CALIFORNIA LEAFY GREENS RESEARCH PROGRAM

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WEED MANAGEMENT SYSTEMS FOR LEAFY GREENS

PRINCIPAL INVESTIGATORS:

Steven A. Fennimore
Dept. of Plant Sciences
Univ. of California, Davis
Salinas, CA
safennimore@ucdavis.edu
831-755-2896

David C. Slaughter
Dept. of Bio. & Ag. Engineering
Univ. of California, Davis
Davis, CA
dcslaughter@ucdavis.edu
530-752-5553

Richard F. Smith
University of California
Cooperative Extension,
Monterey County
Salinas, CA
rifsmith@ucdavis.edu
831-759-7357

COOPERATING PERSONEL:

Laura Tourte
University of California
Cooperative Extension,
Monterey County
Salinas, CA

Thuy Nguyen
Rekha Raja
Burt Vannucci
Leland Neilson
Dept. of Bio. & Ag. Engineering
Univ. of California, Davis
Davis, CA

HannahJoy Kennedy
John Rachuy
Dept. of Plant Sciences
Univ. of California, Davis
Salinas, CA

ABSTRACT

The Californian lettuce industry has been largely dependent on either manual labor for hoeing or on one herbicide – pronamide (Kerb) to control weeds. The loss of the Kerb registration for leaf lettuce in August 2009 seriously reduced the lettuce herbicide options. While some new weed control equipment from Europe has been developed, these systems cannot reliably distinguish between leafy green vegetables and weeds, but rely on a number assumptions (such as the crop plant always being larger than the weed) that may not be reliable in commercial fields, causing the performance to degrade when these assumptions are invalid. As an alternative, we have developed a new concept for an automatic weed control machine based a novel method, called crop signaling, for making leafy green vegetable plants machine readable. This method allows the UC Davis weeding robot to reliably distinguish lettuce seedlings from weeds. Our results show that the crop signaling approach can reliably distinguish lettuce seedlings from weeds, with no false positives (i.e., it never mistakes a weed plant for a lettuce plant). When used with a mechanical, robotic weed knife, the crop signaling system works in weedy fields with all levels of weed density, demonstrating the advantage of the approach over other robotic approaches. Replicated research trial results demonstrated that the robot could automatically remove 65% of the weeds on average in a lettuce field. This level of automated weed removal translated into a manual hoeing labor savings of 3% to 73%.

OBJECTIVES

The long-term goal of this project is to provide leafy vegetable growers with tools and information that leads to cost-effective and labor-efficient weed management systems that will be sustainable in the long-term. Our team at UC Davis has developed several novel technologies for creating a unique crop marking system. This new technology makes the crop machine readable by temporarily marking the crop for automated machine recognition and differentiation from weeds and does not involve use of biotechnology or transgenes. In this project we are developing and testing a machine vision system that identifies lettuce plants vs. weeds in real-time on a farm from a tractor-drawn smart cultivator based upon this novel technology.

PROCEDURES

Five field trials in the romaine lettuce cultivar Solid King were conducted in 2016-2017 at the USDA Agricultural Research Service/University of California Cooperative Extension research station in Salinas, CA. One trial used a topical marker (Fig. 1) and four used a physical label (Fig. 2). The topical marker used was green or orange fluorescent water-based paint diluted with water to 45-50% concentration. Biodegradable beverage straws made from polylactic acid (PLA) or "corn plastic" were used as the physical plant labels in the study.

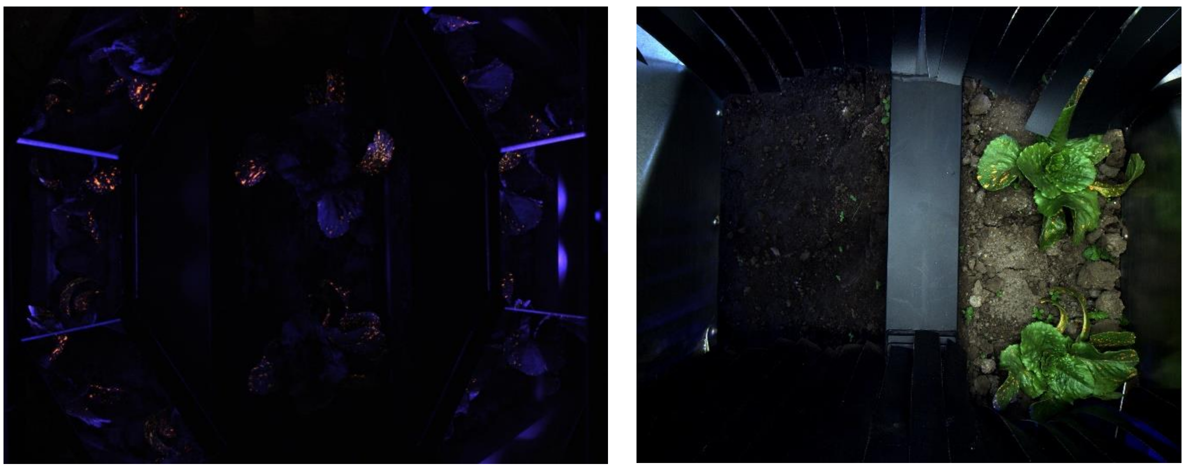
Six weeks after seeding, the whole plot was cultivated with a standard mechanical cultivator. The standard cultivator left a 6-inch uncultivated band around the seedline to protect the crop from cultivator damage. For the physical label trials, randomly selected rows were also cultivated with the intelligent cultivator. In the rows with the topical marker, image data for evaluation of the machine learning method were collected with the goal of developing a weed map of the 6-inch uncultivated band for precision spot spraying of weeds.

Figure 1. Topical marker applied to lettuce seedling.

Figure 2. Physical labels adjacent to lettuce plants.

In the control rows and the rows with the physical labels, weed density counts were measured in the six-inch uncultivated band (three inches on each side of the seed line) in each of two 20-foot samples in the field. Weeds were considered dead if they were, cut, uprooted or had roots exposed. Any crop plants killed during cultivation were noted. The whole plot was then hand-weeded by a farm worker with a hand hoe who weeded the field to commercial standards. The time taken to hand weed the 20 ft sample plots was recorded. The hand weeding was timed in the same sample sections as the weed counts were taken. The 2017 lettuce trials were maintained until commercial harvest so marketable yield data could be collected (number of marketable heads and weight of marketable heads).

Figure 3 shows an image set of a lettuce plant where its leaves were painted with orange paint at planting as shown in Fig.1 (Model of paint: Wildfire Visible Luminescent Paint, Wildfire Inc., Venice, California, USA). Fig. 3a shows the image captured under ultraviolet (UV) light for fluorescent signaling. The UV imaging chamber was designed to be entirely dark inside when the support skids rested upon the soil surface, so that no sunlight leaked from outside. Fig 3b shows the same lettuce plants and weeds in 3a, but with the image captured under white light.



(a) (b)

Figure 3. A set of lettuce plants where the leaves were painted with orange paint at planting. (a) UV image, (b) White image.

A custom developed software (LabVIEW, National Instruments Corporation, Austin, Texas, USA) was used for camera image acquisition, object detection, and wheel encoder reading. The distance between UV chamber and the white chamber was about 24 inches. Once an image has been acquired an algorithm was developed to classify the weeds and lettuce plants based on both UV and white images. The plant was detected based on top-view of images. In the top-view, a region of interest (ROI) was first defined statically based on viewing chamber where the plant was going through. The size of the ROI width was set to fit an average lettuce plant size viewed from above and the height was set as the length of image. Fig. 4(a) shows the corresponding segmented sub-image from the original image in Fig. 3(a) and Figure 4(c) shows the corresponding segmented sub-image from the original image in Figure 3(b). The algorithm then marked the lettuce plants as machine readable crop plants (those contains orange dots), and marked the rest of the plants as weeds. The weed-plant detection algorithm was developed using some advanced image processing tools in Matlab R2017a.

(a) (b) (c) (d)

Figure 4. Processed images from Fig. 3. 4a: UV ROI, top view, 4b: lettuce leaves with crop signaling markings shown in white. 4c: White light ROI, top view, 4d: binary image showing weeds and lettuce leaves in white.

RESULTS AND DISCUSSION

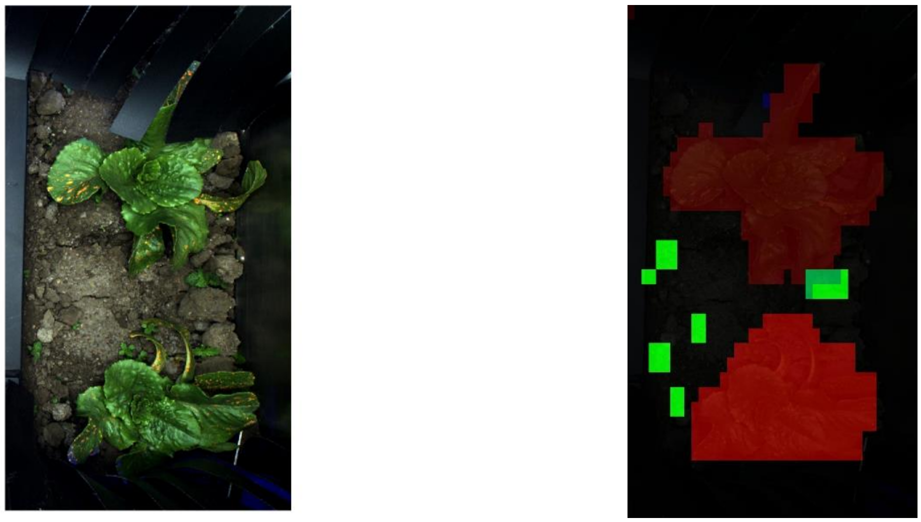
The overall performance of the crop signaling concept for automated weed control in leafy greens was good.

Crop Signaling Performance

(A) (B)

Figure 5. Photographs showing the weed control trial in Salinas in 2016 using the biodegradable plant label crop signaling method. Fig. 3A shows an overview of the field, while 3B shows a close-up photo with a Romaine lettuce plant in the center of the image.

To illustrate the power of the crop signaling concept, Fig. 5 shows the use of the biodegradable plant label crop signaling method in a very weedy Romaine lettuce field in 2016. In this example, the majority of the bed is covered in weeds and weeds are touching most of the lettuce plants in the field. Traditional machine vision methods fail under these conditions because they rely on being able to easily isolate the crop plants to evaluate their size and shape.



(a) (b)

Figure 6. (a) cropped white image, (b) Weed-plant grid map (weeds shown in green, lettuce shown in red).

The results of the foliar-based crop signaling method from Fig. 1 are shown in Fig. 6b, where crop plants (lettuce) are marked in red color and the weeds are marked in green color. The results in Table 1 are presented for 30 different images taken in Salinas 3 weeks after transplanting the plants in the field.

Table 1. Results of the algorithm developed for weed-lettuce mapping for precision herbicide applications.

Lettuce plants	Lettuce Plants detected	Lettuce Plants detected as weeds	Weed plants	Weeds detected	Weeds detected as Lettuce plants	Weeds not detected
31	92.9 %	7.1 %	404	81.6 %	15.8 %	2.47 %

Among the 31 crop plants in the field study, 93% of the lettuce plants were detected and 7% of lettuce plants were mis-detected as weeds because the lettuce plants were occluded by the sunlight control curtains and the curtains obscured the orange dots. If this mechanical issue is corrected the lettuce plant recognition rate was 99%. In total there were 404 weeds, of which 81.6% were detected, 15.8% weeds were mis-detected as crop plants due to occlusion by crop plants or because they were located very near to the crop plants, and 2.5% of weeds were not detected due to their very small size or their color which was not green or was similar in color to soil. There were some weeds that were also not detected by the algorithm because they were located at a dark region (shaded by the curtains) in the image.

Weed Control Performance

The efficacy of weed removal was determined to be the difference between pre-cultivation weed counts and post-cultivation weed counts. The most efficacious treatment removed the greatest proportion of weeds. Significantly fewer weeds remained after the automated cultivator went through the fields than after the standard cultivator. In the lettuce trials, 0.99 weeds per row-ft-1 remained after automated cultivation while 2.8 weeds per row-ft-1 remained after standard cultivation, which is a 65% reduction in the number of weeds remaining after cultivation.

Figure 7. Photograph showing the UC Davis robotic hoe automatically avoiding the lettuce plant containing the biodegradable, machine readable plant label.

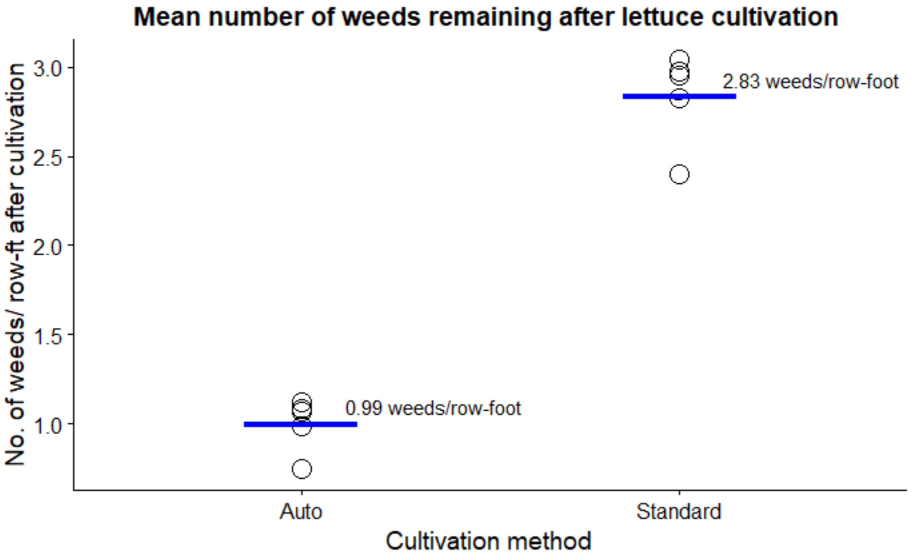


Figure 8. Plot of weed densities in lettuce trials following automated and standard cultivation. The centerline represents the means of the six lettuce trials with the circles representing the mean from each trial so that the variation around the mean is visible.

Table 2. Effect of cultivator type on in-row weed densities in lettuce.

Lettuce Trial	Cultivator	No. weeds row-ft^{-1} after cultivation[2]	Lower confidence interval	Upper confidence interval	P value	% weed reduction
Overall[1]	Automated	1.0 a	0.86	1.14	<.0001	64.9
Overall[1]	Standard	2.8 b	2.59	3.09	<.0001	

[1] All lettuce trials for 2016-2017.

[2] Values in the same column with different letters are significantly different at the 5% level of probability according to the least-square means method with Tukey's adjustment.

Significantly less time, 73%, 44%, and 46% respectively, was spent hand-weeding the rows weeded with the automated cultivator than the rows weeded with the standard cultivator in 2016 Trial 1, 2017 Trial 2, and 2017 Trial 3. However, in 2016 Trial 2 and 2017 Trial 1, a significant difference in time spent hand-weeding could not be detected even though there was a significant difference in the number of weeds removed by the two cultivation methods. 2017 Trial 1 likely did not have a significant difference in hand-weeding time between the cultivation methods due to an inexperienced farm worker doing the hand-weeding.

Table 3. Effect of cultivator type on hand-weed time following cultivation in lettuce.

Lettuce Trial	Cultivator	Time spent hand-weeding after cultivation hr $acre^{-1}$	Lower confidence interval	Upper confidence interval	P value[1]	% time reduction
2016 Trial 1	Auto	11.8	7.40	18.97	<.0001a	72.9
2016 Trial 1	Standard	43.7	27.32	70.04	<.0001b	
2016 Trial 2	Auto	11.1	7.06	17.55	<.0001a	48.2
2016 Trial 2	Standard	21.5	11.40	40.46	<.0001a	
2017 Trial 1	Auto	49.3	30.87	78.79	<.0001a	2.9
2017 Trial 1	Standard	50.8	32.12	80.32	<.0001a	
2017 Trial 2	Auto	51.7	40.82	65.50	<.0001a	44.0
2017 Trial 2	Standard	92.3	70.26	121.22	<.0001b	
2017 Trial 3	Auto	17.7	14.26	22.00	<.0001a	45.5
2017 Trial 3	Standard	32.5	25.41	41.53	<.0001b	

[1] Values in the same column with the same letters are not significantly different at the 5% level of probability according to the least-square means method with Tukey's adjustment.

No significant difference was found in yields between rows cultivated with the automated or standard cultivator. This suggests that the automated cultivator was just as safe as was the standard cultivator.

Table 4. Effect of cultivator type on yield following cultivation in lettuce.

Lettuce Trial	Cultivator	No. heads marketable $Acre^{-1}$	Lower confidence interval	Upper confidence interval	P value[2]
Overall[1]	Automated	15851.5	11729.7	21421.7	<.0001a
Overall[1]	Standard	14944.9	11014.0	20278.9	<.0001a

[1] All lettuce trials taken to yield for 2016-2017. Trials 2-3, and 10-12 in Table 1.

[2] Values in the same column with the same letters are not significantly different at the 5% level of probability according to the least-square means method with Tukey's adjustment.

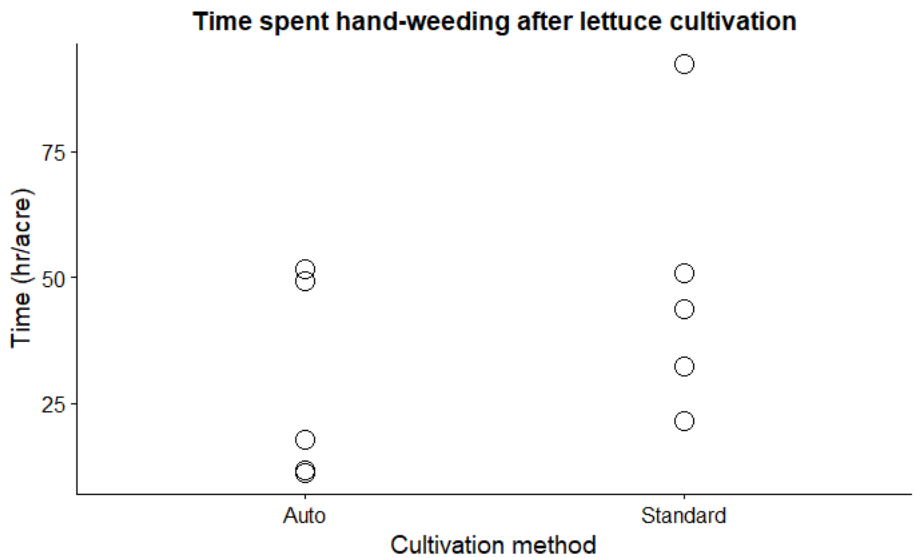


Figure 9. Plot of hand-weeding time in lettuce trials following automated and standard cultivation. The circles represent the mean from each trial so that the variation between trials is visible.

Table 5. Effect of cultivator type on yield following cultivation in lettuce.

Lettuce Trial	Cultivator	Lb. marketable Acre^{-1}	Lower confidence interval	Upper confidence interval	P value[2]
Overall[1]	Automated	40885.9	28909.1	57824.6	<.0001a
Overall[1]	Standard	33921.8	23731.6	48487.6	<.0001a

[1] All lettuce trials taken to yield for 2016-2017. Trials 2-3, and 10-12 in Table 1.

[2] Values in the same column with the same letters are not significantly different at the 5% level of probability according to the least-square means method with Tukey's adjustment.

This research demonstrated the two primary advantages to the crop signaling method for automated weed control in leafy greens. First, as shown in Figure 5, by using the crop signaling method, a robot can automatically distinguish lettuce plants from weeds under very weedy field conditions. Second the research validated the premise that the crop signaling method is resistant to problems with false identification of weeds as crop plants common to conventional machine vision system currently employed for weed control. The crop signaling materials used in the UC Davis system are not naturally present in leafy green farms and thus their unique appearance greatly minimizes the risk of a false identification of a weed as a lettuce plant.

The average weed removal rate across trials in 2016 and 2017 for the plant label implementation of the crop signaling method was 65%. The amount of time savings in hand weeding after the automated weeding system was operated in the field ranged from 3% to 73% compared to the standard cultivator. Time savings in manual weeding is not always proportional to weed removal rates due to the proximity of the remaining weeds to the crop plant.