoli and lettuce stands in a commercial evaluation.

Noncultivated band width	Weed densities		Hand-weeding time		Crop stand	
	2005	2006	2005	2006	2005	2006
Cm	no./m^2		h/ha		1,000/ha	
Broccoli						
5.1	—	3.4 b[a]	—	8.9 a	—	159.7 a
7.6	18.9 b	—	19.2 a	—	125.5 a	—
10.2	21.8 b	5.5 a	20.8 a	10.1 b	125.7 a	165.9 b
12.7	33.8 a	—	29.6 b	—	122.5 a	—
Lettuce						
5.1	13.2 b	1.0 b	54.9 a	10.3 a	95.4 a	81.2 a
10.2	31.4 a	1.8 a	47.9 b	13.5 b	94.6 a	87.3 b

[a] Means with the same letter within columns are not significantly different according to Fisher's Protected LSD test (P = 0.05).

These data indicate that a machine-vision guidance system, such as the EcoDan® can accurately guide the cultivator closer to the crop row and achieve a reduction in weeds. The ability to cultivate closely depends on soil conditions; cloddy soil reduces the option to cultivate at narrower cultivation widths.

Economic Analysis. Broccoli yields in 2006 were highest in the 12.7-cm DCPA band compared to the no-DCPA treatment, but in 2005 there was no significant difference in yield (Table 4). In field evaluations for broccoli in 2005 and 2006 net returns above production cash costs were highest in the DCPA band widths of 7.6 and 12.7 cm (Table 4). Likely the lower hand-weeding times and higher broccoli yields in the 12.7-cm DCPA bands led to the highest net returns (Tables 2 and 4). The effect of noncultivated band width did not correlate with the highest net returns for broccoli (data not shown). The effect of pronamide band width on lettuce carton yield, a fresh weight measurement, was not significant in 2005 or 2006 and the highest net returns were found in the no-pronamide treatment (Table 5). Hand-weeding times were lower where pronamide was applied in a 7.6- or 12.7-cm band, but this lower cost of production with pronamide did not compensate for reduced lettuce yield on the net returns for lettuce (Tables 2 and 5). Sometimes lettuce yields are reduced by pronamide and this may be the reason for the higher net returns in the no-pronamide treatment (Tickes and Kern 1996). The lettuce weed management system is an integrated system with multiple components including cultivation and hand-weeding, so weeds not removed by pronamide are removed by cultivation and hand-weeding. In an evaluation of the effect of preplant irrigation on lettuce weed management,

Table 4. Net returns for broccoli main effects using DCPA or cultivator band width in 2005 and 2006.

	Broccoli 2005				Broccoli 2006			
	Yield[a]	Gross returns[b]	Production costs[c]	Net returns[d]	Yield	Gross returns	Production costs	Net returns
	crtns/ha	$/ha			crtns/ha	$/ha		
Herbicide band width (cm)[c]								
0	1,102	7,274	817	6,457	782 b[e]	5,195	1,511	3,684
7.6	1,114	7,352	593	6,759	860 ab	5,711	1,153	4,558
12.7	1,132	7,470	672	6,798	890 a	5,910	1,230	4,681
ANOVA P values								
Herbicide band	0.8936				0.0357			
Noncultivated band	0.2434				0.1081			
Herbicide band × noncultivated band	0.8997				0.5018			

[a] Yield is in 10.0-kg cartons.

[b] Gross returns = experimental yield in cartons per hectare × $6.60 (2005 price per carton for Monterey County, CA) or × $6.64 (2006 price per carton).

[c] Production costs include equipment, fuel, lubrication, repairs, herbicides, labor and interest on operating capital; they are rounded to the nearest dollar.

[d] Net returns above production costs (gross returns − production costs).

[e] Means with the same letter within this column are not significantly different according to Fisher's Protected LSD (P = 0.05).

researchers found that the contribution of pronamide to the lettuce integrated weed management scheme was important, but no more important than other cultural weed management practices such as use of a stale seed bed (Shem-Tov et al. 2006). Although narrow noncultivated bands had fewer weeds and lower weeding times in lettuce, noncultivated band width did not significantly affect net returns for lettuce (data not shown). The critical time of weed removal in lettuce is about 3 to 4 wk after planting (Fennimore and Umeda 2003; Roberts et al. 1977). Because weeds were removed by cultivation and hand-weeding by about 4 wk after seeding, weed competition likely did not reduce lettuce yields. Lettuce is planted throughout the entire year in Arizona and California, and as a result is subjected to moderate seasonal variations in weather (Ryder 1999). These trials were conducted during the spring and summer months in periods of little rain and unrestricted field access for cultivation and hand-weeding allowed for timely weed removal. In contrast, pronamide use is likely more critical to net returns for lettuce grown in rainy winter months during which time access to the field for timely cultivation and hand-weeding can be limited by wet soil conditions. Pronamide provides a consistent weed control tool for lettuce that prevents catastrophic yield loss when other weed control tools such as cultivation and hand-weeding are not available.

Management Implications. There was no evidence that reducing DCPA band width increased net returns in broccoli. However, net returns in broccoli were higher where DCPA was used compared to no DCPA. Pronamide applied in lettuce in 7.6- and 12.7-cm bands improved weed control and reduced hand-weeding times. However, pronamide use did not improve net returns in lettuce. This was likely due to efficient removal of weeds by hand-weeding and cultivation prior to the critical period of weed removal so no yield loss occurred. However, pronamide is the base treatment for a

Table. 5. Net returns for lettuce main effects using pronamide or cultivator band width in 2005 and 2006.

	Lettuce 2005				Lettuce 2006			
	Yield[a]	Gross returns[b]	Production costs[c]	Net returns[d]	Yield	Gross returns	Production costs	Net returns
	crtns/ha	$/ha			crtns/ha	$/ha		
Herbicide band width (cm)[c]								
0	1,383	10,305	114[e]	10,191	2,079	19,296	1,160	18,135
7.6	1,242	9,251	173	9,078	1,806	16,761	1,267	15,495
12.7	1,136	8,461	215	8,246	1,987	18,437	1,151	17,287
ANOVA P values								
Herbicide band	0.1614				0.1650			
Noncultivated band	0.5925				0.3977			
Herbicide band × noncultivated band	0.2787				0.9242			

[a] Yield is in 22.7-kg cartons.

[b] Gross returns = experimental yield in cartons per hectare × $7.45 (2005 price per carton for Monterey Co. CA) or × $9.28 (2006 price per carton).

[c] Production costs include equipment, fuel, lubrication, repairs, herbicides, labor and interest on operating capital; they are rounded to the nearest dollar.

[d] Net returns above production costs (gross returns − production costs).

[e] Production costs in 2005 were labor for thinning lettuce only.

reliable and consistent weed control program for lettuce. When cultivation and hand-weeding are not possible in wet weather, pronamide is the primary weed control option. Net returns due to pronamide would have likely been more favorable during wet weather when cultivation and hand-weeding would be ineffective or impossible. Narrow noncultivated bands control weeds better than wide noncultivated bands in either crop, but this difference did not influence net returns, likely due to timely weed removal by hand-weeding so yield was probably not lost due to weed competition. Close cultivation with machine-vision cultivation may allow for reduced herbicide input in broccoli and this may help maintain low costs should DCPA costs increase disproportionately. Conditions that allow for efficient weed removal with cultivation and hand-weeding in lettuce may allow for complete elimination of pronamide from the herbicide program. The machine-vision cultivator tested here could be best described as a machine-assisted interrow cultivator. Interrow cultivation leaves a noncultivated band over the seed line where weeds must be removed by herbicides and hand-weeding. An intrarow cultivator that cultivates in the row leaving few or no weeds has the potential to eliminate the need for hand-weeding (O'Dogherty et al. 2007). But the economic impact of that technology remains unknown.

Sources of Materials

[1] Stanhay® Webb Ltd., Grantham, Lincolshire, United Kingdom NG31 6JE.

[2] Dacthal® 75W, Amvac Chemical Corporation, Los Angeles, CA 90023.

[3] Kerb® 50W, Dow AgroSciences LLC, Indianapolis, IN 46268.

[4] 4002E-SS TeeJet® Nozzle, Spraying Systems Co. Wheaton, IL 60189.

[5] Eco-Dan® guidance system, ECO-DAN A/S, Bøgeskovvej 6, DK-3490 Kvistgaard Denmark.

[6] SAS® system for Windows, Version 9.1, SAS Institute Inc. SAS Campus Drive, Cary, NC 27513.

[7] Budget Planner, Version 2.0, Karen Klonsky, Department of Agricultural and Resource Economics, University of California, Davis, CA 95616.

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Literature Cited

Bell, C. E. 1995. Broccoli (*Brassica oleracea* var. *botrytis*) yield loss from Italian ryegrass (*Lolium perenne*) interference. Weed Sci. 43:117–120.

Bruggeman, A. C., S. Mostaghimi, G. I. Holtzman, V. O. Shanholtz, S. Shukla, and B. B. Ross. 1995. Monitoring pesticides and nitrate in Virginia's groundwater—a pilot study. Trans. ASAE (Am. Soc. Agric. Eng.) 38:797–807.

Cook, T. D. 1978. Soil Survey of Monterey County, California. Washington, DC: U.S. Department of Agriculture U.S. Forest Service and University of California Agricultural Experiment Station. 235 p.

Fennimore, S. A. and K. Umeda. 2003. Time of glyphosate application in glyphosate-tolerant lettuce. Weed Technol. 17:738–746.

Gast, R. 2008. Industry view of minor crop weed control. Weed Technol. 22:385–388.

Haar, M. J. and S. A. Fennimore. 2003. Evaluation of integrated practices for common purslane management in lettuce. Weed Technol. 17:229–233.

Hahn, R. H. and E. E. Rosentreter, eds. 1994. American Society of Agricultural Engineers Standards Yearbook. 41st ed. St. Joseph, MO: American Society of Agricultural Engineers. 246 p.

Lanini, W. T. and M. LeStrange. 1991. Low-input management of weeds in vegetable fields. Calif. Agric. 45(1):11–13.

Lauritzen, E. 2005. Monterey County, Crop Report 2005. Salinas, CA: Monterey County Agricultural Commisioner. 19 p.

Lauritzen, E. 2006. Monterey County, Crop Report 2006. Salinas, CA: Monterey County Agricultural Commisioner. 20 p.

Martin, P. 2007. Farm Labor Shortages: How Real, What Responses? ARE Update. University of California, Davis. http://www.agecon.ucdavis.edu/extension/update/articles/v10n5_3.pdf. Accessed: February 18, 2009.

[MDCH] Michigan Department of Community Health. 2003. Health Consultation. Dacthal® Groundwater Contamination Additional Toxicological Data Coloma Township, Berrien County, Michigan. http://www.michigan.gov/documents/DacthalDiAcidHealthConsult_71729_7.pdf. Accessed: February 18, 2009.

O'Dogherty, M. J., R. J. Godwin, A. P. Dedousis, L. J. Brighton, and N. D. Tillett. 2007. A mathematical model of the kinematics of a rotating disc for inter- and intra-row hoeing. Biosyst. Eng. 96:169–179.

Roberts, H. A., R. T. Hewson, and M. A. Ricketts. 1977. Weed competition in drilled summer lettuce. Hortic. Res. 17:39–45.

Ryder, E. J. 1999. Crop Production Science in Horticulture 9: Lettuce, Endive, and Chicory. Wallingford, UK: CABI. Pp. 79–89.

Shem-Tov, S., S. A. Fennimore, and W. T. Lanini. 2006. Weed management in lettuce (*Lactuca sativa*) with pre-plant irrigation. Weed Technol. 20: 1058–1065.

Slaughter, D. C., P. Chen, and R. G. Curley. 1999. Vision guided precision cultivation. Precision Agric. 1:199–216.

Smith, R. F., W. E. Chaney, K. M. Klonsky, and R. L. DeMoura. 2004. Sample Costs to Produce Fresh Broccoli. University of California Special Publication. http://coststudies.ucdavis.edu/files/broccolicc2004.pdf. Accessed: February 18, 2009.

Tickes, B. R. and D. R. Kerns. 1996. Lettuce injury from preplant and preemergence herbicides. University of Arizona Cooperative Extension. http://www.docstoc.com/docs/3837888/ARIZONA-COOPERATIVE-EXTENSION-The-University-of-Arizona-College-of-Agriculture. Accessed: February 18, 2009.

Tourte, L. and R. F. Smith. 2001. Sample Production Costs for Wrapped Iceberg Lettuce in Monterey and Santa Cruz Counties. University of California, Davis, Cost and Return Studies. http://coststudies.ucdavis.edu/files/lethead2001.pdf. Accessed: February 18, 2009.

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