

To the Graduate Council

I am submitting herewith a thesis written by Philip Brooks Allen entitled "Developing a Technique for Evaluating Weed-Specific Mapping Systems." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

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Developing a Technique for Evaluating Weed-Specific Mapping Systems

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Philip Brooks Allen
December 2007

Acknowledgements

There are many people whom I'd like to acknowledge for their significant contribution to this body of work. Funding for this research was provided by the United States Department of Agriculture. The Biosystems Engineering and Soil Sciences department provided me with coursework, a constructive environment, and a sense of community in which I could further myself as a person, as well as a student and a researcher.

As my major advisor, Dr. John B. Wilkerson's invaluable guidance, support, and flexibility allowed me to pursue my research with a feeling of confidence and independence. He went out of his way to provide me with resources and opportunities, and was always willing to listen and give input on new ideas. Technical assistance by Dr. Hart during the preliminary testing and data-collection phase of this work paved the way for developments that would have not otherwise been possible. Dr. Saxton's comments during committee meetings and editorial reviews supplied valuable direction and support. Dr. Stacey Worley, David Smith, and Craig Wagner all provided technical assistance that enabled parts of this research.

My parents Pam and Terry Allen, as well as my girlfriend Erin Herndon, patiently and warmly supported me during a process that often found me spending late nights and long weekends at work or in the field. I also want to acknowledge the contribution of my brother, Jeffrey Allen, whose knack with computers re-sparked my interest in programming that empowered me during this research.

Abstract

Federal regulation and public awareness of agricultural chemical use have fueled precision agriculture research for the last decade. An extensive body of research on potential reduction of herbicide inputs by automated patch-spraying or site-specific management has developed. Two dominant methods have developed for site-specific application of herbicide. Map-based systems use predefined application maps to direct herbicide application and sensor-based systems use real-time weed sensors to identify and treat weeds as the sprayer moves through the field. Weed maps, generated for map-based application of herbicide are beneficial for out-of-field decision-making but are labor intensive to create and sensitive to many types of sampling errors. Real-time sensor-based systems are not as labor-intensive but have historically made no record of what parts of the field received herbicide and are subject to weed discrimination errors. The University of Tennessee Weed Mapping System (UTWMS) is made up of a digital event recorder and a WeedSeeker discrete herbicide application system. The overarching objective of this study was to evaluate the UTWMS under field conditions. Specific objectives included the use of georeferenced manually-sampled plots for evaluation of map accuracy; development of an automated documentation system for quantifying hits, misses, and false triggers of a real-time sensor-based spraying system; updating the logging software of the UTWMS to include a count of spray transitions; and investigate potentials for reducing number of sensors to reflect the existing spatial correlation of weeds. Manually sampled subplots at one-meter resolution did not correlate with weed

maps and only weakly correlated when averaged by plot (8x30m). A video documentation system was successfully developed for evaluating discrimination accuracy of sensor-based sprayers. While investigating sensor resolution reduction to reflect spatial correlation of weeds, a sensor was replaced with a conditionally triggered solenoid valve during a simulation. More than 75% of the simulated weeds were accurately sprayed for all four conditional scenarios tested. A software modification to the UTWMS provided enumeration of spray transitions for weed scientist to investigate weed distribution during “percent time on” integration. The update rate of the GPS unit in the UTWMS should be increased if weed maps are to be representative of small research subplots.

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Chapter 1 – Introduction

Introduction

With the rising cost of herbicides, mounting chemical restrictions by the EPA, and increasing public awareness of environmental pollution, the reduction of herbicide use in agriculture is a major concern for both researchers and producers alike. Statistics published by USDA (2000) indicate that between 1990 and 1997, 209.5 million acres, or 86% of crop acres, were treated with herbicides one or more times. Tian *et al.* (1999) note that the trend towards reduced-tillage and no till agriculture will result in increased chemical inputs due to the chemical requirements of these techniques. As of 1996, 86% of herbicide applied to corn was being broadcast (USDA, 2000).

A number of articles have examined the potential reduction of herbicide by automated patch spraying or site-specific management (Audsley, 1993, Zanin *et al.*, 1998, Oriade *et al.*, 1996, Tian *et al.* 2002, Swinton, 2005) as opposed to broadcast spraying. In 1996 more herbicide was used in the production of corn (*Zea mays* L.) than in any other American crop (Oriade *et al.*, 1996). Tian *et al.*, (1999) realized a 42% reduction in herbicide use with an automated weed-specific application system. However, due to the cost of implementing site-specific weed control, bio-economic modeling has demonstrated that profits from site-specific management techniques are maximized when weed patchiness is high along with weed pressure (Oriade *et al.*, 1996) and would not be economically viable if weed distribution were more uniform or patch sizes were

large (Audsley, 1993, Oriade *et al.*, 1996, Swinton, 2005). Many researchers have shown that weeds are not uniformly distributed across fields but are patchy in distribution (Zanin *et al.*, 1998, Tian *et al.*, 1999, Rew and Cousens, 2000, Lamb and Brown, 2001). Two dominant methods have emerged for identifying and locating weed patches in fields for patch spraying (Bajwa and Tian, 2001): 1) real-time sensor-based systems and 2) map based systems. More detail on these methods will be given later. However, it is important to note that while real-time sensor-based systems treat weed infestation at the time of identification, systems that are currently commercially available do not record information on areas treated. Map-based systems rely on pre-defined maps of infestation to target treatment. These weed maps can prove valuable for out-of-field decision making but are labor intensive and subject to many types of errors. The number of samples (Zanin *et al.*, 1998), sampling-grid size and orientation relative to crop rows (Wiles *et al.*, 2002), and the interpolation technique utilized (Dille *et al.*, 2002) can all affect the accuracy of the weed map.

In 2002, Moody *et al.* developed a digital event recorder for mapping discrete field operations (discussed later). The event recorder was evaluated for documenting activity of a commercially available real-time sensor-based spraying system. When evaluated over a known foliage pattern, there was good agreement between the activity map and the known foliage layer. The combination of digital event recorder and real-time sensor-based sprayer for weed mapping allows for the timeliness of real-time chemical application and out-of-field decision making made possible with weed maps. The accuracy of the

weed mapping system has not been evaluated in a field-application setting. The overarching objective of the following work is the development of an automated field validation system for a real-time weed-mapping unit.

Objectives

Specific objectives were:

- 1) Develop a georeferenced manual sampling technique to ground-truth weed maps created by the University of Tennessee Weed Mapping System (UTWMS);
- 2) Develop, implement, and evaluate a video documentation system for investigating hits, misses, and false triggers of the real-time weed specific spraying units used with the UTWMS;
- 3) Develop a refined sampling and signal processing technique for the UTWMS to estimate weed density based on percent cover and number of spray transitions within a defined integrated period (i.e. ~1 sec); and
- 4) Evaluate spatial correlation of weeds as a means to optimize the number of weed detection elements required to maintain an acceptable targeting accuracy within row middles.

Thesis Organization

Chapter 2 is a review of literature relative to site-specific herbicide application and serves as background information and state-of-the-art for this

technology. Chapter 3 focuses on Objectives 1 and 2, evaluating errors associated with the UT weed mapping system. Chapter 4 describes a modification to the UTWMS that allows refined sampling and signal processing techniques to quantify both percent coverage and number of spray transitions over an integrated sampling period (Objective 3). Chapter 5 provides details on a simulation study investigating potential optimization of the number of weed detection elements to reflect spatial correlation of weeds (Objective 4). Chapter 6 is a summary of chapters 3, 4, and 5, and presents conclusions and recommendations based on this work.

Chapter 2 – Review of Literature

Map-Based vs. Sensor-Based Systems

The cost of site-specific weed management can be attributed to the time and technology necessary to identify weed patches from non-weed patches in the field and the cost of selective application (Oriade *et al.*, 1996). Currently there are two dominant methods for identifying and locating weeds for discrete herbicide application (Thompson *et al.*, 1991, Bajwa and Tian, 2001): 1) real-time, sensor-based systems and 2) map based systems. Real-time, sensor-based systems employ spectral reflectance or machine-vision to differentiate weed from soil and crop and typically treat weeds at or very close to the time of identification.

Map-based systems utilize an application map for the entire field, often generated at least a week prior to application by field scouting and interpolation of discrete point counts (Bajwa and Tian, 2001). Map-based systems are less expensive than real-time systems in terms of capital investment but may have substantial labor cost related to weed map creation. With reference to weed maps, the cost of point sampling typically dominates the considerations when choosing a sampling resolution but when data is collected with “on-the-go” sensors, the cost structure is very different (Sadler *et al.*, 1998). An up-to-date computer and geographic information system (GIS) software package is required for producers to create their own weed maps with a resolution necessary for site-specific management. Care must also be taken during sampling and map

creation because the number of samples (Zanin *et al*, 1998), sampling-grid size and orientation relative to crop rows (Wiles *et al*, 2002), and the interpolation technique utilized (Zanin *et al.*, 1998, Dille *et al.*, 2002) can all effect the accuracy of the weed map. An accurate weed map allows the determination of the type and amount of herbicide needed before the sprayer enters the field (Brown and Noble 2005). Weed maps can also help detect the presence of herbicide resistant species (USDA, 2000). The ability to tailor herbicide formulation and concentration to specific infestation situations is a benefit of map-based systems and could further reduce the amount of herbicide applied if maps are created properly.

Both map-based and real-time systems identify areas of the field requiring treatment with herbicide. Real-time systems treat these areas upon identification but do not record any information on areas treated. Map-based systems use pre-recorded information (weed maps) to locate and treat areas in the field. The advantages of having information on areas in a field that required treatment include: tailoring herbicide formulation and concentration to the current year's infestation, pre-emergent herbicide application, accurate chemical use reporting, and herbicide resistant weed identification. Automatically identifying and treating weeds in the field removes this opportunity for out-of-field decision-making. The primary advantages of both real-time and map-based systems can be realized by integrating the ability to make out-of-field decisions of map-based systems with the low labor costs and high data resolution of real-time systems by generating

weed maps from the real-time data. This study will focus on the real-time sensor-based approach to discrete herbicide application.

Sensor Based Systems

Machine Vision

Machine-vision is a system that has been under development for use in agriculture for some time. Tian *et al.* (1997) note that machine vision was first studied for use in a field setting for fruit harvesting applications by Parrish and Goksel in 1977. Guyer *et al.* (1986) evaluated the use of plant leaf geometry parameters for differentiating between plant species. Since then many researchers have attempted to apply machine vision systems to the detection of weeds in agricultural fields (Shearer and Holmes, 1990; Woebbecke *et al.*, 1992; Zhang and Chaisattapagon, 1995; and Tian *et al.*, 1997 and 1999). Many of the systems developed not only identified discrete weed patches from soil, but also could differentiate weed from crop and weed species A from weed species B with varying degrees of success.

There are commonly several steps involved in the process. Most systems include digital image acquisition, image segmentation (subdividing images into regions of similar characteristics) (Tang *et al.*, 2000), plant shape or organization recognition often using artificial neural networks (Aitkenhead *et al.*, 2003), and decision/sprayer control, some of which have utilized fuzzy logic techniques (Yang, 2000), or economic thresholds (Tian, 2002) to decide whether a location

in the field gets treated. Problems with this type of system include the need for high-resolution images (1 to 2 mm for identification of leaf shape characters) (Tian, 2002), potential occlusion (parts of leaves being hidden) (Brown and Noble 2005), and complicated and computationally expensive detection algorithms (Tian, 2002). Thompson *et al.* (1985) found that cereal crop canopy severely limits the area of the field in which weeds can be detected as soon as the first few weeks after planting. In autumn-sown cereals as much as 60-90% of the field area was obstructed. Tian *et al.* (1999) tested a machine-vision-controlled sprayer in corn and soybean crops. Overall system accuracy was tested at different chronological ages in soybean crops. A trend towards reduced accuracy with weed and crop age was evident. The unit had a max speed of 4.2 km/h (2.6 mph) due to the processing speed of the computer used at the time. Based on this maximum speed, the overall accuracy of the system was “100% in bare soil zone detection, 75% in weed infestation zone detection, and 47.8% in crop plant zone detection”. Tian (2002) overcame problems of variations in illumination often present under field conditions by using an environmentally adaptive image segmentation algorithm. He also developed object partition methods that minimize errors due to occlusion. However, weed identification systems that employ machine vision remain experimental and are not commercially available. Cost, speed, and target illumination are the primary concerns still being addressed.

Spectral Reflectance

Thompson *et al.* (1991) reviewed literature pertaining to the “Potential for automatic weed detection and selective herbicide application”. The authors indicated that chlorophyll’s selective absorption and reflection of radiation at certain wavelengths make it easy to distinguish plants from other materials such as soil, stone, and straw. Their review found little success differentiating between plant species using reflectance characteristics and attributed this to the number of variables that contribute to the reflectivity of an individual plant. These characteristics include: morphology, geometry, chemistry, moisture stress, nutrient deficiency, disease, plant growth stage, and insect damage.

In a more recent review, Scotford and Miller (2005) observed that specific wavelength bands in the visible (400-700nm) and near infrared (700-2500nm) ranges have potential application in agriculture for detection of physiological and biological functions of soils and crops. They found that, from varying sensing platforms and measurement resolutions, spectral reflectance was being used to characterize: crop establishment, weed control, crop protection (from insects and diseases), and crop nutrition in northern European cereals.

Spectral reflectance has been used to measure nitrogen status (Sui *et al.*, 2004) and estimate defoliation requirements (Ritchie and Bednarz, 2005) for cotton in the southeastern United States. Brown and Noble (2005) mention a ground-based adaptation of satellite and airborne remote sensing using non-imaging sensors to detect vegetation patches and automatically trigger valves to spray those patches for weed management applications. This type of non-

imaging system that employs a normalized ratio of red and near infrared reflected light, commonly referred to as NDVI (Normalized Difference Vegetation Index), is available commercially and is used in many agricultural and industrial applications. Smith and Thomson (2003) of the USDA agricultural research service state that “the sensor controlled hooded sprayer for row crops is one of the most important technologies for maintaining weed control while minimizing spray drift and chemical inputs”. In this research three WeedSeeker (Ntech Industries, Ukiah, CA) units were mounted under a 0.7m wide hood to cover three zones that made up the full width of the hood. See Figure 1 for an illustration of how the WeedSeeker works. Actual volume sprayed was measured and compared with a conventional spraying system run over the same ground. Both systems were calibrated to apply 126L/sprayed hectare. An 85% savings in herbicide was realized using the sensor-controlled valves.

Green vegetation detection systems, like those mentioned by Brown and Noble (2005), are simpler than machine-vision based systems. They sense changes in the NDVI ratio due to increased reflectance of near infrared light by plants when compared to bare soil. This type of system, unlike machine vision systems, does not require characteristics that are often difficult to identify under field conditions such as leaf shape, structure, orientation, and texture. However, the simplification of the measured data as compared to machine vision systems leads to limitations (Brown and Noble, 2005). In agricultural settings, green vegetation detection systems are only applicable in row-cropping systems for the treatment of weeds between rows since they lack the ability to differentiate weed

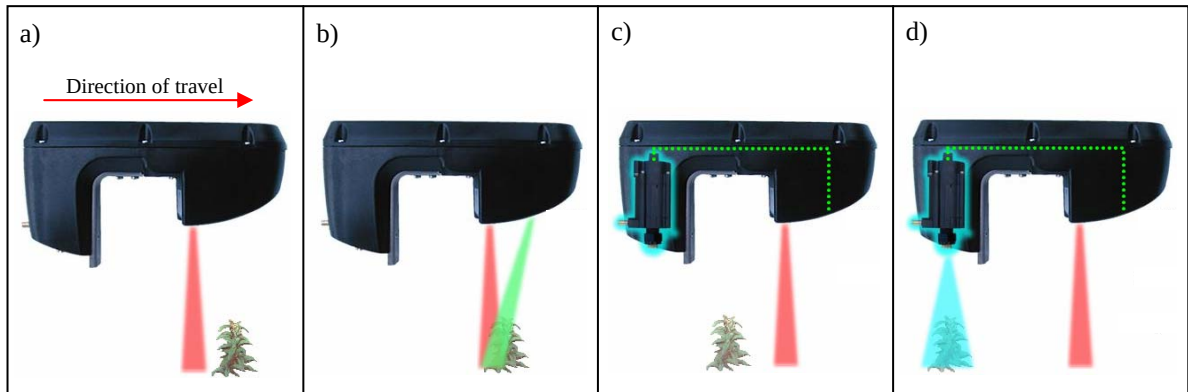


Figure 1. Illustration of the non-imaging optical sensor. LED modulated light source emits light on ground (a). The detector reads the reflected light (b). Onboard electronics activate the valve cartridge if a weed is detected (c). Valve sprays weeds only (d). Images were taken from <http://www.ntechindustries.com/demo.html>.

from crop. Furthermore, as mentioned previously, they are unable to differentiate between species of weeds because very few plants have spectral signatures unique enough for identification. Another problem is the threshold of detection for non-imaging sensors. While large weeds may be accurately detected, small seedlings distributed over the field-of-view may pass undetected (Brown and Noble, 2005). Finally, as with machine-vision controlled systems, current spectral reflectance systems do not log activity and allow for out-of-field decision-making.

Mapping Weeds Using a Real-Time Sensor-Driven Herbicide Application System

Moody *et al.* (2002) developed a digital event recorder for mapping field operations. The event logger was evaluated for documenting activity of a commercially available weed-specific spraying system over a known foliage

pattern. The selective sprayer utilized in this research consisted of nine weed-specific sprayer units that each included non-imaging optical sensors for discriminating foliage from bare soil and stubble. Figure 1 illustrates the operation of the sensing/spraying units. When deployed in an agricultural field, the University of Tennessee Weed Mapping System (UTWMS) logged, in real time, information on sprayer activity and location. A value representing the percent time on for each of the sensing/spraying units is logged each second with a GPS coordinate for the sprayer at that time. The documented activity layer created during testing agreed well with the known foliage layer used in the experiment and demonstrated the viability of this method for herbicide application mapping. The resulting points on the map of weed-specific sprayer activity could be interpreted as percent weed cover at that location in addition to accounting for herbicide applied.

An example implementation of this technology would be a tractor carrying the UTWMS connected with an array of WeedSeeker units. If the tractor were traveling at 3mph, a weed map could be generated that was equivalent to manually sampling weed cover (area requiring treatment/area, %) with 1.3m long quadrats laid end to end up and down every row of the treated field. The width of the sampled area would be determined by the sensor height above the ground. The accuracy of this map would be dictated by the sensitivity and accuracy of the selective sprayer heads in identifying and spraying weeds.

Weed Mapping State of the Art

The central premise of precision agriculture is treatment of field-scale variation. This notion of addressing variation by managing parts of a field differently was pioneered by researchers like Johnson *et al.* (1983) who developed the concept of 'custom prescribed tillage' (Stafford, 2000) and Haggard *et al.* (1983) who tested a prototype hand-held patch sprayer activated by spectral differences in weed and soil. Field maps of in-field variation have become vital tools for both researchers and managers. Position information has become incorporated into many common production and research management activities as GPS accuracy and availability have improved. Yield monitoring (Taylor *et al.*, 2001) and variable rate fertilizer application (Yang *et al.*, 2001) are two such activities that have seen increased use over the last decade. Similar to variable rate fertilizer application, site-specific herbicide application uses predefined maps of weed location to reduce and target herbicide use in fields. Weed maps have proven useful in both pre- and post-application of herbicides. As discussed earlier in this chapter, weed maps can be used for directing application, herbicide formulation, detection of resistant species, pre-emergent chemical application, as well as record keeping. Weed maps are subject to many types of errors. Some of these include: number of samples (Zanin *et al.*, 1998), sampling-grid size and orientation relative to crop rows (Wiles *et al.*, 2002), and the interpolation technique utilized (Zanin *et al.*, 1998, Dille *et al.*, 2002).

Manual grid sampling, combined with GIS interpolation techniques, is the typical method by which weed maps are created (Clay *et al.*, 1999, Rew and

Cousens, 2001, Gerhards and Christensen, 2003). This type of sampling is labor intensive and the resulting map is dependent upon the resolution at which the samples are taken (Clay *et al.*, 1999). In 1998, Wallinga *et al.* reviewed measures for describing weed spatial patterns at varying resolutions and their impact on patch spraying. An example from that study was an arable field divided into 10m x 10m sections, with each section assessed for presence of weeds. Very little of the field would be seen as weed free and patch spraying would not be chosen to minimize herbicide input. However, if the “sampling” resolution is 1mm x 1mm, a very large fraction of the field would be seen as weed free. They also point out that if weed free area is to be used to judge potential herbicide reduction by patch spraying then the resolution of the patch sprayer will dictate the scale at which the field should be sampled. This sampling also must be mediated by the need for timeliness of the information, as the time necessary for sampling increases proportional to the resolution of sampling.

With a labor-intensive sampling effort, Clay *et al.* (1999) manually sampled 2 65ha fields using 0.1m² plots on either a 15x30m grid (1,352 points in each field) or 30x 30m (676 points in each field). All plots were georeferenced and spatially analyzed. Plots sampled on a 15x30m grid were spatially dependent and a representative weed map was created using the Krigging interpolation technique. They point out that grid-sampling production fields at such a resolution may have “limited usefulness” due to time, cost, and labor constraints. Gerhards and Christensen (2003) note that a “major step towards a practical solution for site-specific weed management is the development of precise and

powerful sampling techniques to automatically and continuously determine in-field variation of crop cover and weed seedling populations”. One such method is aerial remote sensing.

Until recently, success in remote sensing-based weed detection has been limited. Weeds grown in controlled monocultures are distinguishable, but when growing naturally in a post-emergent crop setting, they have proven difficult to detect (Thorp and Tian, 2004). In a review article, Thompson *et al.* (1991) found that even at early stages of growth, crop canopy presented multiple challenges for weed detection. Lack of spectral difference between weed and crop complicated differentiation and occlusion of weeds (crop blocked 60-90% of field area). Differing soil backgrounds and residue-covers hinder vegetation detection and have been ignored in most remote sensing-based detection studies (Thorp and Tian, 2004). Technological advances from color photography of the 1980's, to current digital technology and hyperspectral imaging have “begun to stimulate more thorough investigations into the nature of wavelength dependent light interaction in plants and plant canopies” (Thenkabail *et al.*, 2000, Thorp and Tian, 2004). Thorp and Tian (2004) note that few of the studies reviewed pertaining to remote sensing weeds in agriculture “extended their proposed weed detection techniques into the arena of variable-rate herbicide applications”. They suggest that since variable-rate herbicide application is the objective of weed detection activities, more studies should include variable-rate herbicide application. A step towards automatic and continuous weed sampling that included application of variable-rate herbicide is a technique published by Luschei *et al.*

(2001) and Van Wychen *et al.* (2002). Their technique used a weed scout driving an all-terrain vehicle (ATV) with a toggle switch flipped to indicate presence of weeds. The position of the switch and GPS position were logged as the scout moved through the field (Figure 2). In 1999, weeds were mapped in 4 fields in Montana that had varying degrees of wild oat infestation (29-93% infested). Weeds were mapped at the 2-6-leaf stage. Each transect or swath was 9.2m wide. Each field was subdivided into 12-14 replicates, which were split into broadcast and site-specific herbicide treatments. The site-specific herbicide treatment was applied based on a prescription map created in GIS from weed scout field data. Wild oat infestation in all fields was rated by a researcher in the cab of the harvesting combine and grouped into categories of none, low, medium, and high (0,0-10,10-50,50-100% weed cover). Data were analyzed using a paired t-test. The site-specific treatment did not influence wild oat control in two of the four fields. The estimated added cost of site specific application due to mapping technology, crop-consultant fee, and custom herbicide application was \$12.36 ha⁻¹. With this number they calculated a “break even targeted percentage” of 72%. This meant that unless 72% or less of the field was targeted by the site-specific treatment it would not be profitable. This threshold was further reduced to 56% for one of the 4 fields because of a negative effect on wheat yield caused by wild oat escapes and therefore site-specific treatment showed no advantage over broadcast spraying. Of the 3 remaining fields, one had a 95% targeted percentage and showed no advantage over broadcast, and

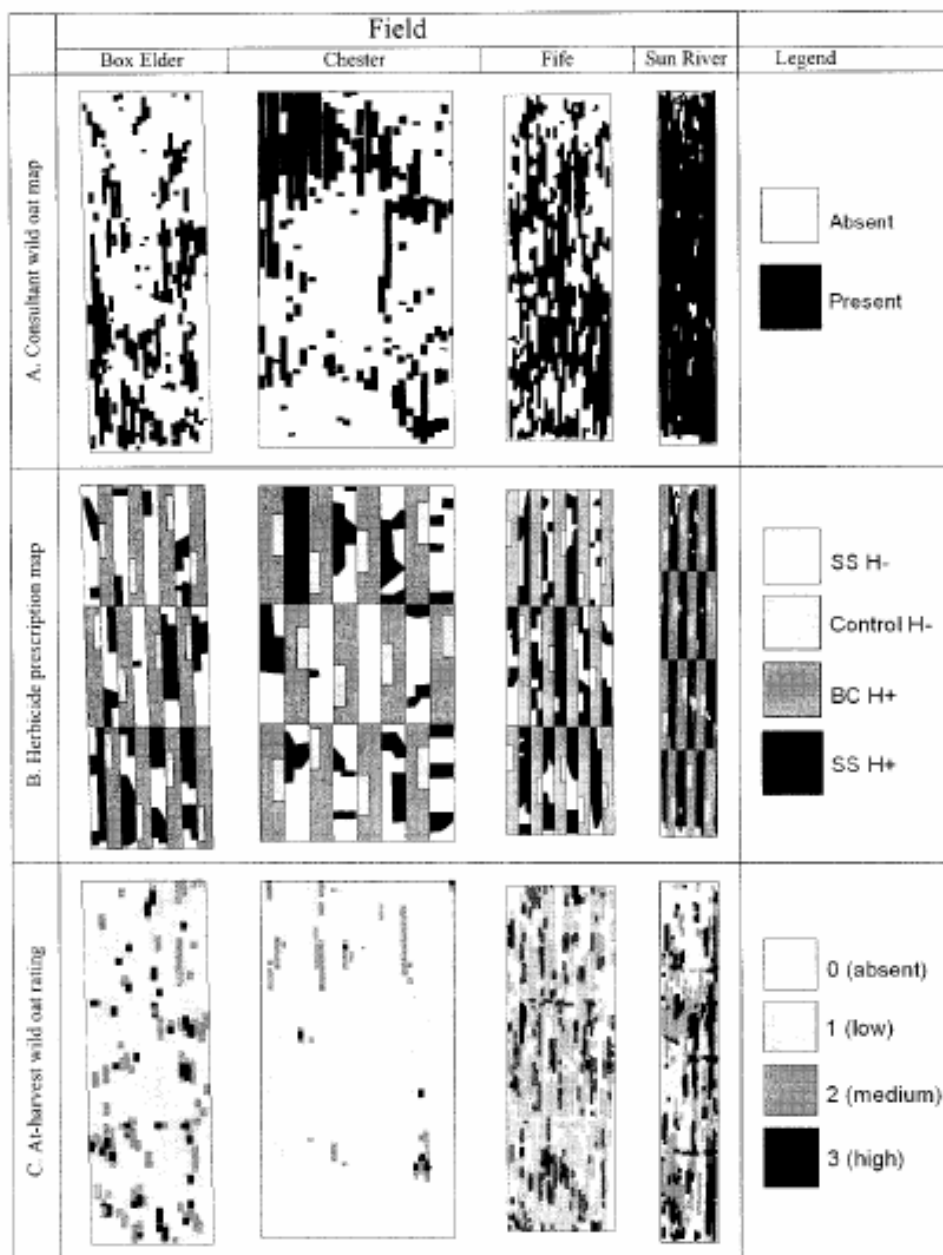


Figure 2. An example weed map (top), herbicide prescription map (middle), and weed rating (bottom) from Luschei *et al.* (2001). Weed map data was collected by logging GPS position and on/off position of switch controlled by a weed scout.

two fields had 46% and 40% targeted percentages respectively, returning \$14.21 ha⁻¹ and \$20.00 ha⁻¹.

The three techniques for weed map creation described (grid sampling, remote sensing-based detection, and georeferenced scout observation) have all focused on creating maps prior to herbicide application. Maps are created in advance and used as “target files” for identifying field area requiring treatment fall into the map-based site-specific herbicide application method described previously. Downey *et al.* (2004) described a georeferenced imaging technique that recorded continuous video of the ground and associated GPS coordinates based on GPS time and video time-stamp in a post-processing step. Video frames were segmented with software and frame cells were identified as containing the single weed species present, cotton plant, or both. This system did not treat identified weeds.

Sewell (2002) developed and evaluated a data acquisition system for evaluating spatial accuracy of “selective-type sprayers”. The system evaluated “selective-type sprayers” by mapping their activity and comparing it to georeferenced images of the fields that were mapped. A data-recording unit (DRU) logged analog data from an interface box that optically isolated the DRU from the spraying system. An external GPS unit supplied position information at a 1 Hz update rate. Each WeedSeeker input from the interface box was scanned 138 times per second and “percent on time” was calculated and recorded for each WeedSeeker every time the GPS position was updated. Activity was mapped for two “selective-type sprayers” at two speeds each. Hits, misses, and

false triggers were quantified for each system at each speed. A hit was defined by a valve open 100% of a second when the unit was over plants. A miss was defined by a valve open 0% of a second when the unit was over weeds. False triggers were defined by a valve open 100% of a second when the unit was over bare soil. Values of “percent on time” between 0% and 100% were discarded. The data acquisition system was successful at logging hits, misses, and false triggers.

The University of Tennessee Weed Mapping System (UTWMS), described previously, maps weeds based on the activity of a commercially available real-time sensor-based herbicide application system. A value, representing the percent of the integration period that a sensor/sprayer is firing, is recorded for each of 13 channels (sensor/sprayers) every time new GPS position information is available. The integration period is determined by the update rate of the GPS unit and is currently set at 1 second. This means that if the sprayer is traveling at 4mph, the UTWMS records the percent time each spray control valve was “on” over the previous 5.8 feet (1.78m) traveled. The width scanned by each channel is approximately 0.98 feet (0.3m). Moody *et al.* (2003) compared weed maps generated with the UTWMS to georeferenced photographs of the test field planted with a known foliage pattern. Weed maps were found to agree well with known foliage but because logging activity of a real-time sensor-based spraying system is a novel approach to weed map generation, methods do not exist for evaluating accuracy of this system.

Target-specific evaluation techniques

When comparing the WeedSeeker to another commercially available system, Felton *et al.* (2002) noted that the WeedSeeker's "modulated emissions in the R (red) and NIR (near-infrared) wavelengths are synchronized to the detection circuitry and can be isolated from sunlight energy" which allows it to work well in bright sun-light, shadows, or total darkness. This is an advantage over the other system that is dependent on sunlight. They also note that the field of view of the WeedSeeker is 300 by 7mm enabling identification of smaller weeds compared to the Detectspray system (Detectspray International Pty Ltd, Avalon, NSW) with a field of view of 600 by 200mm. This study however did not present any evaluation technique for assessing this type of system.

Biller (1998) described techniques used in both laboratory and field environments to evaluate "optoelectronic sensors" for weed detection. During laboratory testing, light, soil, and plants were simulated. For the purposes of this document, only field evaluation techniques will be described. One section of a commercial spray rig was outfitted with the system to be evaluated. This system consisted of 5 sensors and 5 nozzles and testing was conducted on conservation-tilled fields prior to crop emergence. Four 130m long test strips were used and 20 1m² plots were photographed prior to treatment. Plots were photographed again two weeks following herbicide application. Results on system accuracy were drawn from evaluation of these photographs combined with field inspections. In this study, 100% of weeds were considered "sprayed" because all weeds died. This evaluation technique is not valid for evaluating

accuracy of sensor/sprayer systems for use in weedmapping because results can be confounded by herbicide formulation and weeds species present. Evaluation of spraying systems for use in weedmapping must directly represent weed identification accuracy rather than spray accuracy.

Antuniassi *et al.* (2003) evaluated WeedSeeker sprayer accuracy over four different soil backgrounds, eight combinations of weeds, and four sensitivity level settings on the WeedSeeker. The four soil backgrounds used were: bare red soil, bare red soil with large soil aggregates, red soil with straw, and bare white sand soil. Three weed species were grown in a greenhouse until specific size was reached. Plants were then transplanted into field plots in groups of plants or individual plants to construct plots with certain species and certain leaf areas. All tests were conducted at 5km/h, spraying clean water, and WeedSeekers were not fitted with nozzles so that when the solenoids fired they left a distinct mark on the ground. "The performance of the system was measured by calculating the percentage of plants that were actually sprayed in each treatment". Total leaf area ranged from 1.5cm² to 39.68cm². The system detected 100% of weeds when leaf areas were larger than 9.92cm² and there was no difference between soil backgrounds when leaf area was greater than 5.32cm². Sensitivity level 1 was seen to cause false triggers by the system and sensitivity level 3 did not achieve 100% detection for smaller leaf areas. Quantifying hits, misses, and false triggers of the WeedSeeker unit is an important part of evaluating the systems accuracy for use in weed mapping. As

Antuniassi *et al.* (2003) have shown, the sensitivity setting on the WeedSeeker is a critical setting for maximizing hits and minimizing false triggers and misses.

A precision sprayer developed by Tian *et al.* (1999) used machine vision coupled with a “Weed Coverage Algorithm” and a “Discrete Wavelet Transform Algorithm” to make decisions for turning valves on and off to spray weeds. Their system differentiated imaged multiple crop rows. The initial distinction between weeds and background could be made based on intensity of pixels because a near-infrared filter was used. Additional algorithms were needed due to irregularity of weed shape and background texture. System response (on/off) and field images were recorded to assess system accuracy (Figure 3). More than 200 images were visually evaluated to verify accurate classification. While this system did not log positional information, the recording of both sensed area and system status (classification result) is a powerful error-checking tool. This system is similar to the evaluation technique used below for evaluating accuracy of WeedSeeker units as a part of the UTWMS.

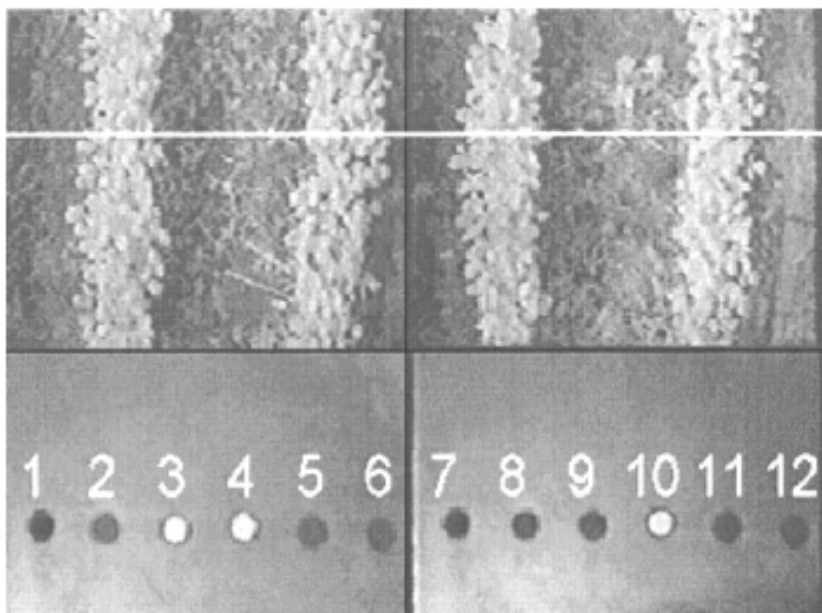


Figure 3. Figure from Tian et al. (1999) showing recorded field image with system status for nozzles 1 through 12.

Chapter 3 – Evaluation of weed-mapping system accuracy by ground-truthing and automated video analysis

Introduction

This chapter describes the evaluation techniques developed to quantify errors associated with real-time sensor-based weed mapping. The University of Tennessee Weed mapping System (UTWMS) maps weeds by recording activity of a commercially available real-time sensor-based spraying system. The sensor/sprayer units used by the UTWMS are WeedSeekers (Ntech Industries, Ukiah, CA). WeedSeekers were used during the development of these evaluation techniques but should only serve as an example of a real-time sensor-based spraying system. The techniques developed could be adapted to evaluate any non-imaging sensor/sprayer units that create maps based on discrete sensor activity.

Materials and Methods

The objective of the error evaluation was to evaluate identification accuracy of the sensor and not to evaluate treatment efficacy. Targeting analysis by mortality can be confounded by choice of herbicide formulation and weed species composition. For this reason, weed damage or mortality was not observed. A video documentation system was developed for recording the area

beneath the center hood of the Weedseeker sprayer used in the UTWMS. A custom software application was developed to scan each frame of video collected and detect plants within the scanned region of the image and indication of valve activity. Automating the process of classifying images into hits, misses, and false triggers was necessary due to the large number of observations needed to accurately quantify accuracy in large plots (8x30m).

Comparing weed maps to plots sampled by weed scientists was used to assess weed map accuracy. Foliar cover was quantified through analysis of digital images of plots sampled by weed scientists. Weed map repeatability was assessed by collecting weed map data twice in the same day.

The UTWMS developed by Moody *et al.* (2003) has been used as part of a multi-state collaborative initiative to identify methods for reduction of herbicides in row-crop systems. The test fields established in Lubbock, TX (described below) served as the field setting for this field validation of the UTWMS. Herbicide application methods were being compared using 24 8x30m plots in both cotton and corn crops. These plots provided an evenly distributed grid within which variability in weed distribution and density was expected as a result of treatments.

Test Site Description

A multi-state project was funded by the United States Department of Agriculture to evaluate the effectiveness of herbicide formulation and application

method on weed communities. The project established fields in Texas, Mississippi, and North Carolina where each received a randomized complete block design with four treatment replications. Each plot was 8 rows wide (~8m) and 30m in length. Treatments began in the spring of 2005 and included:

- 1) Untreated plots for assessment of weed population and density.
- 2) Cooperative extension recommendations for post-emergence non-residual and residual herbicides applied using a commercial broadcast sprayer. Residual herbicide was not used in the first year of the study to allow mapping of temporal and spatial distribution of the weed species.
- 3) Residual and non-residual herbicide recommendations made by HADSS (Herbicide Application Decision Support System) applied with a commercial broadcast sprayer. HADSS is a weed management decision support system developed at NC State University and requires weed species, size, and density data specific to each field. For this project, each field was represented by an average of 5 1m² plots.
- 4) HADSS herbicide recommendation for non-residual herbicide applied in the row middles using the UTWMS. Separate Over-The-Row (OTR) nozzles simultaneously applied a 15cm banded application of herbicide over the crop drill (area where seed is planted).
- 5) Herbicide application as described in treatment 4 with the addition of residual herbicide after the first year.

- 6) HADSS herbicide recommendation for non-residual herbicide applied in the row middles using the UTWMS. The UTWMS triggered an OTR nozzle to spray the crop drill if either WeedSeeker bordering the crop drill was firing.
- 7) Herbicide application as described in treatment 6 with the addition of residual herbicide after the first year.
- 8) Weed free plots maintained with commercial standard weed management systems supplemented by weekly hand weeding.

The WeedSeeker was used to apply treatments involving weed-specific application to the row middles. A summary of treatments is provided in Table 1.

Video Documentation System for Error Evaluation

Frames of the video were scanned for presence of weeds and a spray valve activity indicator by collecting video of the area being sensed/sprayed by

Table 1. Summary of Treatments

Summary of Treatments	
1) Untreated (control)	5) Same as 4 But With Residual Herbicide
2) Extension Recommendations Broadcast	6) Weed-Specific Row Middles, Or-triggered OTR
3) HADSS Recommendations Broadcast	7) Same as 6 But With Residual Herbicide
4) Weed-Specific Row Middles, Continuous OTR	8) Weed free plots

the Weedseeker along with an indication of valve activity (on or off),. This evaluation technique is similar to the machine-vision-controlled sprayer tested by Tian *et al.* (1999). Tian *et al.* recorded images of soil, weed, and crop with the addition of controller decision (valve activation). Where they were making decisions based on the image, and overlaying valve activity for error checking, this system will solely serve as error checking for a non-imaging sprayer.

A prototype documentation system was tested in Stoneville, MS (July 2006). The prototype system consisted of a high-resolution micro-miniature video camera (Toshiba, IK-M40A), a digital video recorder (SuperCircuits, MDVR-12), and a red LED mounted in the field of view of the camera. The LED was switched using a phototransistor mounted on the valve-cartridge-activity LED. This was the same technique used by Moody *et al.* (2003) in which a phototransistor potted in a milled plastic block was mounted on the outside of the WeedSeeker unit, covering the activity LED on the valve-cartridge (Figure 4). For the documentation system, when the valve-cartridge LED switched on, the LED in the field of view of the camera was switched on, powered by a supplemental battery (Figure 5).

Documentation of a spray event was triggered by the valve-cartridge LED illumination which turned on the LED in the field of view of the camera. This optical linkage and a supplemental battery power source electronically isolated the documentation system from the WeedSeeker system.



Figure 4. A photograph of a WeedSeeker valve cartridge and the phototransistor potted in a milled plastic block used to monitor the valve status.



Figure 5. Photograph illustrating the underside of a three WeedSeeker cluster mounted in a spray hood, video camera, LED, and supplemental lighting used during testing in Stoneville, MS (July 2006)

Preliminary evaluation

Several problems with the system were found when the prototype video documentation system was tested in Mississippi. The test was conducted during the last spray event for the season and cotton crop canopy was over 3 feet tall. The shadows cast on the hood by the canopy caused inconsistent lighting for video documentation. The sides and upper portion of the video image under the hood was very dark relative to areas closer to the rear opening of the hood. Artificial lighting was added under the hood in the form of 2 small halogen lights, but these were not sufficient to evenly illuminate the soil surface. A second problem encountered during initial testing was the LED mounted in the field of view of the camera as the nozzle activity indicator. Large weeds present in untreated plots at the end of the season frequently brushed the LED out of the field of view of the camera. In 2007, when the LED was replaced with a digital overlay in the video image, this was no longer an issue.

A red filter was tested in 2007 to aid plant discrimination. Because plants absorb light at red wavelengths, live plants on the soil surface should appear darker than background material. Ambient lighting beneath the hood was again insufficient to prevent shadowing and irregularity. When data was collected with no filter, early in the 2007 growing season, light levels were sufficient for video documentation. All images collected were sufficiently illuminated to allow automated video analysis.

Data was collected in Lubbock TX in June 2007. The LED in the field of view of the camera was replaced by digitally overlaying a block of pixels over the video when the valve-cartridge was active. The documentation system consisted of a high-resolution micro-miniature video camera (Toshiba, IK-M40A), a digital-overlay board (Intuitive Circuits, OSD-232), a Basic Stamp II microcontroller (Parallax), and a digital video recorder (SuperCircuits, MDVR-12). The camera had a 90-degree field of view and was mounted facing down beside the center WeedSeeker unit, between the sensing optics and the valve cartridge. The activity of the valve cartridge was monitored using the externally mounted phototransistor technique (Moody *et al.*, 2003). When the LED on the valve cartridge turned on, the basic stamp monitoring the state of the phototransistor sent an “ON” command to the digital-overlay board in the form of a serial string. The digital overlay board would then turn on a 10x20 block of white pixels in the upper left corner of the video image

Video was recorded on the digital video recorder at the fastest frame rate possible, approximately 20 frames per second with a resolution of 720x480 pixels. The file type was AVI and was compressed with a DIVX codec. Video files were decompressed prior to analysis using Open Video Converter software (DigitByte Studio, <http://www.008soft.com>). Individual video frames were analyzed with custom analysis software written in Visual Basic 6. Video overlay switching speed (from off to on) was confirmed in a laboratory test to ensure all valve activity was represented in the video images.

An infrared LED was modulated at the same rate as the LED's in the WeedSeeker (240Hz). This LED was aimed at the optical receiving lens simulating a weed and causing the WeedSeeker to fire. The period that the LED was kept on was reduced until the WeedSeeker was no longer firing in response to the on-time.

A field test was conducted in a field on the Knoxville Research and Education Center near Knoxville, TN to verify the video resolution was sufficient to detect plants as small as or smaller than the WeedSeeker could detect. Four species of weeds, three broadleaf species (sickle pod, prickly sida, and pitted morning glory) and one common grass species (broadleaf signal grass), were propagated in the greenhouse with the help of weed scientists from the University of Tennessee until they reached one true leaf. Single plants of each species were transplanted in one of two 12-foot strips at one-foot intervals and then pairs of each species were planted in the other strip for a total of 12 sampling locations per strip. The first strip was planted in soil that had been recently worked under conventional tillage practice and hand cleared of weeds. The second strip was also hand cleared of weeds prior to planting but had been maintained under no-till conditions. Fresh residue resulting from a recent corn harvest covered the soil surface. Two passes were made over each strip for two speed ranges: slow (1mph) and fast (4mph). A single WeedSeeker was mounted under a hood with the video documentation system collecting video. The WeedSeeker was set at the highest sensitivity setting to ensure it would have the greatest chance to detect the smallest weeds.

Video Analysis Software

Custom analysis software was created with Visual Basic 6 (Microsoft Corp.). A differentiation technique was developed for discriminating between plant and soil in video frames. Pixel color information for one row of pixels per video frame (1x720 pixels) was collected for approximately 10 video frames. Sampling transects were chosen so that each transect included both weed and bare soil (Figure 6). Intensity data for each pixel, from each transect, was broken into three component colors (Red, Green, and Blue) (Figure 7). After plotting this data, a relationship between the three component colors was observed. Different combinations and ratios of the component colors were tested to find a method for discriminating live plant from bare or residue covered soil. The ratio of Red minus Green over Green minus Blue provided a value that, when a threshold was applied, accurately identified pixels representing plant material in the image.

The region of each image (video frame) scanned for weeds was limited to the area sensed by the center WeedSeeker under the center hood (Channel 7 in Figure 8). Only the center WeedSeeker was monitored for valve-cartridge activity. The width of this region was defined by the width of the visible band of red light projected from the center WeedSeeker. The length of the region, or distance integrated by the software, was approximated using the speed of the sprayer during the spray event (4mph) and an estimated dynamic response time for the WeedSeeker (20ms).

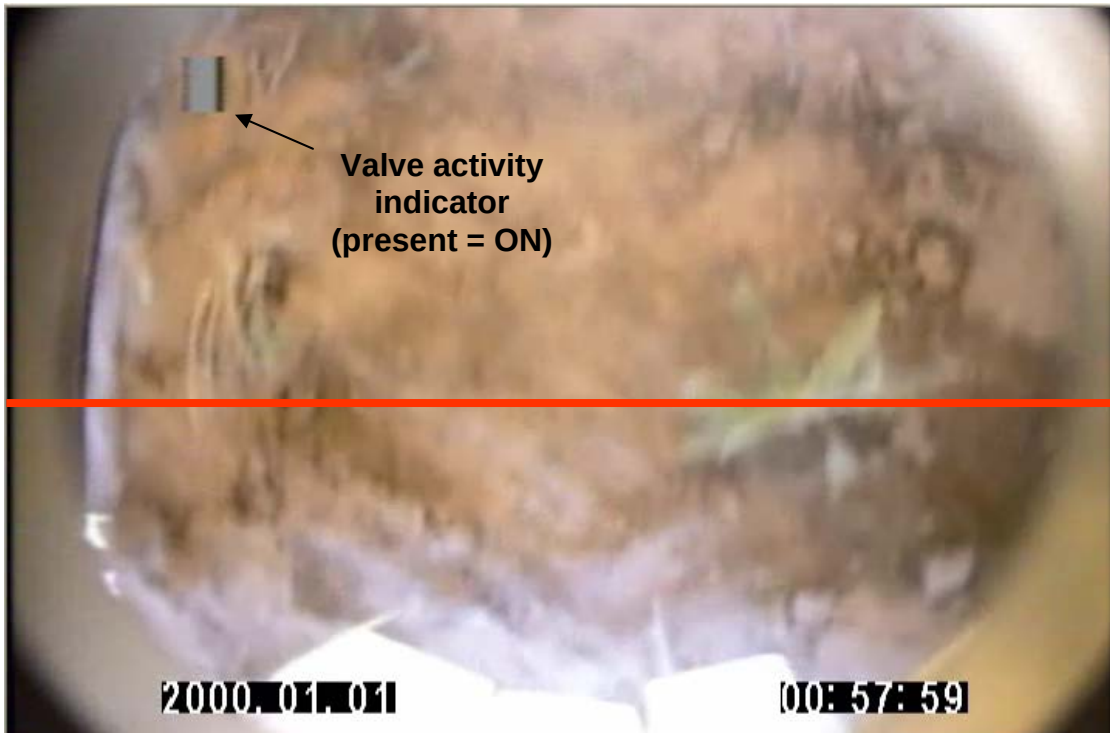


Figure 6. Example video frame with red line representing single-pixel transect of image including plant and bare soil. Valve activity indicator is present in the image indicating spray.

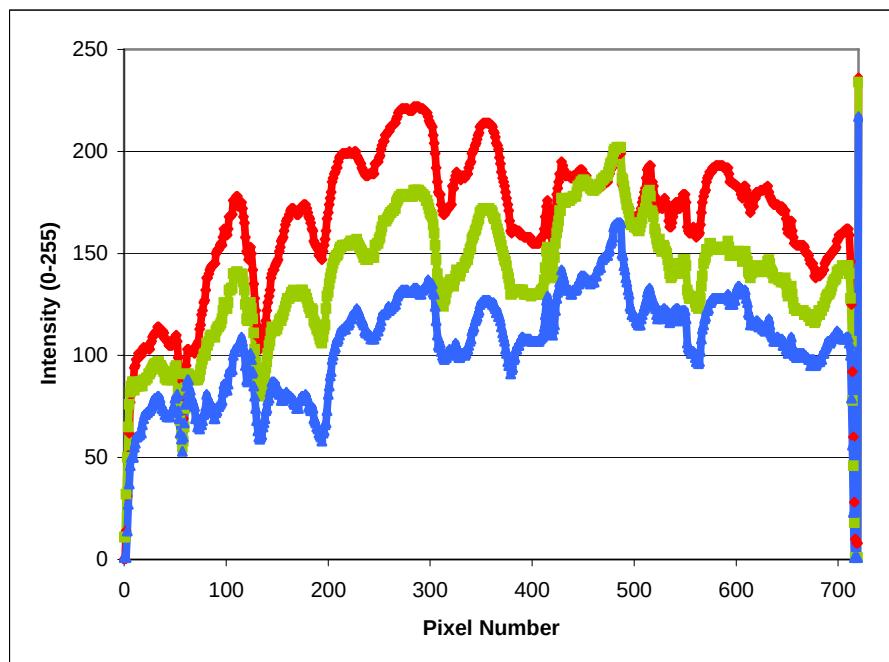


Figure 7. Plot of component colors (Red, Green, Blue) from a single-pixel transect



Figure 8. Typical deployment of WeedSeeker sprayers, under hoods in row crops, with three units under interior hoods and two units under exterior hoods.

The software also scanned each image for the presence of the activity pixels overlaid in the upper left hand corner of the image. For each image, the sensed portion of the image was scanned for green pixels and if the number of green pixels was greater than a noise threshold, a PlantPresent flag was set to one. If the activity pixels were present then the Spray flag was set to one. The appropriate counter variable was incremented based on the combination of PlantPresent flag and Spray flag (Figure 9). The software stepped through the video frame by frame and scanned each frame, counting hits, misses, and false triggers (Figure 10).

		Spray flag	
		1	0
PlantPresent flag	1	Hit	Miss
	0	FT	Hit

If a plant is detected in the “sensed” region of the image, the PlantPresent flag is set to 1 or else it is set to 0. If the activity pixels are detected in the image the Spray flag is set to 1 or else it is set to 0. Counter variables for Hit, Miss, and False Trigger (FT) are incremented based on the combination of PlantPresent and Spray flags.

Figure 9. Definition of Hit, Miss, and False Trigger used during video analysis.

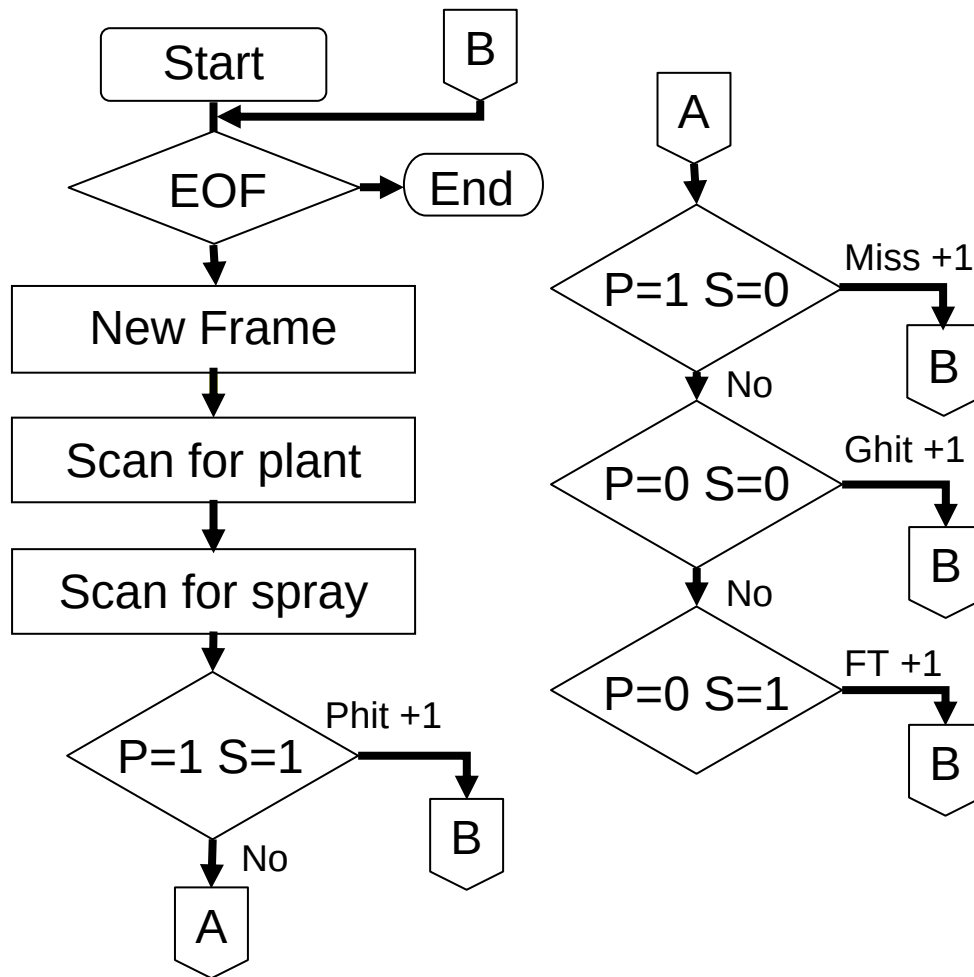


Figure 10. Flowchart for video frame scan software. Counters are incremented based on combination of PlantPresent (P) and Spray (S) flags. The program executes until the end-of-file (EOF).

Assessing map accuracy based on ground-truth plots

Map accuracy was evaluated using georeferenced data collected from the previously described weed-science experiment in Lubbock, TX. In June 2007, weed-scientists estimated weed density of ten common weed species for each experimental plot using four manually sampled subplots (1x1m). There were a total of 128 subplots in this experiment. Spatial location information was collected for the center of each subplot using a handheld Trimble GeoExplorer GPS receiver. The GPS unit was capable of sub-meter accuracy with the use of WAAS differential correction. Subplot position was the average of five readings taken five seconds apart. Weed maps were created with the UTWMS during spray events the following day (Figure 11). A camera-mounting frame was constructed out of aluminum to hold a digital-camera a fixed distance from the ground (1.06m) and delineate a fixed area (0.37m²). The frame was designed to be two feet square (60.8cm square), intentionally less than the 1x1m subplots used by the weed scientists. This reduction was made to better approximate the width within the full hood used with the WeedSeekers. Reducing the width of the frame also allowed it to sit flat on the ground between planting beds used in Texas for furrow irrigation. Prior to the spray event, this frame and camera was centered over each subplot and a picture was taken of the soil surface.

A software program was created to quantify percent foliar cover by weeds in each plot (Figure 12). The plant/soil discrimination technique for these still images was similar to the technique used for the video analysis but was simpler

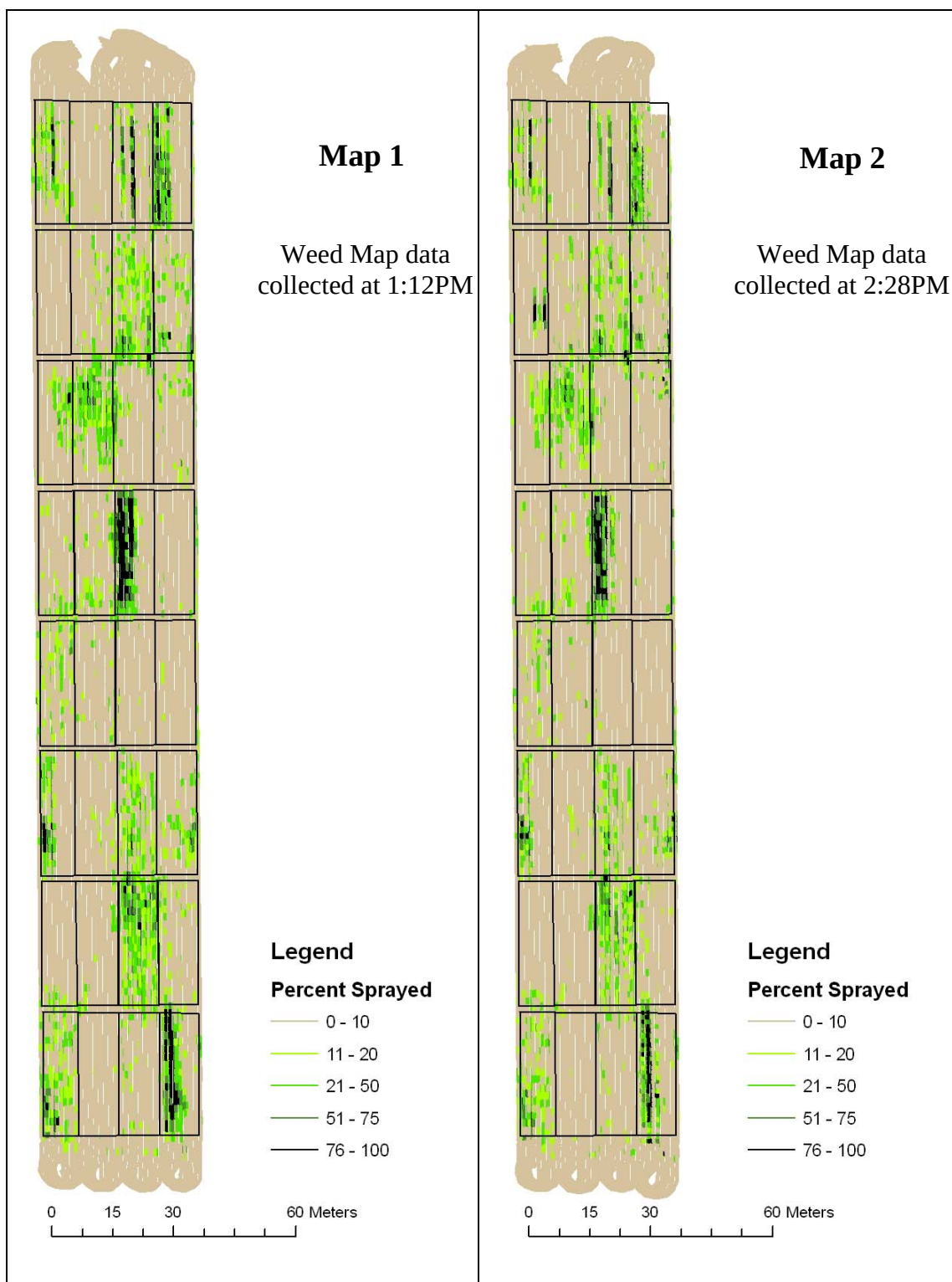


Figure 11. Two weed maps created from data collected in Lubbock, TX on the same day over the same field.

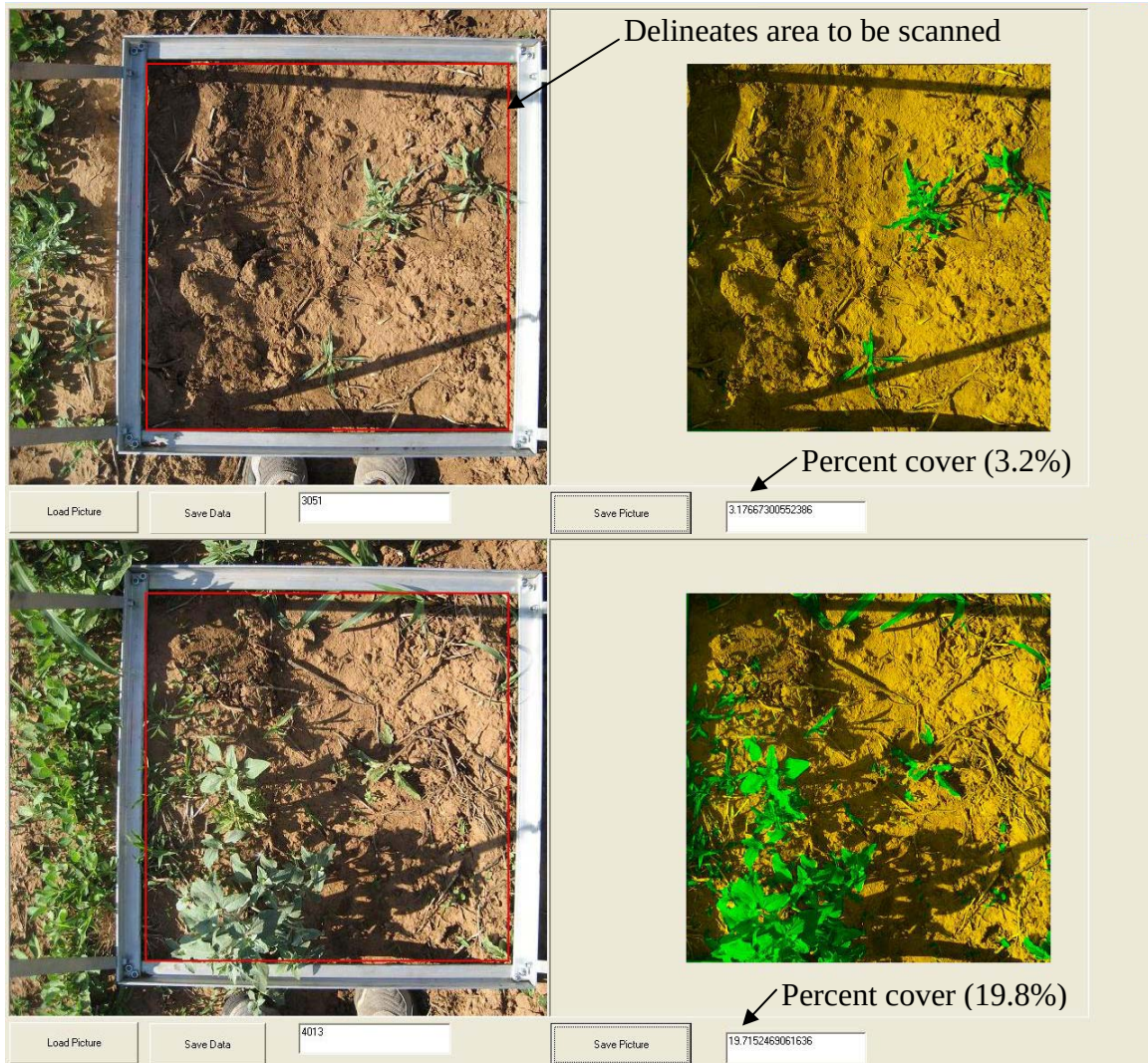


Figure 12. Two example screen-captures of the cover quantification program. On the left side of both images is the original picture taken in the field with a digital camera mounted on the photo frame. The right side of each image shows the processed images.

due to the high quality of the still images. An image was loaded into the right preview window of the software. The part of the image to be analyzed was delineated with the cursor by dragging a box around the area of interest. Image analysis was limited to the area within the camera-mounting frame for all images in this study. When the delineation box was released, the software scanned through each pixel in the image. Pixel intensity was split into the three component colors (Red, Green, and Blue). Blue was removed from the pixel and live plants were differentiated from soil background based on Red and Green intensities. If green was greater than red then the pixel was considered a plant, if red was greater than green then the pixel was considered soil background. This simple differentiation was only possible because of the high contrast between green plant and the red soil. After analysis, the portion of the image that was analyzed was redrawn in the right preview window for error checking. Doubling the original green intensity intensifies pixels identified as green. Every subplot image from this study was manually analyzed with this software (128 images) and checked for errors in identification. No identification errors were observed.

A custom tool was created in ArcMap (ESRI, Redlands, CA) to create subplot polygons of a user specified size. The subplots were oriented based on the direction of travel during data collection. Projecting coordinates for the corners of the subplots was achieved using the same method used for post-processing data from the UT weedmapper. In ArcMap, the weed-map map layer was spatially joined to the subplots map layer. This resulted in a new map layer

in which each subplot feature received an average percent time on of all weed-map observations that fell within it. Subplot layers were created for both 1x1m square subplots as well as rectangular subplots (3x1m) that were extended in the direction of travel of the sprayer to account for the 1.78m integration period. Both data sets were exported and Pearson correlation coefficients were generated with SAS (SAS Institute Inc.) to investigate the relationship between weed-map subplot-averages and true weed cover at subplot locations. Correlation between layers was also investigated for the average of the four weed cover subplots by plot and average percent sprayed by plot. Average percent sprayed was generated for a plot by dividing the number of observations within a plot with percent time on greater than 0 by the total number of observations for that plot.

A complete application of all herbicide treatments in Lubbock required multiple passes over the field on a single day. Two complete weed map data sets were created with the UTWMS during the June 2007 spray event. Full weed map layers were created with both data sets from the UTWMS (Figure 11). ArcMap was used to spatially join the observation points in map layer 1 (first data set created at 1:12PM CST) to the observation points in map layer 2 (second data set created at 2:28PM CST). By doing this, a single new point layer was created that contained all observation points from map layer 2 with an additional field containing the feature attributes of the closest point from map layer 1. A difference field was created by subtracting map layer 2's percent time on values from the closest points from map layer 1. Correlation between maps was also investigated using SAS.

Results and Discussion

Accuracy evaluation

There was no correlation between percent foliar cover from the photos and the average percent on time from weed maps at the subplot level. This is likely a resolution issue due to the one-second integration time of the UTWMS. The sprayer speed during application was four miles per hour. Four miles per hour is equal to 1.78 meters per second, which is almost twice the length of the subplots currently used in this experiment for quantifying weed characters. Even when a longer subplot is used to average observations from the UTWMS to account for this, there was no correlation ($r=0.05$). Visual inspection determined that spatially shifting data forward or backward along the direction vector would not improve this correlation. Average weed cover was moderately correlated with average percent time on at the plot level ($r=0.49$, $p<0.01$). Based on the current settings, the UTWMS does not have the resolution to accurately represent small research subplots. Cover measurements would need to come from subplots elongated in the direction of travel in order to compare with percent time on of the UTWMS.

Repeatability of maps based on the comparison of two maps created during the June treatment date was good. Seventy one percent of observations were within 5% absolute of the closest corresponding observation from the other map (Figure 13). The two maps were very closely correlated ($r=0.99$, $p<0.001$)

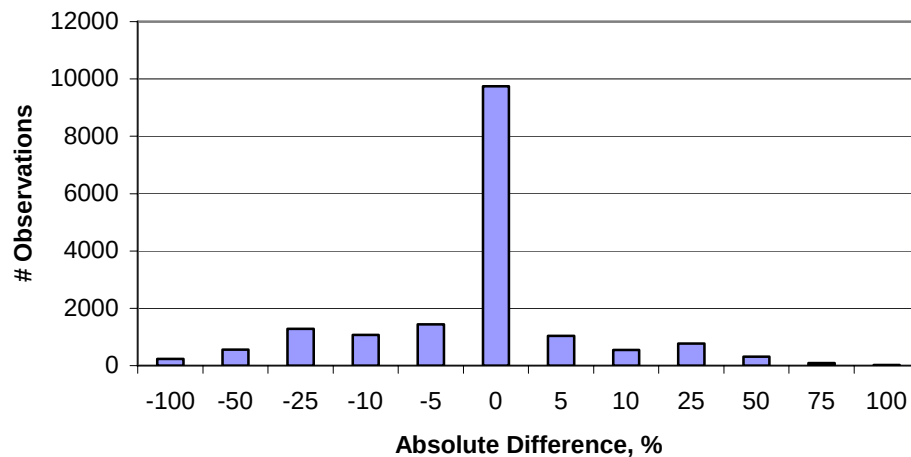


Figure 13. Frequency histogram of absolute difference between passes of the weed mapping system shows good repeatability.

when subplot areas were represented on each of the two weed maps and weed map data was averaged by subplot area, (Figure 14).

More than 100 video frames were visually verified for correct classification by the software. The software correctly classified all video frames that were randomly checked.

Results of the laboratory tests verified that in all cases the overlaid pixels were visible in the recorded video until the WeedSeeker stopped responding. Field test results for individual small plants over different soil background verified that the video resolution was high enough that small plants could be detected. Single blades of grass were difficult to see in all frames video at the fast speed (4mph). The WeedSeeker false triggered often during the test and did not appear to reliably detect the single blades of grass. This was consistent with the findings of Antuniassi *et al.* (2003).

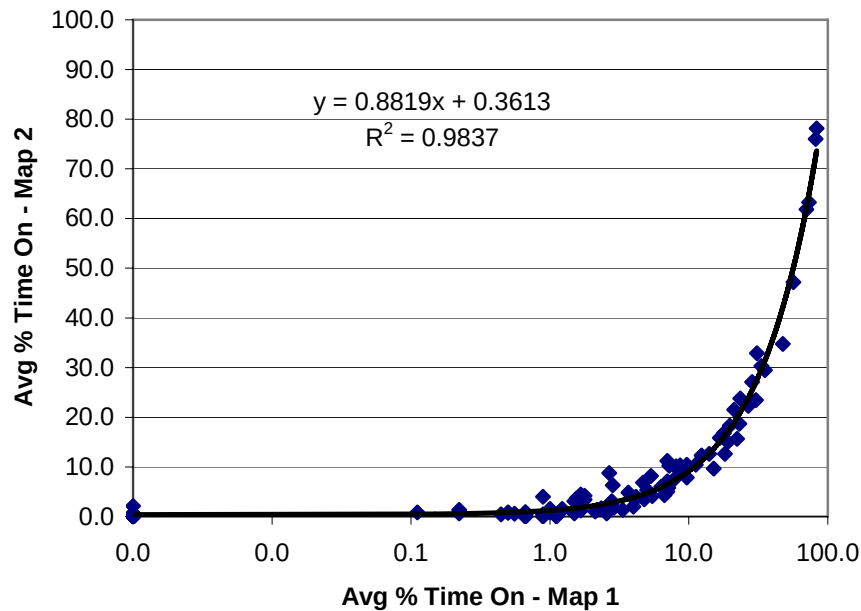


Figure 14. Relationship between Map 1 and Map 2 when sampled by subplots.

After decompressing the video from the test field in Lubbock, TX, there was a total of ~32GB of video (~30min). Video during turning maneuvers at the end of rows was removed prior to analysis. Upon completion, approximately 22,000 frames of video were scanned and classified as hit, miss, or false trigger. Eighty seven percent of frames were classified as hits (having been correctly identified by the WeedSeeker). When broken out into soil hits and plant hits, 84% of all video frames scanned were classified as soil hits and 3% were classified as plant hits (Figure 15). This higher percentage of soil hits was due to the generally weed-free conditions of plots in Lubbock. Because the miss percentage was approximately 5 times greater than false trigger percentage, the

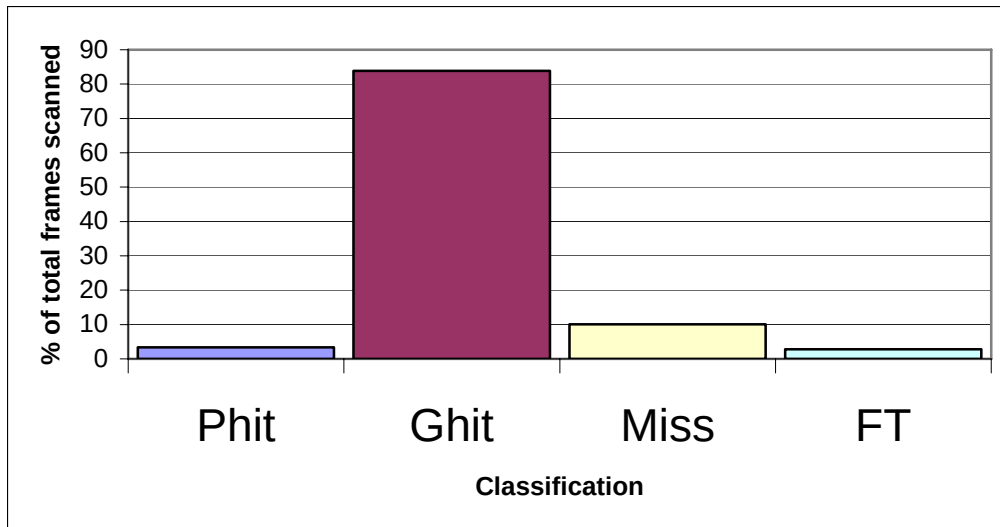


Figure 15. Histogram of percentage of total frames by classification. Phit = Plant hit, Ghit = Soil hit, FT = False trigger

sensitivity setting used by weed scientist on this project in Lubbock, TX, was likely set too low.

User inputs to the software did influence the outcome of these results. If the noise threshold was set too high, small plants detected by the WeedSeeker were missed and such frames were classified as “false trigger”. If the noise threshold was set too low, noise was detected as plant and frames were classified as “miss”. With the current version of the software, the noise threshold was best set by watching analysis take place and verifying only plants are detected as plants. The level could likely be set automatically if a calibration video were collected over bare soil so that noise levels could be detected and appropriate corrections applied. Another drawback to this initial version of the software is that different soil, residue, and lighting conditions will require a

discrimination relationship be developed for discriminating plant from soil. Again, a calibration video could possibly be used to set this relationship but this will require additional testing.

Chapter 4 – Automated weed distribution within sample interval

Introduction

Currently the data stored every second for each WeedSeeker in the UTWMS is “percent time on”. The abbreviation PTO will be used to represent “percent time on” during the remainder of this chapter. The PTO value represents the percent of the last one-second interval that the WeedSeeker valve was firing. For example, if a sprayer is moving through the field at four miles per hour, it traverses 1.78 meters of ground per second. A PTO value of 50% would indicate that during the last one-second period (over the last 1.78 meters of ground traveled) the WeedSeeker would have sprayed 0.89 meters of ground (one half of 1.78). Currently, weed maps are generated from this PTO data and associated GPS coordinates. Weed scientists have used these weed maps to verify that WeedSeeker units are functioning correctly by checking to see that each unit turns on and off where expected (Gilbert, 2006). Additionally, they have been used to coarsely identify weed patches and account for volume of herbicide applied. However, map interpretation into weed characteristics (species, density, functional type, growth stage, etc.) is limited by the lack of information on how the PTO is distributed across the distance traveled. For example, in the previous illustration of PTO, we don’t know if the 50% cover was one large patch or many smaller patches of weeds. Further research in correlating weed characteristics for weed map interpretation would be possible if information pertaining to the distribution of PTO were available. The objective of

the following work was to modify the current data logging software used by the UTWMS so that a count of spray transitions for each WeedSeeker is logged along with PTO.

Materials and Methods

Current software description

Moody et al. (2003) describes the current logging software in detail (Figure 16). In this software, a temporary storage buffer in the form of a one-dimensional array is used to count the number of scans in which valves were firing. Each WeedSeeker unit is represented by one element in the array. A scan of I/O ports polls the current status of each WeedSeeker and reports a bit value (1 = firing, 0 = not firing) for each. Each bit value is added to the corresponding element of the temporary storage buffer. This increments appropriate array elements where the valve was firing and does nothing to elements where the valve was not firing. When a new position message arrives, each element in the temporary storage buffer is divided by the total number of scans that have occurred since the last position message update. Data is then converted to storage form and put in the file buffer along with parsed position information. All elements in the temporary storage buffer are reset to zero, as is the total scan count variable, and scans begin again.

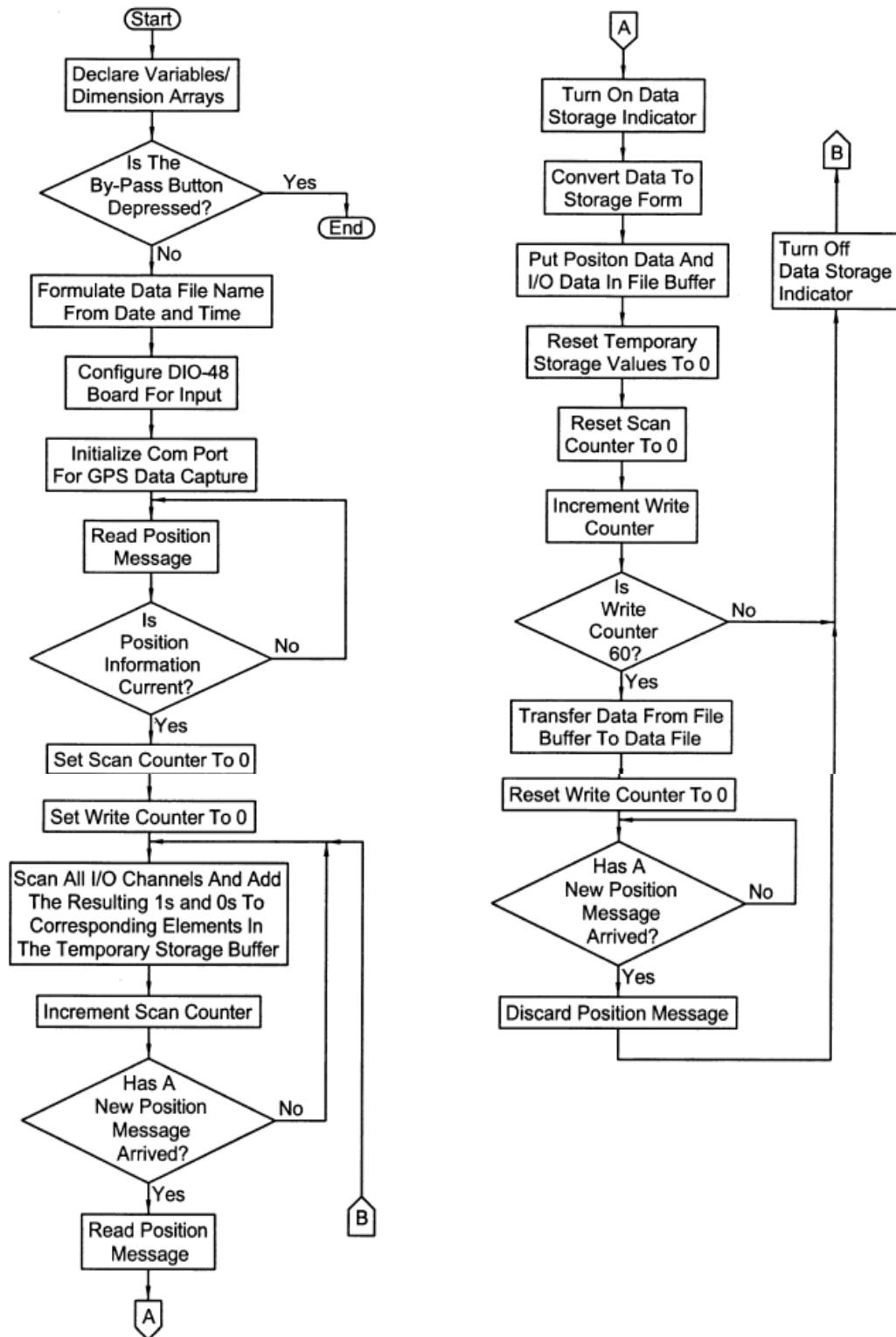


Figure 16. Flow chart of UTWMS logging software from Moody *et al.* (2003)

Amended software description

Logging spray transition is accomplished by using two temporary storage buffers in addition to the one used in the original logging software, a transition-count storage buffer, and a last-value storage buffer. Each of these arrays has a number of elements equal to the number of WeedSeeker units as in the original temporary storage buffer. Each of the new buffers is initially filled with zeros. During a scan, each status bit is compared to the corresponding element in the last-value buffer. If the status bit is greater than the value in the last-value buffer, then the corresponding element in the transition-count buffer is incremented by one. This means that if the last value was zero and the current value is one, then add one to the transition count for that WeedSeeker, otherwise do nothing and move to the next WeedSeeker. When a new position message arrives, the transition-count buffer is converted to storage form along with the temporary storage buffer. Data is written to the file buffer and all buffers are set to zero.

Testing the transition logging software

Laboratory tests were conducted on the UTWMS following installation of the new version of logging software. Transition count was tested by simulating the “WeedSeeker on” condition seen by the UTWMS. The “WeedSeeker on” condition appears to the UTWMS as a positive five-volt voltage potential on the digital I/O line. Zero is the “WeedSeeker off” condition. The UTWMS counts the rising edge of a signal as transition, meaning a transition from zero to one. A PC

running a GPS simulator supplied position information to the UTWMS at a rate of 1 Hz. Because there was a five-volt potential supplied at the connector of the UTWMS, simulating the “WeedSeeker on” condition simply meant connecting a five-volt supply to the digital I/O channel to be tested. A continuous five-volt supply at one of the digital I/O channels, starting before a position update and ending after the following position update, would be logged as zero transitions (Figure 17a). A continuous five-volt supply, starting before the first position update that is then switched to a continuous zero-volt supply held until after the next position update will also be logged as zero transitions (Figure 17b). Signals were also supplied to the UTWMS to simulate a single transition and three transitions (Figure 17c,d). This was verified for each channel of the digital I/O board that would typically receive data from a WeedSeeker.

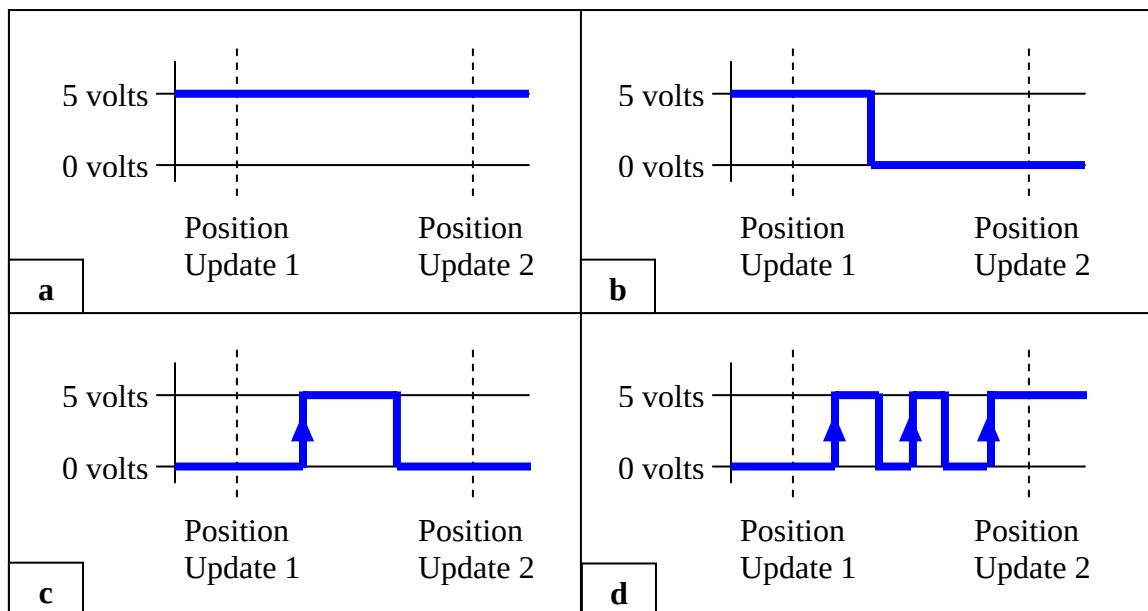


Figure 17. Four example signals sent to each channel on the digital I/O board of the UTWMS to test spray transition logging. Only the rising edge of a signal is counted as a transition: a) zero transitions, b) zero transitions, c) one transition, d) three transitions.

Example application of transition information

As an example investigation using transition information, weed density by species was compared for weed map points with similar PTO values. A high value for number of transitions was compared to a low value for number of transitions. The objective of this investigation was to determine if trends were present in the relationship between species density or community composition and number of transitions. Weed scientists will also have other biological information about weed communities that may be reflected in number of transitions, PTO, or a combination of both. This example will use a PTO range of 38-42% and transition values of one and six.

ArcMap was used to select points matching the above criteria from a weed map data set collected in the previously described weed science experiment in Texas (Figure 11). Points that fell outside the experimental plots were excluded. Subplot information was then spatially joined to the selected points; resulting in each selected point receiving the subplot number it was closest to. There were a total of 29 points selected and the average distance the observations were from the subplots was approximately four meters. The maximum distance was approximately 6 meters. The 29 points received information from 19 subplots with some points receiving the same subplot information. The maximum number of points to receive the same subplot information was two, and in all cases, both points had the same number of transitions.

Results and Discussion

Modifications to the UTWMS logging software were successfully made to incorporate a count of spray transitions (off to on). Effects on the overall performance of the UTWMS were minor. Due to the increased processing time incurred by adding code to the program, the scan rate (scans/second/WeedSeeker) was reduced from approximately 330 to approximately 300. All tests performed on all channels of the UTWMS were 100% successful.

Following field-data collection, PTO was plotted against number of transitions (Figure 18). The reverse heteroschedasticity seen in the plot is expected as a result of the dynamic response time of the WeedSeeker. As PTO approaches its outer limits (0 or 100%), the dynamic response time of the WeedSeeker would have to approach zero to maintain a constant number of spray transitions. Because the minimum dynamic response time of the WeedSeeker is fixed, number of transitions will be limited at the outer limits of PTO.

A point to note in Figure 18 is that there are PTO values other than 0 and 100% with zero spray transitions. With zero spray transitions, it is impossible to obtain PTO values of anything but 0 or 100%. The reason for this is that only the rising edge of the signal is recorded as a transition (Figure 17b). If a valve is firing when a sampling interval begins, and stops firing before the sampling interval ends, a spray transition value of greater than 0% will be recorded. Due

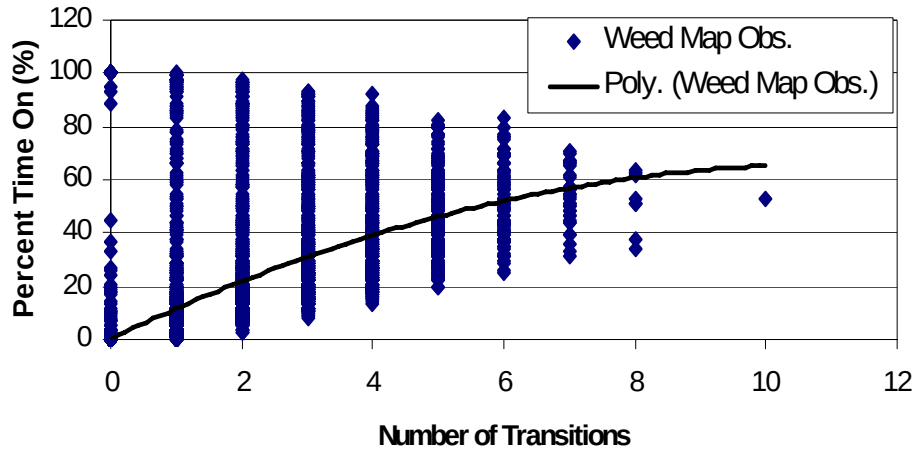


Figure 18. A plot of “Percent Time On” and Number of Transitions from a weed map data set. There are 13263 observations in this plot and many are overlapping. Values on X-axis represent a range rather than a number of transitions. For example, six transitions on the X-axis represents six or seven transitions, two represents two or three.

to this fact, spray transition count will have a potential uncertainty of +1 spray transition.

Example application results

When density data from the subplots was examined, only nine of the ten species counted appeared in the subplots selected for this test. Of the 19 subplots selected, nine were joined to points with one transition and six were joined to points with six transitions. The remaining four points were discarded because the closest subplot was missing its density data. Total plant density was calculated for each subplot. The percent each species contributed to that total density was then calculated by dividing the density for a species by the total density (Table 2). A plot of the average percent contribution by number of

transition value is represented in Figure 19. There is no apparent trend that would suggest that any one of these species is the cause for the difference in number of transitions at this same PTO. Experts in the biological aspect of this study would do true analysis and interpretation of this type of data. As previously noted, weed scientists will have more information about these plots and about these weed species that would allow them to group these species by other characters such as functional type, size, growth stage, maturity, etc.

Table 2. Percent contribution of each species to the total density in a plot.

Number Transitions	Total Density From Subplot	Lovegrass	Pigweed	Silverleaf	Devilsclaw	Sunflower	Johnsongrass	Blueweed	Bindweed	Venice Mallow	Nutsedge
1	65	92.3	7.69	0	0	0	0	0	0	0	0
1	7	0	0	0	0	0	100	0	0	0	0
1	53	56.6	22.6	0	3.77	0	15.1	0	0	1.89	0
1	81	12.3	9.88	1.23	0	2.47	74.1	0	0	0	0
1	21	57.1	9.52	4.76	0	0	0	0	4.76	23.8	0
1	14	0	0	35.7	0	0	64.3	0	0	0	0
1	12	0	0	8.33	0	0	0	91.7	0	0	0
1	28	0	0	0	0	0	10.7	53.6	0	35.7	0
1	12	0	8.33	0	0	0	0	0	0	91.7	0
6	6	0	0	50	33.3	0	0	16.7	0	0	0
6	14	0	0	0	0	0	0	100	0	0	0
6	14	0	71.4	14.3	0	0	0	0	0	14.3	0
6	30	0	0	0	0	0	66.7	0	0	33.3	0
6	46	0	0	2.17	0	0	0	0	0	97.8	0
6	240	83.3	0	2.92	0	2.5	2.92	0	0	8.33	0

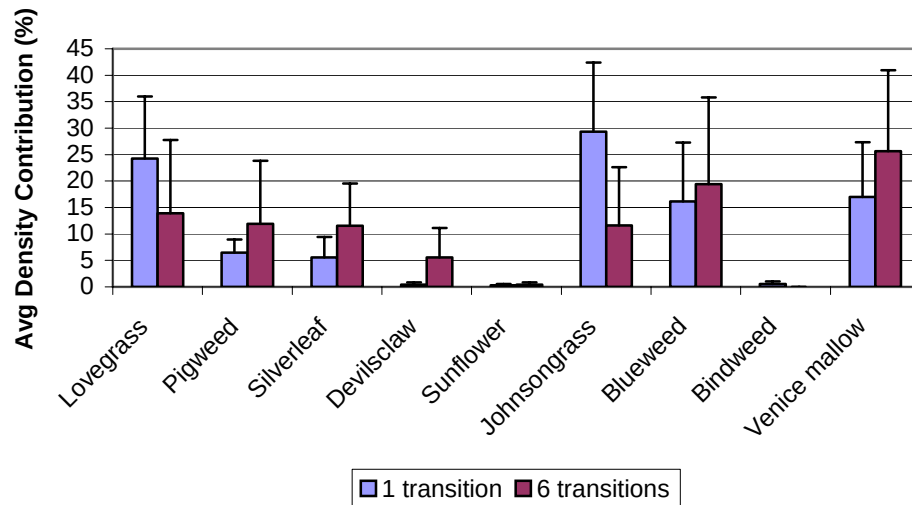


Figure 19. A plot of average percent contribution by number of transitions for each of the species.

Chapter 5 – Sensing optimization simulation

Introduction

The accuracy and reliability of spatial information has greatly improved as field-positioning systems for precision agriculture have moved from hand-drawn maps, to dead-reckoning, to GPS, and on to DGPS and RTK-GPS. With accurate positioning systems available, a significant body of research on the existence and impact of the spatial correlation of weeds developed. As spatial correlation, or patchiness of weeds, was demonstrated (Zanin *et al.*, 1998, Tian *et al.*, 1999, Rew and Cousens, 2000, Lamb and Brown, 2001), research was being conducted on automated patch spraying technologies to exploit this patchiness for herbicide use reduction. As previously stated, the economic savings of patch spraying is dependent on the patchiness of weeds in a field. The cost can be attributed to the time and technology necessary to identify and treat weed patches (Oriade *et al.*, 1996). Identification and treatment costs can be reduced with a reduction in sampling resolution but with this comes a reduction in accuracy (Clay *et al.*, 1999).

The objective of this study was to investigate the impact of reduced sampling using a WeedSeeker sensor/sprayer system on spray accuracy. A modified version of the UTWMS was used to record activity of three WeedSeekers underneath a single hood of the system. The logging software of the UTWMS was modified to log discrete activity information rather than the typical integrated value for each WeedSeeker. Using true sprayer activity data

collected from a test field, a simulation program replaced the center WeedSeeker with a conditionally triggered solenoid valve. The predicted activity of the center valve was compared to the true sensed activity of the center WeedSeeker.

Materials and Methods

To conduct a simulation of replacing a sensor with a conditionally triggered solenoid valve, as described above, data from WeedSeekers running in field conditions was needed. The previously described herbicide-application field-experiment in Lubbock, TX provided a field site at which multiple weed densities and distributions were expected as a result of treatments. The 2007 growing season was the third year of differential treatment of plots that included a combination of different herbicide formulations and application methods. It is expected that the final year of treatment would have the most pronounced treatment response by plot and therefore the greatest difference in weed distribution. Field data was collected in August of 2007 from the experimental plots in Lubbock, TX. Two passes were made through each plot with the center of the tractor on the row middles between crop rows 2 and 3 and rows 6 and 7.

The logging software in the UTWMS was modified from its original version described in Chapter 3 (Figure 16). The modified logging software wrote discrete valve status information (1 = firing, 0 = not firing) to the log file without integration. The update rate on the GPS unit was maintained at the standard 1Hz rate and position information was written to the file as it became available.

The resulting data file consisted of a repetition of GPS position string (latitude and longitude only) and between 225 and 275 lines representing scans of valve status (i.e. 3.6-4.4ms/scan). This scan rate was approximately five times faster than the response time of the WeedSeeker valve. A scan of valve status was a row of thirteen 0's and 1's representing the activity of the thirteen valves in the UTWMS.

A sequence of short software programs, mostly custom and written in Visual Basic 6 (Microsoft Corp.), was used to post-process the raw data files logged on the UTWMS. Position information was repeatedly assigned to each row of activity-scan information until a new position was available. This resulted in groups of 225-275 lines, each with the same position information. Discrete position information was calculated for each line in a group. It was assumed that there was no deviation in course or speed over the 1-second duration between position information updates.

Data were plotted in ArcMap (ESRI, Redlands, CA) along with a layer containing experimental-plot boundary information. The boundary information was used to remove data logged outside of the plot boundaries while the tractor was stopped or in transport between plots. Plot information (including plot number, block number, and treatment code) was then spatially joined to the point data file. Prior to export, the data were sorted by plot number to group all data by plot.

The program illustrated in Figure 20 was used to simulate the replacement of the center WeedSeeker from a group of three under a hood with a conditionally triggered solenoid valve. Data from the three center WeedSeekers was used for this study (Channels 6, 7, and 8 from Figure 8 in Chapter 2). WeedSeekers at channels 6, 7, and 8 will be referred to as left, center, and right respectively.

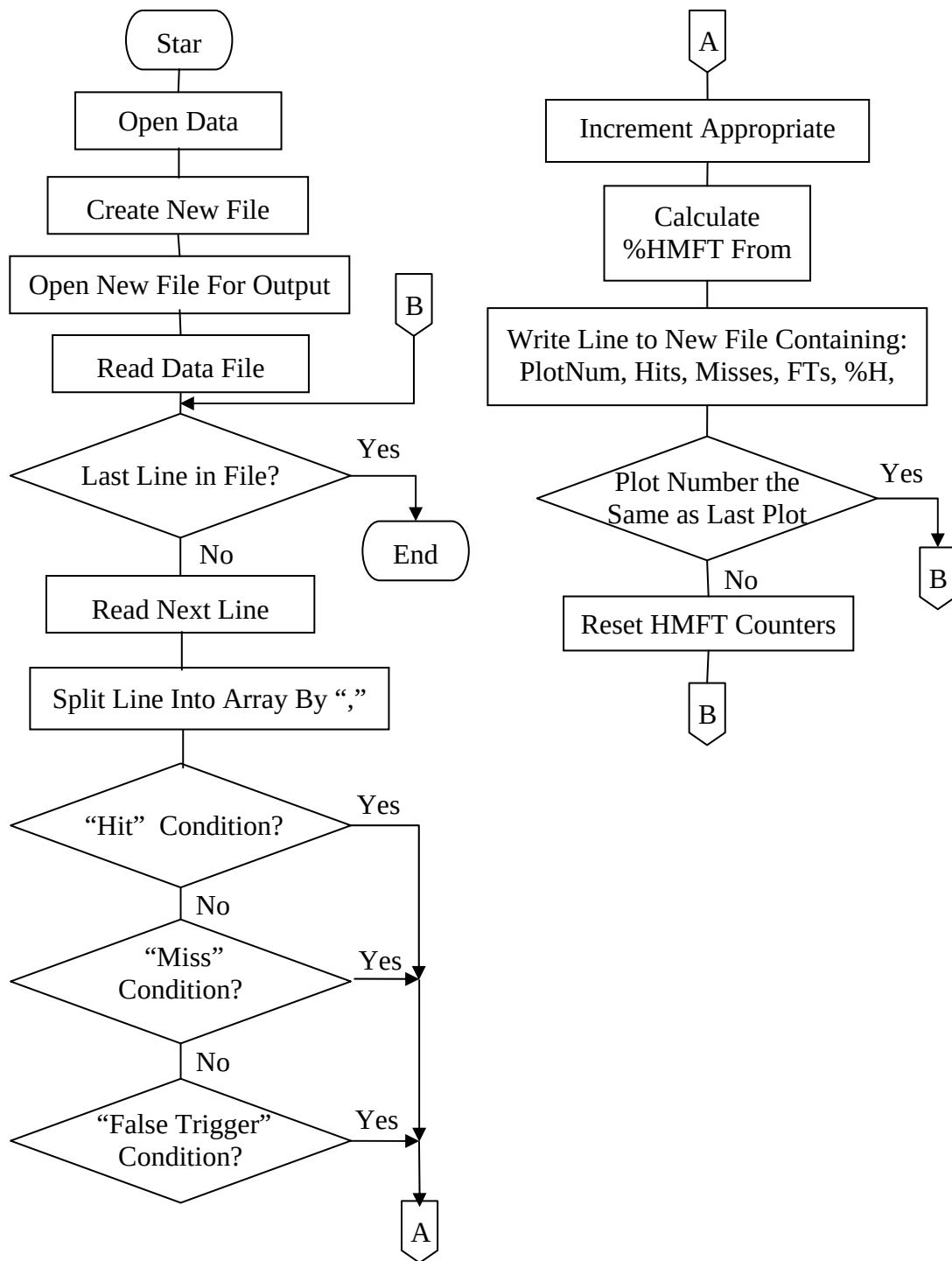


Figure 20. Flowchart of post-processing software for simulation data.

These three WeedSeekers were under the same spray hood and would have targeted portions of the same row-middle. In separate tests, the following conditions were tested for triggering the center WeedSeeker:

- 1) Left = Firing (1) OR Right = Firing (1)
- 2) Left = Firing (1) AND Right = Firing (1)
- 3) Left = Firing (1)
- 4) Right = Firing (1)

The OR condition (1) will be used to describe the analysis method. The data file, now containing coordinates for each scan and plot information, was read in line at a time. For each scan entry, if left = 1 OR right = 1 then a variable representing the center WeedSeeker (Predicted) was set to 1. If neither channel were equal to 1 then Predicted would be set to 0. The data in Predicted was compared with the actual data in the file for the center nozzle (Measured) and the simulated spray event was categorized as a Hit, Miss, or False Trigger (HMFT) based on Table 3.

In addition to reporting a string classification of HMFT, the appropriate counter for Hits, Misses, and False Triggers was incremented by 1. For each

Table 3. Categorization for Hit, Miss, and False Trigger

Predicted (center)	Measured (center)	HMFT
1	1	Hit
0	0	Hit
0	1	Miss
1	0	False Trigger

scan entry of the incoming data file, an entry was made in a new file that contained the plot number, true data for right, center, and left, the HMFT string code, and the current values for the Hit, Miss, and False Trigger counters. Calculations for percent Hit, Miss, and False Triggers based on the current totals was also included in the results string. Hit, Miss, and False Trigger counters were reset each time the program reached a line where the plot number was different from the previous plot number. By doing this, the last entry for any particular plot number represented the performance for that plot. The last line for each plot was extracted and a summary file was created that gave condition-triggered performance by plot. The use of a sequence of small programs for processing and analyzing the original discreet data file allowed for intensive error checking between steps in the procedure.

Prior to data collection with the modified logging software, weed map data was collected for the field using the standard logging software and a weed map was created. ArcMap was used to calculate the percentage of total points in a plot (~445) that had a “percent time on” greater than zero, creating a contrast map. This map represented percentage of the plot that required some amount of treatment for weeds and will be referred to as “plot weed cover”. Plot weed cover will overstate true weed foliar cover because any value of “percent time on” greater than zero will be classified as “cover” and all zero values will be classified as “no cover”. Weed-map points were also used for assessing spatial correlation of weeds in the plots. Weed-map points were chosen because they are evenly distributed across all plots after post-processing. ArcMap was used to create

individual semivariograms for data in each plot. The three key attributes describing a semivariogram, the nugget, sill, and range, were recorded for each plot. Data was analyzed using a mixed model analysis of variance in SAS. The experimental model used in the analysis was a randomized complete block design.

Results and Discussion

Description of plot differences

Based on weed-map data, treatment six (weed-specific row middles with OR-triggered OTR) had the maximum weed coverage (46%). Treatment eight (weed-free plots) had the minimum weed coverage (7%). Treatments will be represented only as a numerical treatment code in this manuscript because response to specific treatment is not the focus of this study. Here the objective is to describe differences in weed cover by treatment. Significant differences were found in average weed cover by plot following a mixed model analysis of variance ($P < 0.001$). Letter groupings for the mean-separation test (LSD, $\alpha = 0.05$) are illustrated in Figure 21 and Figure 22. Average weed cover was approximately four times higher in treatments one, four, and six than in two, three, and eight. Treatments five and seven fell in between. The relative relationships were the same for PTO, but treatment one was around ten times greater than treatments two, three, five and eight, with treatments four, six, and

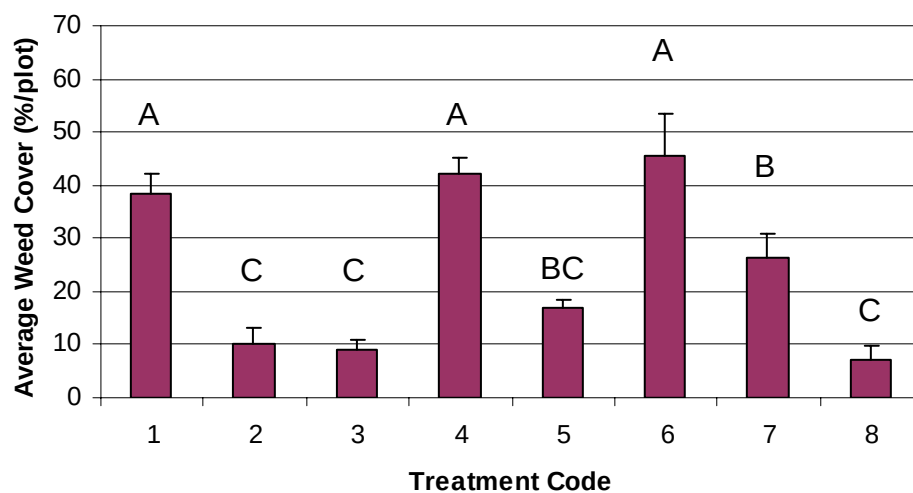


Figure 21. Average percent weed coverage by weed treatment protocol.

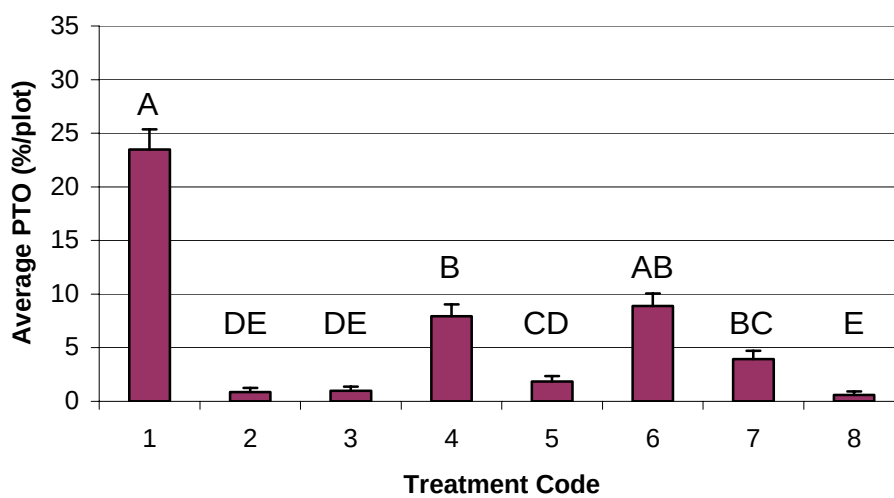


Figure 22. Average Percent Time On by weed treatment protocol.

seven falling in between. Average weed cover will be overestimated due to the classification of any weed map data point with a “percent time on” greater than zero as full weed cover. This is true because an area with a three percent PTO value will be classified as full weed cover the same as an area with 100% weed cover.

Semivariogram analysis results

Range was the semivariogram characteristic of interest, because the range value is the distance at which two points are no longer spatially correlated. Range did not differ by treatment ($P=0.1057$). Even if “marginal” significance is considered at an alpha value of 0.1, the LSD mean separation test ($\alpha = 0.05$) only revealed that treatment one (control) differed from treatment eight (weed free plots), which was on the opposite end of the distribution. Range values for semivariograms with partial sills (sill – nugget) equal to zero were excluded from correlation analysis. Six plots were excluded for this reason. Range did not correlate with treatment ($r = 0.34$, $P = 0.09$). Range also did not correlate with percent hit, percent miss, or percent false trigger at any of the four conditional trigger scenarios.

Simulation results

Percent hit, percent miss, and percent false trigger were all significantly different by trigger scenario ($P<0.01$). The AND condition had the highest

percent hits (91.5%) and miss (7.5%) and the OR condition had the lowest percent hits (85.1%) and miss (2.9%). With percent false triggers, AND had the lowest (1%) and OR had the highest (12%) (Figure 23). These results followed logical expectations. The AND condition, as the most conservative (requiring both neighboring valves to fire), had the most misses but the least false triggers. The OR condition, firing any time either neighbor fired, missed the least and had the most false triggers. The Left Only and Right Only conditions fell in between, still triggering the valve to hit 85-90% of the time. This would suggest that, even though spatial correlation did not show up during the semivariogram analysis, weeds in this field are spatially correlated over very short distances.

An analysis of variance was conducted for each conditional scenario to determine whether percent hit, percent miss, and percent false trigger differed by experimental treatment. For every conditional scenario, there were significant differences by treatment for percent hit and percent miss ($P < 0.02$). Percent false trigger only differed by treatment for the Right Only condition ($P = 0.01$). Percent hits for all conditional scenarios were greater than 75% in all treatments (Table 4). Percent hit, percent miss, and percent false trigger data were analyzed for correlation with average PTO and average weed cover by plot. If they were generated with the OR condition, they were not correlated with average PTO but were each correlated with average weed cover by plot (). Under the AND condition (

Table 5), all three results (percent hit, percent miss, and percent false trigger) were correlated with both measures of weed cover. When single

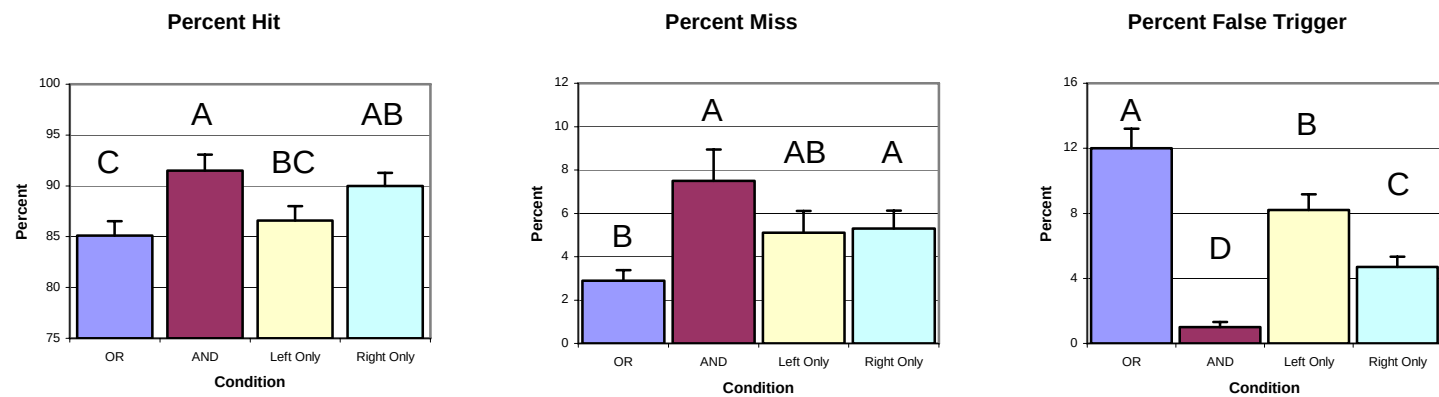


Figure 23. Plots of differences in percent hit, percent miss, and percent false trigger by conditional logic scenario.

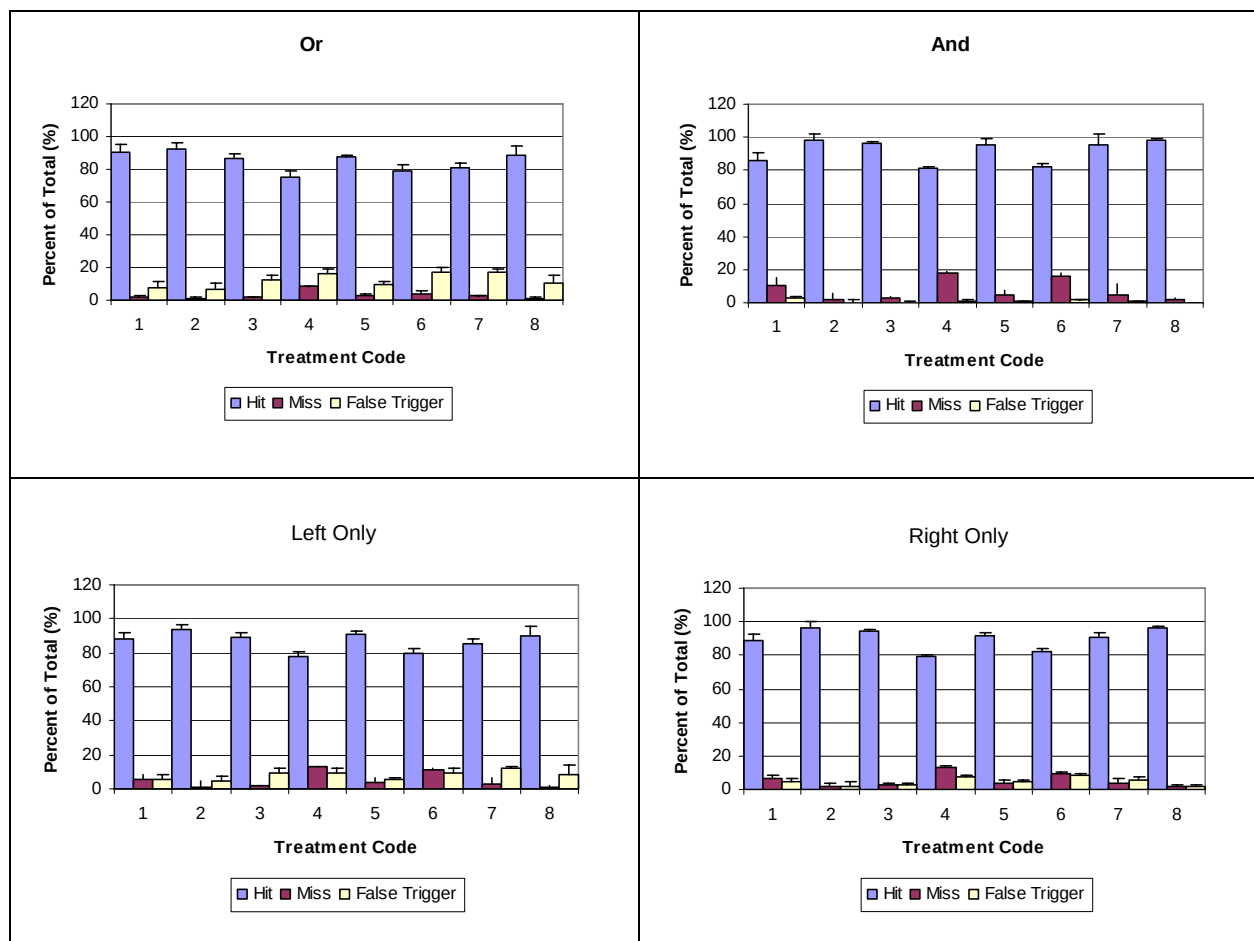


Figure 24. Percent hit, miss, and false trigger by treatment

Table 4. Correlation results for Percent Hit, Percent Miss, and Percent False Trigger with Average PTO and Average Weed Cover for the OR condition

Pearson Correlation (r/P)	Average PTO	Average Weed Cover
Percent Hit	-0.07 0.6890	-0.51 0.0028
Percent Miss	0.15 0.4177	0.58 0.0005
Percent False Trigger	0.03 0.8821	0.37 0.0352

Table 5. Correlation results for Percent Hit, Percent Miss, and Percent False Trigger with Average PTO and Average Weed Cover for the AND condition

Pearson Correlation (r/P)	Average PTO	Average Weed Cover
Percent Hit	-0.76 <0.0001	-0.86 <0.0001
Percent Miss	0.69 <0.0001	0.82 <0.0001
Percent False Trigger	0.65 <0.0001	0.57 0.0007

WeedSeekers on the Left Only (Table 6) and Right Only (

Table 7) were used to trigger the solenoid valve, percent hit and percent miss were correlated with both average PTO and Average Weed Cover but false trigger was not correlated with either average PTO or Average Weed Cover. In all cases, percent hit was inversely proportional to average weed cover by plot. As the average weed cover in a plot increased, the percent hits decreased. Such a trend would suggest that as weed cover increased, weed distribution became less spatially correlated. This is supported by the fact that percent misses and false triggers were positively correlated with weed cover. However, it may only suggest that as weed cover increases, patch size is increasing, and in the case of this study, has increased beyond the limited scale of measure.

Table 6. Correlation results for Percent Hit, Percent Miss, and Percent False Trigger with Average PTO and Average Weed Cover for the Left Only condition.

Pearson Correlation (r/P)	Average PTO	Average Weed Cover
Percent Hit	-0.43 0.0152	-0.70 <0.0001
Percent Miss	0.56 0.0009	0.76 <0.0001
Percent False Trigger	0.025 0.8907	0.20 0.2726

Table 7. Correlation results for Percent Hit, Percent Miss, and Percent False Trigger with Average PTO and Average Weed Cover for the Right Only condition.

Pearson Correlation (r/P)	Average PTO	Average Weed Cover
Percent Hit	-0.55 0.0010	-0.88 <0.0001
Percent Miss	0.59 0.0004	0.82 <0.0001
Percent False Trigger	0.49 0.0041	0.68 <0.0001

Chapter 6 – Summary and Recommendations

Summary

The overarching objective of this study was to field validate an automated weed mapping system. The University of Tennessee Weed Mapping System (UTWMS) combines an array of thirteen WeedSeeker units with a Digital Event Recorder (DER). WeedSeeker units are an example of a sensor-controlled solenoid valve that uses spectral reflectance to differentiate between plant and bare ground, spraying only plants. The DER records the activity of each solenoid valve in the WeedSeeker array by optically monitoring the status (on/off) of an LED on the valve cartridge. The sampling period for the DER is set by the position update rate of the externally attached GPS unit. At the end of each sampling period, the Percent Time On (PTO) during that period is logged for each WeedSeeker unit with GPS position information of the sprayer. Weed maps are generated following post-processing of the data from the DER.

Spatial accuracy of these weed maps was evaluated using 128 subplots sampled by weed scientists. Subplots were sampled as part of an ongoing field experiment in Lubbock, TX in which different herbicide formulations and application techniques were being compared. Position information, in the form of GPS coordinates, was collected for each subplot. Digital photographs were taken of each subplot and software was developed to quantify percent foliar cover for each location. A weed map was generated with the UTWMS and sampled with GIS software using subplot position information. Weed maps were

found to be unrepresentative of what was on the ground when foliar cover and subplot averages of PTO were compared. At the plot level, ground and map information were weakly correlated. When two weed maps collected on the same day were compared, maps agreed very well demonstrating that repeatability of the weed maps was good. Results suggest that the sampling interval for the UTWMS should be decreased when ground-truthing with 1m² subplots.

A technique was developed for automated evaluation of real-time sensor/sprayer units. The WeedSeeker was evaluated as an example of this type of unit. A video documentation system was developed, tested, and installed under the hood of a sprayer to evaluate the accuracy of a WeedSeeker unit under field conditions. The documentation system recorded video of the ground beneath the WeedSeeker and incorporated a digital overlay of pixels indicating the status (on/off) of the WeedSeeker's valve cartridge. Post-processing software was developed to scan each frame of video and quantify hits, misses, and false triggers of the WeedSeeker by scanning for presence/absence of plants in the user-defined sensed region of the frame and presence/absence of the valve-activity-pixel overlay. The example data set showed an 87% targeting accuracy by the WeedSeeker. The remaining 13% was due to 10% misses and 3% false triggers. Adjustments to either the WeedSeeker system or the analysis software will influence the results of this type of analysis.

The logging routine of the UTWMS was updated to include a count of spray transitions for each WeedSeeker along with percent time on. If a

WeedSeeker transitioned from off to on, the transition count was incremented by one. The number of transitions for each WeedSeeker was logged with PTO at the end of each sampling period. The updated logging routine was tested in the lab on each channel of the UTWMS that currently monitors a WeedSeeker. All lab tests were 100% successful and demonstrated that the software update functioned as expected. All transition counts were logged with an uncertainty of plus one count. This was due to the fact that only a positive transition was logged as a transition. An example analysis was also conducted with field data to demonstrate how weed scientists could apply a count of spray transitions.

A simulation study was conducted to evaluate the potential for replacing the center WeedSeeker of a group of three (typical configuration under each spray hood) with a conditionally triggered solenoid valve. This has the potential to reduce system cost by approximately 25%. Four conditional trigger scenarios were evaluated for triggering the center unit: Left OR Right, Left AND Right, Left Only, and Right Only. The AND condition generated the highest percentage of hits and misses but the lowest percentage of false triggers. The OR condition generated the lowest percentage of hits and misses but the highest number of false triggers. Spatial correlation of weeds in the field was evaluated but no correlation was found at the current sampling resolution. Average weed cover and average PTO were significantly different by treatment and percent hit, percent miss, and percent false trigger also differed by treatment. Percent hit was found to be inversely proportional to weed cover in plots while percent miss and percent false trigger were positively correlated with weed cover.

Conclusions

1. Repeatability of weed maps was good when two maps collected on the same day were compared ($r^2 > 0.98$). This would suggest that positional errors of the GPS and repeatability of the WeedSeeker are minimal.
2. The resolution of the data collected from the UTWMS did not adequately represent the high resolution manually sampled subplots. The UTWMS weed map did not correlate with foliar cover data taken from 1m² ground-truthed subplots used by weed scientists in Lubbock, TX.
3. The video documentation system developed for evaluating weed discrimination accuracy of real-time sensor-based herbicide application systems was successfully tested under field conditions. Custom software developed to automate the post-processing analysis of video collected with the video documentation system accurately classified video frames into Hit, Miss, or False Trigger. The current version of this system is limited to use in row-middles or on fallow ground due to its inability to differentiate weed from crop.
4. The video documentation system paired with automated analysis software was useful for optimizing user inputs on the WeedSeeker units. If misses are higher than false triggers then the sensor sensitivity should be increased, and vice versa. This will allow producers to determine the

trade-off between not spraying a weed or spraying when no weed is detected.

5. Software modification to the UTWMS allowed for enumeration of spray transitions while logging percent time on for each nozzle. The added information provides a tool that researchers can use to investigate relationships between percent time on, spray distribution, and weed characteristics currently unavailable from automatically generated weed map data.
6. Results of a simulated removal of the center WeedSeeker from a group of three indicated that a solenoid valve logically AND'ed with the adjacent two WeedSeekers would have 91.5% hits, 7.5% misses, and 1% false triggers.

Recommendations

1. The GPS update-rate for the UTWMS should be set as high as possible if the goal is to represent small research plots because the resolution obtained when the GPS is set at 1Hz is insufficient for comparing to 1m² research subplots.
2. If digital photographs are taken for quantification of weed cover for comparison with weed maps created by the UTWMS, multiple images

collected consecutively along the crop row middle will be more representative of what is sampled by the UTWMS.

3. Systems are available that will encode GPS position on the audio track during video recording. By combining position information with the video documentation system, weed maps created by methods such as the UTWMS could be evaluated using one technique instead of two.
4. Additional information could be collected from the video documentation system by incorporating features that would quantify number and size of weed patches present in the sensed portion of the video frames.
5. Incorporation of all valve status indicators in the video overlay would allow for evaluation of full-hood “modules” of the WeedSeeker system rather than just a single WeedSeeker unit.
6. Investigating the additional processing time it would take to count negative spray transitions in addition to positive would remove the plus one uncertainty error in the data.
7. Additional sensor replacement simulation may demonstrate that satisfactory hit percentages can be accomplished using a single sensor centered between two conditionally triggered solenoid valves.
8. As solid-state storage devices (such as the PCMCIA card used for data storage in the UTWMS) have become larger in capacity and less

expensive, there may be no need for a sampling period and logging of only percent time on. By logging discrete status information for every nozzle, integration time by the mapping system will be greatly reduced. A linear interpolation could be used to project GPS coordinates for every discrete nozzle status scan. There will be less spatial error with this technique using higher position update rates.

9. Another drawback to this initial version of the software is that different soil, residue, and lighting conditions will require a discrimination relationship be developed for discriminating plant from soil. A calibration video could possibly be used to set this relationship but this will require additional testing.

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