CALIFORNIA LEAFY GREENS RESEARCH PROGRAM

April 1, 2016 – March 31, 2017

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

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 temporary loss of the Kerb registration for leaf lettuce in August 2009 was a reminder of the tenuous state of lettuce herbicides. 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 2016 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. Research trial results in 2016 demonstrated that the robot could automatically find and remove 62 to 100% of the weeds in a lettuce field. This level of automated weed removal translated into a manual hoeing labor savings of 55% to 71%.

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 tractor-drawn smart cultivator based upon this novel technology.

PROCEDURES

Two sets of machine learning trials and two sets of weed control evaluation trials were performed outdoors in lettuce fields in Salinas in 2016.

The first type of crop signaling technology used in 2016 involved the direct application of the crop signaling material to the foliage of both Iceberg and Romaine lettuce transplants. An improved application technique was developed in 2016 that increased the pattern size of the specially created speckle pattern, and reduced the camera resolution required for machine detection, while maintaining or improving the plant's photosynthesis ability compared to the original method evaluated in 2015. The experimental crop signaling material used in our research trial is a water-based material sold commercially in California for use in marking grass athletic fields and is not harmful to the plants.

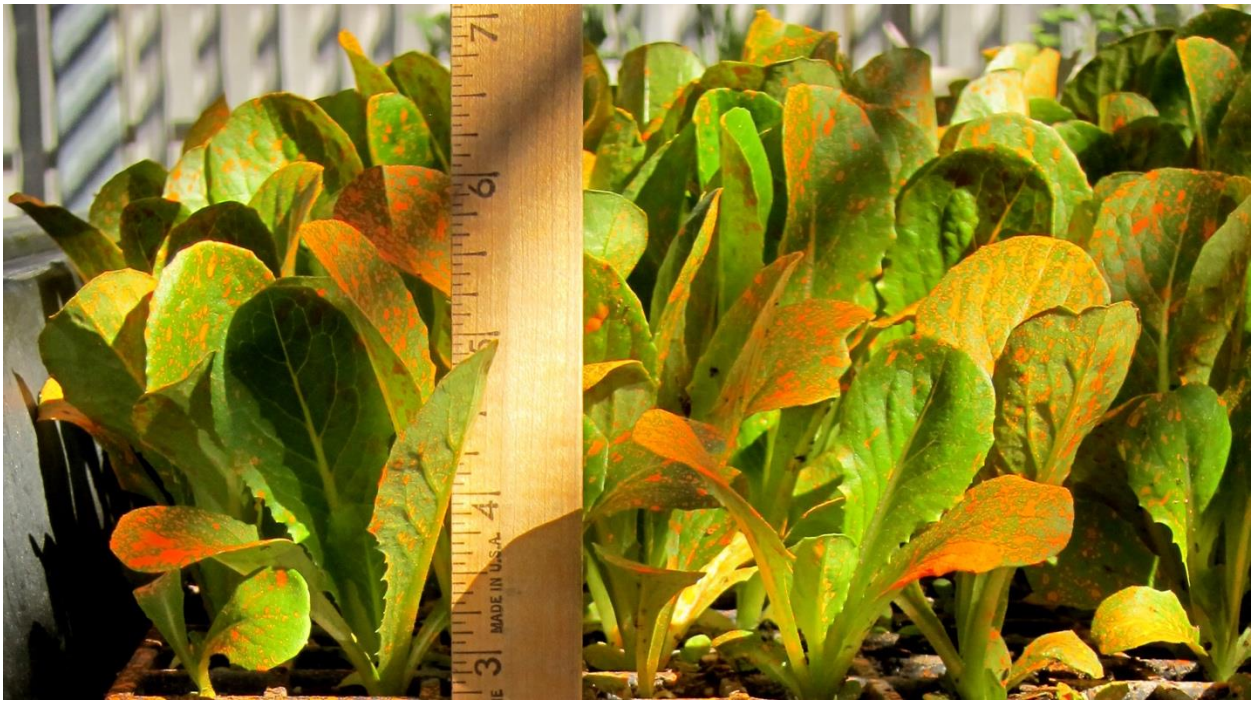


Figure 1. Photograph showing the foliar application of the crop signaling material to the lettuce plants prior to transplanting.

The weed control evaluation trial for the foliar crop signaling method was planted on Sept. 14, 2016 and the robotic weeding system was operated in the field on Sept. 23, 2016. The plots were not treated with herbicides. The plot was split in half, where one half was weeded by the robot, and the other half was a control (i.e. not treated by the robot). Both parts were cultivated using a standard lettuce cultivator. Weed counts were taken before and after the weeding robot was operated to determine the proportion of weeds automatically removed by the robot. In addition to assessing the reduction in weed population, we also conducted a labor savings evaluation where the amount of time required to weed the control and the robot plots by hand with a conventional hoe were determined.

The second type of crop signaling technology evaluated in 2016 was the use of a biodegradable plant label. In this method, the crop signaling material was applied to a plant label rather than the plant itself. The plant label is co-located with the crop plant to provide the crop signal, but without direct application of the crop signaling material to the crop itself. The label material selected in 2016 was one that showed good mechanical strength after a period of 8 weeks when transplanted into beds in a lettuce field and had in-field stability of the crop signaling material under direct sunlight in our 2015 trial.

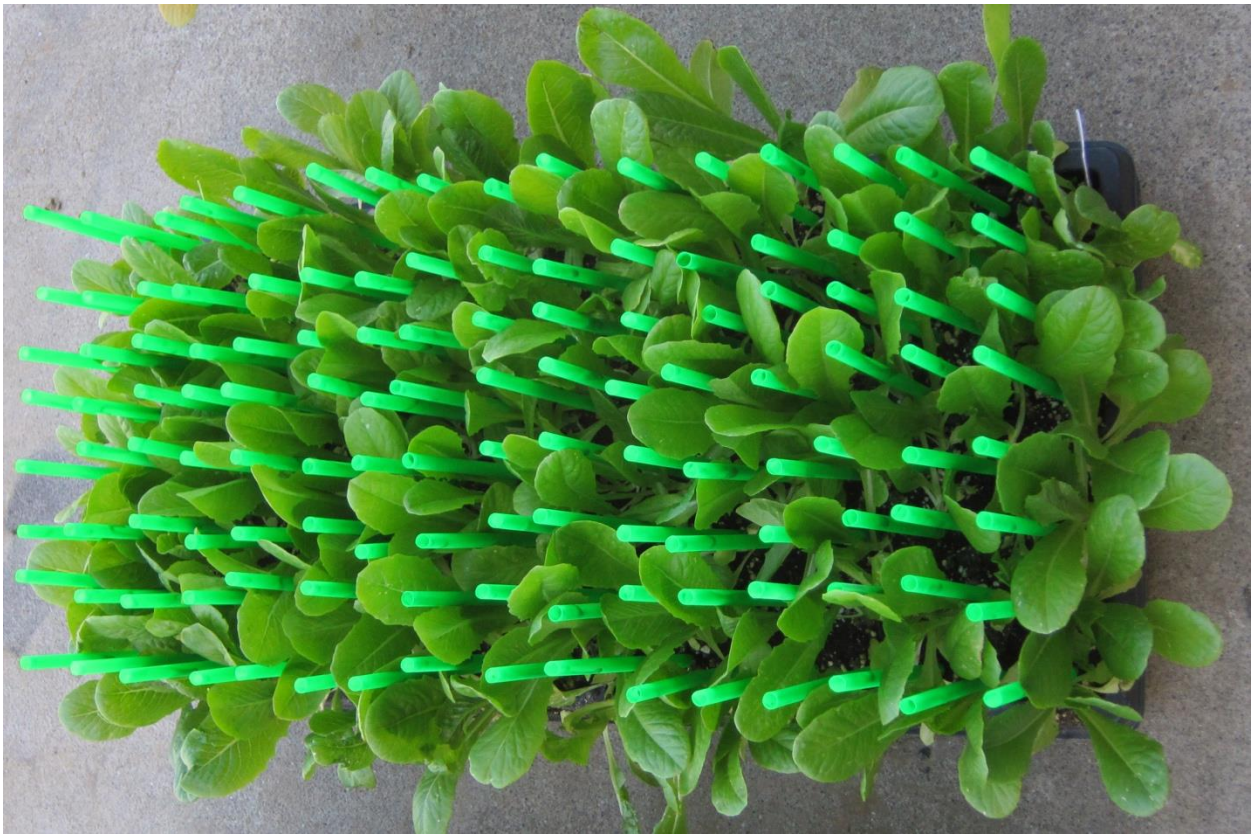


Figure 2. Photograph showing the biodegradable plant label application of the crop signaling material to the lettuce plants prior to transplanting.

The weed control evaluation trial for the biodegradable plant label crop signaling method was conducted in the same manner as the trial for the foliar crop signaling method. The robotic weeding system trial was conducted in Salinas in the field on July 23, 2016.

RESULTS AND DISCUSSION

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

Crop Signaling Performance

To illustrate the power of the crop signaling concept, Figure 3 shows the use of the biodegradable plant label crop signaling method in a very weedy Romaine lettuce field. 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 3. Photographs showing the weed control trial in Salinas 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.

When the weeds surround the crop as shown in Figure 3, conventional machine vision methods fail because they cannot find the crop plants.

In contrast, the UC Davis weeding robot uses two novel approaches to solve this problem. First, the crop signaling compound is machine readable, and second, our robot uses a novel multipose machine viewing system to observe the lettuce plants simultaneously from seven different vantage points. The optically processed image of a lettuce plant in this field is shown in Figure 4. The machine readable feature allows the robot to automatically isolate the crop signal and extract the crop location from the image shown in Figure 4.

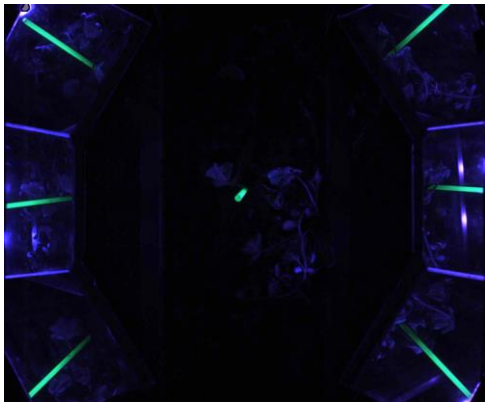
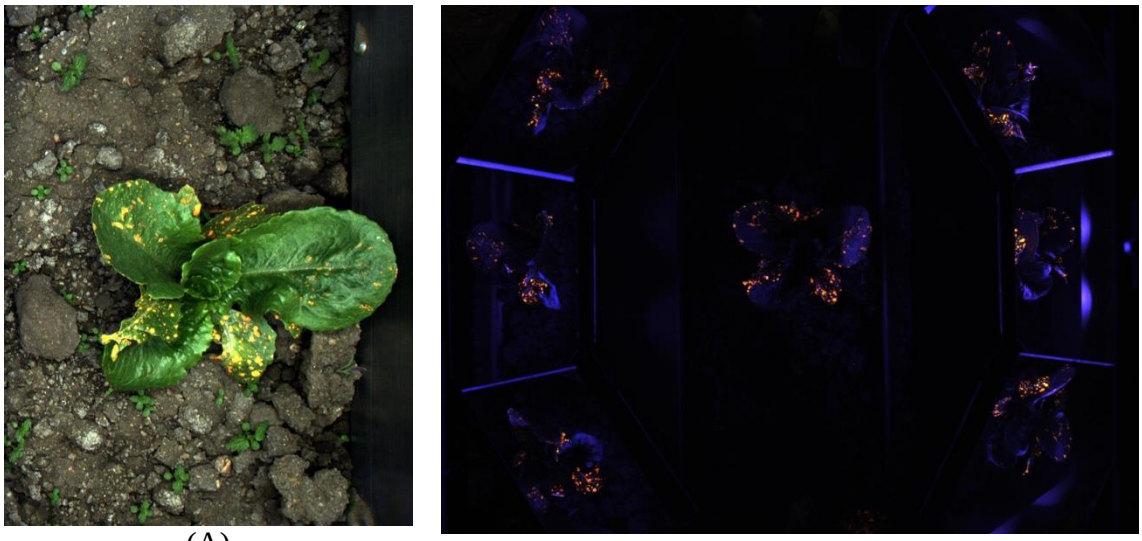


Figure 4. UC Davis robot view of the biodegradable plant label crop signaling method. The green lines point to the base of the lettuce plant.



(A) (B)

Figure 5. Photographs showing the used of the foliar crop signaling method in the weed control evaluation trial in Salinas in 2016. Fig. 5A shows the conventional machine view of a lettuce plant with the crop signaling speckle pattern applied before transplanting to the foliage. Fig. 5B shows the UC Davis robot view of the same plant using the novel machine readable feature.

(A) (B) (C)

Figure 6. Photographs showing the lettuce plants treated with the foliar crop signaling method at harvest. Fig. 6A shows a lettuce plant in the field just prior to harvest. Note the crop signaling material is on the brown senesced leaf at the base, not on the green foliage. Fig. 6B shows the unharvested senesced leaves, including those with the signaling compound. Fig. 6C shows the harvested lettuce plant. None of the leaves remaining green and turgid at harvest contain any presence of the signaling compound.

The photographs in Figure 5 illustrate the in-field performance of the foliar crop signaling method. Figure 5A shows the orange speckle pattern of the crop signaling material on the lettuce plant at the time of cultivation. This lettuce plant is surrounded by weeds. Figure 5B shows the

UC Davis weeding robot's view, where our novel optical processing method has been applied to make the lettuce plant machine readable and its location easily determined.

The photographs in Figure 6 show a lettuce plant from the crop signaling weed control trial at the time of harvest. The plant in Figure 6A was treated with the foliar crop signaling material, which can be seen on one of the brown leaves at the base of the plant. As lettuce plants grow and mature, the first few leaves of the plants become shaded by the subsequent foliage and they senesce, becoming dry and brown. These senesced leaves are the ones to which the crop signaling compound is applied prior to transplanting and shown in Figure 1. At harvest, the dry brown leaves are separated from the turgid green leaves and remain in the field, as shown in Figure 6B. The harvested plant, show in Figure 6C, contains no evidence of the signaling compound, since all the leaves that were treated with the material have senesced and were left in the field at harvest.

Weed Control Performance

The results from the two in-field weed control evaluation trials show that the crop signaling concept is an effective crop vs. weed detection method for automatic control of a mechanical robotic weed knife system. Figure 7 shows a photograph of the UC Davis robotic weed knife system in operation in a lettuce field in Salinas in 2016. The system contains two pneumatically powered, miniature weed knives that can be positioned by the robot to kill weeds growing in the center of the bed. When a lettuce plant is detected using the crop signaling method, the robot separates the knives, as shown in Figure 7 to avoid killing the lettuce plant. Once the robot has passed by the lettuce plant, the knives are automatically repositioned to kill weeds in the center of the bed.

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

The weed control performance of the crop signaling weeding robot in the 2016 field evaluation trials was good. In the trial that used the biodegradable plant label crop signaling method, the proportion of weeds automatically removed by the robot ranged from 67% to 81%, with a mean removal rate of 73%. The 73% weed removal rate translated into a 71% savings in the amount of time required by the manual laborer to remove the remaining weeds when compared to the time required to hand hoe the control rows that only received the conventional between-row cultivation treatment.

The weed control performance in the trial that used the foliar crop signaling method was similar to that of the plant labeling method. When using the foliar crop signaling method, the robot automatically removed 85% of the weeds on average, with a row to row weed removal performance ranging from 62% to 100%. The 85% weed removal rate translated into a 55%

savings in the amount of time required by the manual laborer to remove the remaining weeds when compared to the time required to hand hoe the control rows that only received the conventional between-row cultivation treatment. The time savings in manual weed removal is a function of both the quantity of weeds present as well as the location of those weeds relative to the crop plants present. A worker must slow their work rate when the weeds are in close proximity to the crop plant in order to avoid accidentally killing the crop with the hoe. This fact helps explain why the labor savings was lower in the foliar crop signaling trial than the plant labeling trial despite the higher proportion of weeds automatically removed by the robot.

This research demonstrated the two primary advantages to the crop signaling method for automated weed control in leafy greens. First, as shown in Figure 4, 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. We observed no false positive errors in our field trials in 2016. As identified in our 2015 study, reliable crop plant detection using crop signaling depends upon two factors, first the treated object (foliage or plant label) must still be present (for the label) or attached to the plant at the time of cultivation, and second, the treated object or foliage must not be hidden beneath untreated foliage. Reliable crop plant detection using the crop signaling method requires that the automated weed control operation be conducted in a timely manner and before the crop signal is physically lost or hidden. The plant label approach was less sensitive to this effect as long as the size of the plant label was larger than the plant at the time of automatic crop detection by the crop signal detection system. When this condition was satisfied, the detection rate of the plant label approached 100%.

Overall, the project demonstrated the in-field practical feasibility of using crop signaling as the basis of a smart machine for automatic weed control in leafy vegetables. Plant label-based crop signaling methods had robust in-field performance with detection rates near 100% and with no errors in accidentally misclassifying lettuce as a weed. The automated weed removal performance ranged from 62% to 100%, with an average weed removal rate of 79%. The average time savings for manual hand hoeing to remove the remaining weeds after the robotic weed control treatment was complete was 63%. No crop signaling material was observed on the harvested crop.