DEVELOPMENT AND EVALUATION OF A PROTOTYPE VARIABLE RATE SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICALS IN WILD BLUEBERRY FIELDS

by

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Submitted in partial fulfilment of the requirements
for the degree of Master of Science

at

Dalhousie University
Halifax, Nova Scotia

in co-operation with

Nova Scotia Agricultural College
Truro, Nova Scotia

March 2012

DALHOUSIE UNIVERSITY

NOVA SCOTIA AGRICULTURAL COLLEGE

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “DEVELOPMENT AND EVALUATION OF A PROTOTYPE VARIABLE RATE SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICALS IN WILD BLUEBERRY FIELDS” by Travis Esau in partial fulfilment of the requirements for the degree of Master of Science.

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DALHOUSIE UNIVERSITY

AND

NOVA SCOTIA AGRICULTURAL COLLEGE

DATE: March 13, 2012

AUTHOR: Travis Esau

TITLE: DEVELOPMENT AND EVALUATION OF A PROTOTYPE VARIABLE RATE SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICALS IN WILD BLUEBERRY FIELDS

DEPARTMENT OR SCHOOL: Department of Engineering

DEGREE: MSc CONVOCATION: May YEAR: 2012

Signature of Author

Dedication

To my brother, Brian

Who suffered a C5/C6 spinal cord injury on August 28th, 2011

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

An automated prototype variable rate (VR) sprayer was developed for control of eight individual nozzles on a 6.1 m sprayer boom for spot-application (SA) of agrochemicals in wild blueberry fields. The VR control system consisted of eight ultrasonic sensors and four cameras mounted on a separate boom in front of the ATV, flow controller, VR controller, ruggedized computer, flow valve and solenoid valves. Custom software was capable of processing the images to detect weeds or plants in real-time and automatically send a signal to the VR controller for SA at the correct target. The performance of VR sprayer for SA on weeds (herbicide) and foliage (fungicide) was evaluated in commercial wild blueberry fields. Based on the results of this study, the VR sprayer was reliable, efficient and accurate enough for SA of agrochemicals. The average volume of chemical saved with SA was 70 % herbicide and 30 % fungicide.

LIST OF ABBREVIATIONS AND SYMBOLS USED

A	Ampere
ANOVA	Analysis of variance
AYMS	Automated yield monitoring system
B	Blue
CCD	Charged coupled device
CFIA	Canadian food inspection agency
cm	Centimeters
CN	Control
CRBD	Complete randomized block design
DC	Direct current
DGPS	Differential global positioning system
DJ	Dickey John
FB	Floral bud
FDA	Food and Drug Administration
G	Green
GIS	Geographical information system
GPS	Global positioning system
ha	Hectare
hr	Hour
IL	Illinois
kg	Kilogram
km	Kilometre
L	Litre
LED	Light emitting diode
LMC	Land manager controller
Ltd	Limited
m	Metre
min	Minute
mm	Millimetre
MRL	Maximum residue limit
ms	Millisecond
mV	Millivolt
NB	Number of branches
P	Probability
PA	Precision agriculture
PAC	Percent area coverage
PC	Personal computer
PD	Plant density
PPC	Pocket personal computer
PID	Proportional integrative derivative
R	Red
RGB	Red green blue
RTK	Real time kinematics
R^2	Coefficient of determination

s	Second
SA	Spot-application
SAS	Statistical Analytical Software
S.D.	Standard deviation
SH	Stem height
T_{ic}	Time taken by camera for image acquisition
T_{ip}	Image processing time
T_{rt}	Total response time
T_{vd}	Time from VRC to spray discharge
UA	Uniform application
V	Volt
VR	Variable rate
VRC	Variable rate controller
W	Watt
WAAS	Wide Area Augmentation System
WSP	Water sensitive paper
YD	Yield density
˚C	Degree Celsius
˚N	Degree North
˚W	Degree West
®	Registered
™	Trade mark
µ	Micro

ACKNOWLEDGEMENTS

Many people deserve special recognition for their help throughout my studies. First and foremost I offer my sincerest gratitude to my supervisor, Dr. Qamar Zaman, who has supported me throughout my thesis. His guidance and knowledge allowed me to accomplish my goal and complete my graduate project. I am thankful to my committee members Dr. Arnold Schumann and Dr. David Percival for their support, time, expertise and assistance throughout my project. All my committee members have provided vast amount of advice and inspiration during the past two years. I have been fortunate to have such an excellent group of researchers act as my supervisory committee. I would like to show my gratitude to Dr. Young Ki Chang whose help with numerous aspects of this project from beginning to end made the project a success. Dr. Chang's positive and friendly personality has made him a pleasure to work with over the past two years.

I wish to acknowledge Oxford Frozen Foods Limited, Bragg Lumber Company, Nova Scotia Department of Agriculture Technology Development, Canada Foundation for Innovation, Wild Blueberry Producers Association of Nova Scotia, Agriculture and Agri-Food Canada, New Brunswick Department of Agriculture, Agri-Futures and the Natural Science and Engineering Research Council for funding to complete this thesis.

I would like to thank Dr. Dian Patterson for coordinating the graduate studies program at the Nova Scotia Agricultural College. I would also like to thank Marie Law, Heather Hughes and Sara Murphy of the research and graduate studies office for their administrative support with my graduate program. The Department of Engineering at the Nova Scotia Agricultural College with its close affiliations with Dalhousie University has provided the support and equipment I have needed to produce and complete my thesis. I

would also like to thank Chemical Containers and the University of Florida for assistance with sprayer equipment and supplies.

I would like to thank Scott Read for his endless technical help and support with the project. I am appreciative to Gary Brown and Doug Wyllie for help with field selection and agrochemical applications. Special thanks to Dave Sangster, executive director of the wild blueberry producers association of Nova Scotia, for his kind guidance and generous support. I am very thankful to Kelsey Laking, Aitazaz Farooque, Shoaib Saleem and Fahad Khan for helping in field tests and data collection. Thanks to Dr. Ali Madani for his expertise in presentations, thesis writing and encouragement to complete my M. Sc. I am extremely grateful to Lindsay Lewis who has motivated me daily through the M. Sc program and life's hardships.

I express my greatest appreciation to my father Carl Esau, my mother Marion Esau, and brother Brian Esau who have supported and encouraged me from the beginning. Without their loving support and longsuffering I would not be where I am today.

CHAPTER 1

INTRODUCTION

As production agriculture operations have grown in size and competitiveness, the agricultural equipment industry has followed the trend by providing larger and faster machines to satisfy the producer's demand. The wild blueberry industry is rapidly growing with over 16,500 ha in production in Nova Scotia alone (Williams, 2010). Blueberries rank as the number one fruit crop in Canada with respect to area under production (Howatt, 2008) and farm gate value. At the same time, technologies for agricultural field task improvement have been developed, allowing detailed crop input management and more efficient field operations. Many of the technologies developed to address these issues utilize GPS guided prescription maps and can be quite expensive and relatively complicated to use (Tian, 2002; Schumann et al., 2006a; Michaud et al., 2008). Because of the high cost and complexity in operation, a producer's decision to adopt these technologies has become more difficult. It often takes more management effort to fully utilize the potential of these technologies.

One of the newest innovations in precision agriculture is the real-time variable rate (VR) sprayer for spot-application (SA). Motivation for the development of this type of VR sprayer is increased field performance and lower chemical use and input costs. This type of VR sprayer does not use prescription maps, but relies on sensors or cameras to provide real-time weed and bare spot detection information to the controller for spraying the correct targets. Although research programs throughout North America have concentrated on the development of VR technologies for different crops but to date, little attention has been paid towards wild blueberry production.

Wild blueberry (*Vaccinium angustifolium* Ait.) yields are highly dependent on agrochemicals for adequate weed, disease and insect control. Growers apply most products during the growing season. For example, herbicides mesotrione (Callisto® 480SC) for pre-emergence control of annual broadleaf weeds, propyzamide (Kerb™ WSP) for post-emergence control of grasses and broad-leaved weeds, fungicides for floral blights (*Monilinia* and *Botrytis*) and leaf diseases (*Septoria* and *Thekopsora minima*), and insecticides for the fruit fly. These agrochemicals are traditionally applied uniformly without considering significant bare spots (30-50 %) of the total field area (Zaman et al., 2008) and weed patches that exist within some fields. The repeated and excessive use of agrochemicals in bare spots and plant areas have resulted in an increased cost of production. The extensive use of agrochemicals is also dangerous for the environment, humans, native pollinators and plants. Chemically-polluted runoff from the fields cause contaminated surface and ground water (Pimentel and Lehman, 1993). The targeting of herbicides to weed patches in different cropping systems may lead to reductions in herbicide usage by 25 % (Dammer and Wartenberg, 2007). Similar or more agrochemical saving potential is expected in the wild blueberry industry, given the high proportion of bare spots in typical wild blueberry fields. Therefore, there is an emerging need to develop an affordable and reliable automated VR sprayer for SA of agrochemicals in wild blueberry cropping system.

The **hypothesis** proposed in this study was that uniform blanket applications of agrochemicals are not necessary and the development of an effective and practical VR sprayer for SA can be achieved. With the development of the sprayer system, an important new management tool will be available for use by the wild blueberry industry.

1.1 Objectives

The objectives of this study are to:

i. Develop a prototype VR sprayer using ultrasonic sensors and/or μEye digital color cameras, computerized 8-channel VR controller, Land Manager II controller, handheld Pocket PC with operating software, servo valve, flow meter, solenoid valves, nozzles and a tank capacity of 209 L for small scale SA in wild blueberry fields.
ii. Evaluate the performance of the prototype VR sprayer with ultrasonic sensors for targeting tall weeds in wild blueberry fields.
iii. Evaluate the performance of the prototype VR sprayer with digital color cameras for SA of agrochemical in wild blueberry fields.

CHAPTER 2

LITERATURE REVIEW

2.1 Wild Blueberry Cropping System

Northeastern North America is the world's largest producer of wild blueberries with over 86,000 ha being managed and producing 112 million kg of fruit valued at $482 million annually (Yarborough, 2009). Wild blueberry fields are developed from native stands on deforested or abandoned farmland by removing competing vegetation (Eaton, 1988). Wild blueberry plants are low growing, ten to sixteen centimeters tall, with new shoots of maturing plants developing from dormant buds on underground stems called rhizomes. The rhizomes originate from seedlings and spread under the soil an average of five to eight centimeters per year (Kinsmen, 1993). Zaman et al (2008) found significant bare spots in some fields (30-50 % of the total field area). The four kinds of lowbush blueberries that grow wild in Canada are velvet-leaf blueberry (*Vaccinium myrtilloides*), ground hurts (*Vaccinium boreale*), common lowbush blueberry (*Vaccinium angustifolium* Ait.) and black lowbush blueberry (*Vaccinium angustifolium* f. nigrum) (Kinsmen, 1993). The most abundant *Vaccinium* species found in blueberry fields is the common lowbush blueberry. However, the velvet-leaf blueberry has been reported at up to 50 % coverage in stands of lowbush blueberries (Kalt et al., 2002). Blueberry fields are made up of many different clones of blueberry plants and it is practically impossible to find two morphological identical clones in the same field (Kinsmen, 1993). Generally, it is difficult to detect differences in floral-bud counts or yields between treatments because of the high variability and the natural clonal patchiness of the blueberry crop (Boyd and White, 2010). In most cases wild blueberry fields are managed on a two year production cycle where one year produces vegetative growth, followed by a year in which bloom, pollination, and berry growth and development occurs. Wild blueberries are harvested in August and September (Fig. 2-1). Following the biennial crop management practice they are pruned in the fall or spring of the cropping year by burning or mowing (Malay, 2000).

Figure 2-1 Wild blueberries in August of the cropping year.

Wild blueberry fields have a high proportion of bare spots and weed patches on gentle to severe topography. Weeds are becoming a greater problem in wild blueberry production (Howatt, 2008). Weeds have always been considered as a major yield-limiting factor in blueberry fields (Jensen and Yarborough, 2004). Weed flora in blueberry fields traditionally consisted of slow spreading perennial species. The majority of new species invading blueberry fields are common vigorous annual weeds of arable fields that produce a large number of seeds and require control with herbicides both in prune and production years (Jensen and Yarborough, 2004; McCully et al., 1991). Traditionally, herbicides are applied uniformly with inadequate attention being given to the significant bare spots and plant areas, only to control competing weeds and encourage berry production in the sprout year. Excess usage of herbicide spray in bare spots and blueberry plant areas using conventional methods, may increase production costs and environmental pollution. Malay (2000) reported excessive loss of soil threatens the sustainability of the wild blueberry industry as a result of poor blueberry cover and the excessive use of herbicides.

Growers uniformly apply fungicides for floral blights (*Monilinia* and *Botrytis*) and leaf diseases (*Septoria* and rust), and insecticides for the fruit fly. The commonly used fungicide chlorothalonil (Bravo® 500) for wild blueberry production has resulted in fish mortalities in Prince Edward Island, Canada from chemical run-off (Ernst, 1991; Pariseau et al., 2009). To prevent negative environmental impacts, it is important to consider practices that reduce pesticide run-off and erosion during the production cycle (Mutch, 1999). Fungicides and insecticides could be saved in bare patches using variable rate (VR) technologies. The current crop management practices are implemented uniformly with inadequate attention being given to the substantial variation in soil/plant/weed characteristics, topographic features and fruit yield (Fig. 2-2). Spatial variability in wild blueberry fields is a unique challenge the producers need to overcome (Farooque, 2010). The need for precise site-specific crop management practices is essential for the future success of the wild blueberry industry. These unique features emphasize the pull from producers for the development of automated vegetation detection systems to identify and map weeds/grasses and bare spots for accurate applications.

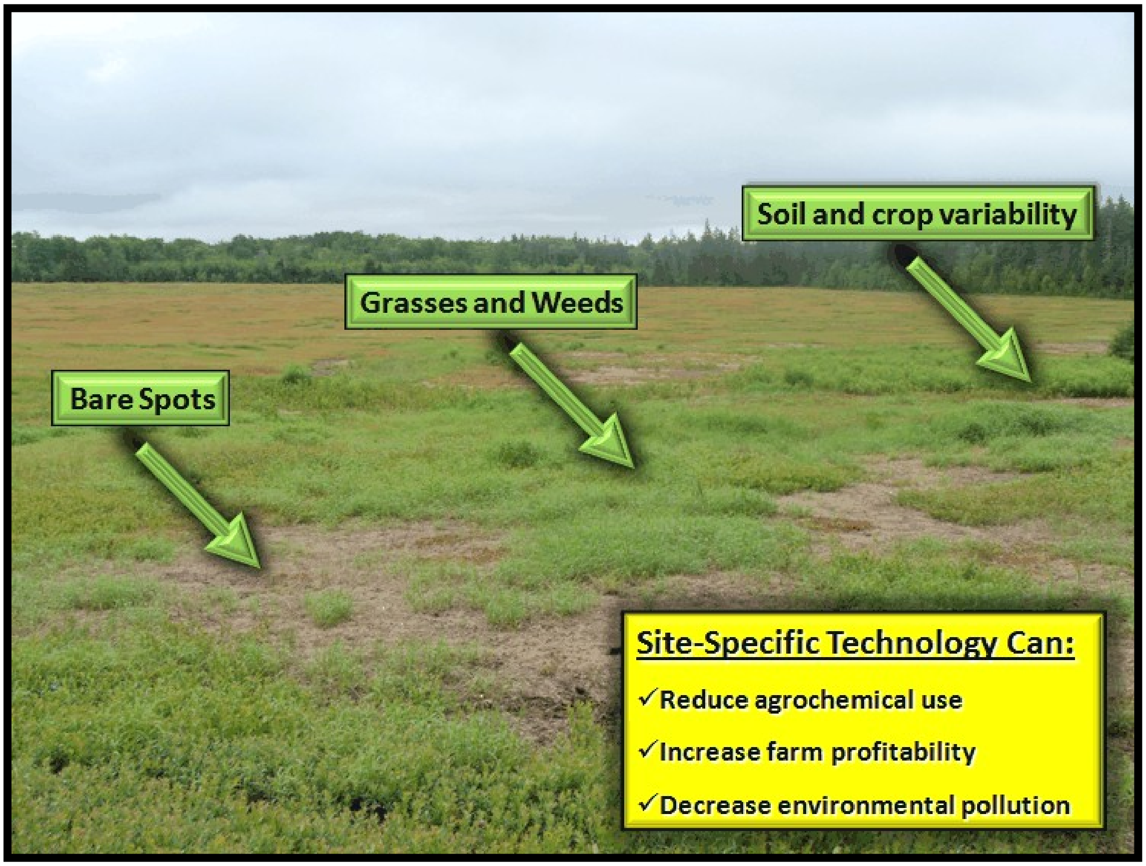


Figure 2-2 Wild blueberry field showing substantial bare spots, grass, weeds and crop variability.

Consumer demand for wild blueberries has increased because of increasing publicity and array of health benefits. Anthocyanins in the berries have a range of potential anti-cancer and anti-heart disease properties including antioxidant, anti-inflammatory, and cell regulatory effects (Beattie et al., 2005). The high concentration of anthocyanins in wild blueberries repairs and protects genomic DNA integrity, reduce age-associated oxidative stress, as well as improving neural and cognitive brain function (Bagchi et al., 2003). Smith et al. (2000) reported that wild blueberries exhibited significant antioxidant activities in both the lipid and aqueous environment as well as being rich in flavonoids. Free radicals oxidatively damage lipids and proteins and compromise genomic DNA integrity (Bagchi at al., 2003). Wild blueberries may be an essential requirement for healthy living, and sustainable management practices play a key role in the industries success. The development of a VR sprayer would promote the management of a healthy crop using environmentally friendly methods of production.

2.2 Weeds and Foliar Diseases Associated with Wild Blueberry Production

Goldenrod (*Solidago* spp.) is a common weed found in many wild blueberry fields. McCully et al. (1991) found goldenrod in 94 % of 115 sampled fields in Nova Scotia. Boyd and White (2010) evaluated the effect of Velpar® DF applied pre-emergent and multiple application timings of post-emergent Callisto® 480SC on goldenrod in wild blueberry fields. The spot-spraying of goldenrod with Callisto® 480SC is generally effective, but labor intensive, and a broadcast treatment is desirable (Boyd and White, 2010). Although broadcast treatments are effective they are not necessary and increase cost of production while polluting the environment.

Kennedy et al. (2011) determined the impact of 14-18-10 synthetic fertilizer and Velpar® DF pre-emergence herbicide on *Rumex acetosella* (sheep sorrel) growth patterns in lowbush blueberry fields. Kennedy et al. (2011) found Velpar® DF decreases the reproductive shoot biomass ratio by as much as 96 %.

Black bulrush (*Scirpus atrovirens*) is another weed in wild blueberry production. McCully et al. (1991) found black bushrush in 8% of 115 sampled fields in Nova Scotia. Boyd and White (2010) evaluated the effect of terbicil (sinbar®) applied pre-emergent and nicosulfuron/rimsulfuron (ultim® 75 DF) applied post-emergent, and multiple application timings of Callisto® 480SC applied post-emergent on black bulrush in wild blueberry fields. Boyd and White (2010) reported 80 to 90 % control of black bulrush was achieved with an application of Ultim® 75 DF or two sequential applications of Callisto® 480SC. Herbicide could be saved in the wild blueberry cropping system with the development and adaption of a VR sprayer that applied spot-application (SA) where needed within the field.

Wild blueberry yields are highly dependent on fungicides for adequate disease control. The two most common foliar diseases found in wild blueberry fields are *Septoria* leaf spot (*Septoria*) and blueberry rust (*Thekopsora minima*) (Percival and Dawson, 2009). *Septoria* leaf spot prevails in late June and rust in late July of the vegetative development stage of the biannual crop production cycle (Wild Blueberry Factsheet, 2009). Both diseases cause visual reductions in green leaf area and leaf area duration and cause reduction in carbohydrate supply to develop floral buds (Percival and Dawson, 2009). Growers apply fungicides during both the vegetative and cropping year to reduce disease pressures and increase floral bud counts and harvestable yields (Percival and Dawson, 2009). Chlorothalonil (Bravo®) is applied to prevent *Septoria* leaf spot and blueberry rust during vegetative year, propiconazole (Topas® 250E) for *Monilinia* blight (*Monilinia vaccinii-corymbosi*), cyprodinil/fludioxonil (Switch™) for *Botrytis* (*Botrytis cinerea*), and Pristine™ (boscalid/pyraclostrobin) for *Valdensinia* (*Valdensinia heterodoxa*) leaf spot and rust during crop year. Traditionally fungicides are applied uniformly without considering bare spots that exist within fields. The repeated and excessive use of fungicides in bare spots has resulted in an increased cost of production. The wrong or over use of fungicide is also dangerous for the environment, for humans, for the native pollinators, and for the plants. Chlorothalonil, the active ingredient in

Bravo® is a fungicide that is heavily used in eastern Canada and has led to significant aquatic contamination (Ernst, 1991; Pariseau et al., 2009). Given the high proportion of bare spots in typical wild blueberry fields, there is a significant fungicide savings potential expected in the wild blueberry industry. Therefore, there is an urgent need to develop an affordable and reliable automated VR sprayer for a more sustainable SA of fungicides in the wild blueberry cropping system.

2.3 Precision Agriculture

Precision agriculture (PA) refers to the management of crop production inputs in an environmentally stable way. PA uses information and the latest technology to target and adjust the correct rate of fertilizers, herbicides, fungicides, insecticides and/or other agriculture inputs on an as needed basis. PA promotes improved management of agricultural production through recognition that the productivity potential of agricultural land varies considerably, even over very short distances (Bramley and Wuabba, 2002). With the increasing need to protect the environment, more attention is being given to manage the fields according to spatial variability in soil properties and crop requirements by varying the agricultural inputs within field. PA contributes in many ways to the long-term sustainability of production agriculture. Sustainability in agriculture is the ability to reduce or prevent environmental degradation from economic activity with the goal to enhance the environmental quality of the resource base which is needed for agriculture providing food for human consumption. The PA benefits to the environment come from more targeted applications of agricultural inputs that reduce nutrient imbalances from excess applications. Other benefits include a reduction in pesticide resistance development (Bongiovanni, 2004). Precision agriculture responds to manage crops on the basis of the variability in land, using a set of technologies to develop sustainable agriculture, to reach a balance between the economic efficiency of operation, and the quality of the harvest mitigating the environmental risks (Castro et al., 2011).

Precision agriculture technologies have spread rapidly around the world. These technologies have been adapted more easily by producers that have farms with larger acreage than small-acre farms, and they rely on universities and extension agencies for information on adoption of the equipment (Winstead et al., 2009). In 2005, a cotton precision farming survey showing results from 11 southern states indicated that 48 % of producers have taken advantage of PA technologies in some form (Roberts et al., 2006). For producers to use these new technologies, they will need more information about the economic returns to justify the adoption costs with investing in the PA equipment (Mooney et al., 2009).

2.4 Sensing and Control Systems for VR Agricultural Applications

Several studies have been concentrated on camera-based, non-destructive fruit yield estimation and mapping techniques (Chinchuluun and Lee, 2006; Schumann et al., 2007). Chinchuluun and Lee (2009) developed a machine vision-based citrus fruit counting system for a continuous canopy shake and catch harvester. The system consisted of a 3CCD camera with a custom image processing algorithm that could identify fruit and measure its size. A digital color camera mounted on a moving vehicle was used to capture georeferenced-overlapping images using red-green-blue pixel ratios and thresholds to identify and quantify numbers of mature fruit. Zaman et al. (2008) evaluated the performance of a cost-effective 10-mega pixel digital color camera for wild blueberry fruit yield estimation. Zaman et al. (2010) developed an automated yield monitoring system (AYMS) consisting of a digital color camera, ruggedized laptop computer, custom software and real time kinematics-global positioning system (RTK-GPS). They successfully estimated and mapped fruit yield in wild blueberry fields. The digital photography technique using cost-effective, reliable color cameras and RTK-GPS might be an option for look-ahead vision technology on a VR sprayer for wild blueberry herbicide, fungicide and insecticide field applications. However, ordinary digital color cameras are not viable for commercial application on a VR sprayer. A better system could involve compact sized, cost-effective, fast and reliable cameras with rapid custom image processing software to develop a VR sprayer for agrochemical applications in wild blueberry fields.

Many researchers have developed machines that operate in real-time using a variety of remote sensing devices. Adsett et al. (1999) developed an automated on-the-go, soil nitrate monitoring system using a nitrate ion selective electrode for real-time in-field soil nitrate measurements. Tumbo et al. (2002) developed an on-the-go system for sensing chlorophyll status in corn using neural networks and fiber-optic spectrometry, which was used to acquire spectral response patterns at a travelling speed of 0.6 km hr^{-1} in five corn field plots. Schumann et al. (2007) developed ultrasonic and optical sensors to control the placement and rate of fertilizers and pesticides with VR fertilizer spreaders in Florida citrus groves. Castro et al. (2011) presents the development of a high-performance fertilizer spreader, which optimizes the balance between the quality of cultivated products and fertilization costs. The spreader was able to automatically adjust a proportional flow valve depending on the tractor speed, depositing the proper amount in conjunction with the rest of the control sensors deployed with a PID (proportional integrative derivative) control algorithm.

Ultrasonic sensors are widely accepted for quantification of plant heights (Sui et al., 1989; Schumann and Zaman, 2005). Swain et al. (2009) developed and tested a low-cost ultrasonic system for weeds (taller than plants) and bare spot mapping in real-time within wild blueberry fields during the growing season. They reported that cost-effective ultrasonic sensors were capable to detect tall weeds (taller than blueberry plants) and bare spots in wild blueberry fields. However, machine vision technology is needed because weeds are not tall enough during spring and fall herbicide applications over the two year production cycle.

Wild blueberry producers and processors have set a goal to reduce agrochemicals usage within the industry. Management of wild blueberry cropping systems will require increased agrochemical use efficiency by replacing conventional technology with new VR technology for SA of agrochemicals. Zhang et al. (2010) developed a ground based, automated machine vision system using cost-effective digital photography technique to measure and map bare spots in wild blueberry fields. Therefore, this machine vision technology could be incorporated into a VR sprayer to save fungicide applications in bare soil zones within wild blueberry fields.

Several techniques are being tested for weed detection and mapping in different cropping systems (Giles and Slaughter, 1997; Gillis et al., 2001; Tian, 2002; Dammer and Wartenberg, 2007). Sogaard (2005) constructed active shape models for weed identification based on a set of training images. Gerhards et al. (2005) used real-time differential images of near infrared (NIR) wavelength obtained with digital cameras to save 81 % herbicides on broad leaved weeds and 79 % for grass weed herbicides in cereal crops using a VR sprayer. Sharp (2008) discriminated sheep sorrel (*Rumex acetosella* L.) using a Field Spec® 3 hand-held spectral radiometer. These research efforts have not yet resulted in generic technologies probably due to the inherent difficulties of the methods utilized and the relatively high computing and economic cost involved.

Several machine vision systems have been developed to detect weeds in different cropping systems (Sui et al., 1989; Shearer and Holmes, 1990; Zhang and Chaisattapagon, 1995; Tian, 2002), because real-time weed detection at the time of spot-spraying could be very valuable for lowering chemical costs and reducing environmental contamination. However, these vision systems generally needed a relatively high image resolution and the detection algorithms were quite complicated and computationally expensive (Meyer et al., 1998). Zhang et al. (2009 and 2010) used cost-effective digital color cameras and fast image processing techniques to detect weeds and bare spots in wild blueberry cropping system. Therefore, cost-effective sensors/cameras and fast image processing techniques are able to sense the weeds in real-time and provide the weed detection information needed by fast VR controllers for spraying the correct targets in wild blueberry fields.

Chang et al. (2012) developed a color co-occurrence matrix based machine vision algorithms for wild blueberry fields. The developed algorithms were designed to identify bare spots, wild blueberry plants and weeds in wild blueberry cropping fields. Chang et al. (2012) used four color cameras to take images in real-time and transfer via USB link to a ruggedized laptop with custom-written programs coded in Microsoft Visual® C++.

The textural features of each image were extracted using MATLAB® Image Processing Toolbox Version 7.8.0 (Math Works, Natick, MA, USA) and later analyzed with SAS® (SAS Institute, Cary, NC). The accuracy levels of developed algorithms for detecting weeds, blueberry plants and bare spots ranged from 91.4 to 94.9 % with processing time of 27 to 55 ms which will bring the maximum vehicle travel speed of 6.3 to 3.1 km hr^{-1}, respectively. Therefore, a cost-effective digital photography technique could be used on a VR sprayer for SA of agrochemicals in wild blueberry cropping system.

Advances in sensing technology have offered cost effective alternatives for detecting weeds in specific sections of the VR sprayer boom. Advances in VR control systems have made it possible to respond quickly. Many commercial controllers have been developed to deliver agrochemicals on a site-specific basis using GPS guided prescription maps within the field (DICKEY-john Land Manager II: DICKEY-john Corporation, Auburn, IL; MidTech Legacy 6000 controller: Midwest Technologies, Springfield, IL; Raven 660 controller: Raven Industries Inc. Sioux Falls, SD). Schumann and Hostler (2009) with the partnership of a machinery manufacturer (Chemical Containers, Inc., Lake Wales, FL, USA) developed an 8-channel computerized VR controller consisting of electronic hardware with internal firmware and matching Windows Mobile 6.0 software on a handheld pocket PC (PPC). The controller is linked with the PPC using wireless Bluetooth. Typically this controller does not use prescription maps, but relies on sensors to provide real-time weed information which is used to dispense the correct herbicide rate for the weed eradication within the field.

Researchers throughout North America have concentrated on the development/adoption of PA technologies for horticultural/agronomic crops (Giles and

Slaughter, 1997; Tian, 2002; Carrara et al., 2004; Zaman et al., 2005; Schumann et al., 2006b; Dammer et al., 2008). However, very little attention was paid to the wild blueberry cropping system. A prototype VR sprayer consisting of ultrasonic sensors and/ or digital color cameras, 8-channel computerized VR controller, Land Manager II controller, solenoid valves, PPC with operating software could be developed for in-season real-time weed detection and spot spraying in wild blueberry fields.

2.5 VR Spray Technologies

Agricultural sprayers with VR technology have the potential to improve farm profits by lowering input and application costs while still being able to increase yields (Mooney et al., 2009). The two main types of VR application methods are prescription map based VR technology and real-time sensor based VR technology. The prescription map based approach uses a VR controller to monitor and adjust the target application rate based on the applicators exact field location usually featuring an on-board GPS device and a computer generated applied map. Maps are most commonly created using GIS software and geo-referenced data on soil properties and yield (Mooney et al., 2009). The prescription map can be generated using manually collected data from the field or from aerial or satellite photos. Real-time sensor based VR technology eliminates the need for prescription maps and uses sensors mounted on the moving farm implement that acquires the crops spatial data without GPS or GIS. However, GPS and GIS can still be used in combination with real-time sensor based VR technology to geo-reference and record application maps for later referencing purposes.

Vehicle traveling velocity is always an important factor when using an agrochemical sprayer in the field. Changes in sprayer ground speed are effected by slope, roughness of terrain, gross vehicle weight, and available power (Qiu et al., 1998). GopalaPillai et al. (1999) tested an electronic flow control system for site-specific herbicide applications with the ability to travel at various ground speeds. They found that the time lag of the VR nozzle for a change in flow rate from minimum to maximum was less than 30 seconds and the smaller the change in flow rate, the shorter the time lag. The Synchro VR controller (Capstan Ag Systems Inc., Model No. VN6593) was used to adjust the herbicide application accurately while travelling at low speeds. However, at higher speeds it would be desirable to modify the controller for higher valve frequencies compared to the 10 Hz already used. Alvin and Quy (2001) developed a variable-flow fan nozzle using the control pressure and line pressure to achieve independent flow rate and droplet size spectral control for on-the-go VR application of crop production chemicals.

VR application of herbicides based on soil properties and harvestable yield could be a viable method of reducing the amounts of herbicide applied to agricultural crops. Qiu et al. (1998) completed a feasibility study of direct injection for VR pre-emergence herbicide application in corn and used factors such as in-line mixing location, hose diameter, nozzle spacing, nozzle size, and ground speed for performance testing procedure. They used GIS software to generate herbicide application rate maps and the corresponding error rate maps and found that application errors for direct injection systems were as high as 40 % for mistreated areas of the field, with some changes in chemical concentration at the nozzles occurring as much as 80 m beyond the target location. Based on the results this system would not be accurate enough for use in agrochemical applications in wild blueberry fields.

Vogel et al. (2005) evaluated the ability of a conventional spray system converted to VR application to successfully apply herbicides site-specifically. Nine prescription maps from various fields in Kansas State were uploaded into the Farmworks Farm Site Mate VRA6 V.8.22 software (The Farm Office, Tavistock, Ontario N0B 2R0) with prescribed pre-emergence and/or post-emergence application rates. They determined that weed patches could be managed using commercially available VR technology for use in corn and soybean. However, prescription maps are time-consuming and costly to develop and affordable GPS positional accuracy is insufficient.

Commercially, three common techniques for applying herbicides to roadsides weeds include; hand spraying, truck and boom sprayers and weed-activated boom sprayers (Gillis et al., 2001). Hand spraying is time consuming and very labor intensive but can accurately spray the weed targets without wasting chemical. Truck boom sprayers can complete the job very quickly however, large amounts of herbicide is wasted in areas where no weeds are present resulting in environmental contamination and wastage of money. More recently, companies have begun to use sensors to detect red and near-infrared light reflectance from the weeds. The sensors are mounted in front of the nozzles on the sprayer boom and sending information to a central processing unit that relays triggering information to the corresponding solenoid valve to open the corresponding spray nozzle where the weed was first detected (Blackshaw et al., 1998). This hybrid system has the ability to operate in a timely manner while at the same time not wasting chemical as compared to uniform application (UA). The main factor that affects the operation of the hybrid system is fluctuations in solar radiation that can be caused from the time of year, time of day or degree of cloudiness. They tested the sensing system at the Lethbride Research Centre and determined operators must wait 70 to 80 min after sunrise to attain sufficient irradiance for maximum performance as well as cease at a similar time period before sunset. They also found that the sensor detection system can effectively control sprayers to apply herbicides only where weeds are present.

Michaud et al. (2008) developed a VR prototype sprayer to deliver pesticides based on prescription maps, developed in GIS software, using aerial spectral scans of wild blueberry fields. The system was sensitive to positional error caused by the inherent characteristics of affordable global positioning systems (GPS). Also, obtaining up-to-date aerial photography was expensive, the quality was quite variable, and data processing for weed detection was also intensive and difficult. Instead of using a prescription map based VR sprayer, an automated VR sprayer for SA of agrochemicals in wild blueberry cropping systems could be developed using cost-effective sensing and control systems for real-time field operation.

Gillis et al. (2001) developed a fluid handling system to allow on-demand chemical injection for a machine-vision controlled sprayer. A Raven Direct Injection System (Model SCS-750, Raven Industries) was added to a target activated sprayer. They concluded that the use of a commercial chemical injection system for target-activated, offset sprayers is feasible with keeping chemical concentration rates within 10% of the desired and pressure fluctuations of only 5%.

Tian et al. (2000) developed a machine-vision-system-guided precision sprayer using a low resolution wide view camera and a real-time discrete wavelet transformation algorithm to effectively reduce herbicide application amounts for corn and soybean crops. With average weed coverage of 1.5 % the precision sprayer was able to save 58.4 %

chemical compared to a UA broadcast sprayer. The overall accuracy of the sprayer was determined to be 100 % with bare soil detection, 75 % in weed infested zones and 47.8 % in crop plant zone detection with a time-delay of 0.37 s and a maximum vehicle travel speed of 4.2 km hr^{-1}.

2.6 Economic Impact of SA of Agrochemicals

The wild blueberry is the most important horticultural crop produced in eastern Canada with over 16,500 ha under management in Nova Scotia alone (Williams et al., 2010). Wild blueberry yields are highly dependent on pesticides for adequate weed, disease and pest control (Jensen and Yarborough, 2004; McCully et al. 1991).

Jenson and Yarborough (2004) claimed the increasing appearance of herbaceous perennials such as sheep sorrel and narrow-leaved goldenrod was most likely the result of reduced Velpar® rates rather than herbicide resistance. The reason for reducing the Velpar® rate was to prevent soil and water contamination as well as blueberry harm. Also, the use of excessive agrochemicals with conventional methods has resulted in an increased cost of production and has developed concerns with weed and grass resistance to such herbicides as Velpar®. Typically, herbicides are broadcasted on an entire field without regard to the spatial variability of the weeds to be controlled resulting in just as much herbicide in areas where no or few weeds exist as in areas with a high weed population (GopalaPillai et al., 1999). Estimates indicate that a reduction of 11 % of pesticide agent by using VR sprayers in different cropping systems (Mooney et al., 2009). Carrara et al. (2004) saved 29 % herbicide with VR application as compared to conventional application in a wheat crop field. Similar or more agrochemical savings potentials are expected in the wild blueberry industry, given the high proportion of bare spots (30-50 %) in newer developed wild blueberry fields (Zaman et al., 2008) in typical wild blueberry fields.

When pesticides are applied to agriculture crops residues may remain in/on the food. The maximum residue limit (MRL) is the maximum pesticide residue legally allowed in/on a food at the time of sale regulated by the Canadian Food Inspection Agency (CFIA). Canada has a set table for the MRLs of commonly used pesticides (Pest Management Regulatory Agency, 2006). Zhang et al. (2002) mentions strict international environmental legislations force farmers to significantly reduce usage of agrochemicals. Compliance with the requirements of international markets with respect to improved quality and reduced chemical (MRL) use in blueberry production will facilitate export of the crop (Howatt, 2008). Matching chemical inputs to the needs of different field areas (site-specific farming) can result in the reduction of farming costs and environmental contamination by reducing the amount of chemicals applied (Al-Gaadi and Ayers, 1999).

Many producers lack the information about the profitability of VR technology for their use in combination with agricultural spreaders and sprayers. Mooney et al. (2009) developed an economic framework to evaluate the returns required to pay for the investments in VR technology. One major factor that determines the profitability of VR technology is the degree of spatial variability. The cost savings from VR technology as compared to traditional UA technology systems is greater in fields with higher spatial variability because the ideal application rate would need to be adjusted more frequently. They suggested that real-time sensor-based VR technology systems have higher ownership cost but lower recurring annual costs than prescription map based VR technologies. The ownership costs for VR technology systems include the initial investment required to purchase the added equipment over and above the typical UA equipments price. Also, it includes any increase in taxes, insurance, and storage. The recurring annual costs or information-gathering costs include the prices of things needed each year to be able to use the VR technology such as GPS correction subscription, aerial photographs, manual labor costs in gathering prescription data, data analysis and training, etc. In general, producers with larger acreages will have a faster payback period for real-time sensor based VR technologies especially if the land is spatially variable. VR technology can be used in almost every aspect of farm management including fertilization, planting, spraying, yield monitoring and harvesting.

The uniform fertilization practices on agricultural crops that is not supported by rational criteria could alter the balance between productivity and quality, a methodical planning of fertilization, as measured by the criteria and objectives is essential for obtaining quality production (Castro et al., 2011). Excessive applied fertilizer contributes to ground and surface water contamination, and farther, increases costs of production from the mismanagement of resources (Castro et al., 2011). Bongiovanni (2004) reported that agriculture cannot be sustainable if farmers use practices that are socially unacceptable or not profitable.

Economic threshold decisions are often made on a field-average-wide basis, except weeds are not typically spread evenly across a field but are distributed into patches. A producer could site-specifically apply herbicides in areas of the field where weed densities exceed the economic threshold (Vogel et al., 2005). Minimizing agrochemicals usage in wild blueberries is a unique approach that producers can use as a marketing tool. Therefore, there is an urgent need to develop an affordable, reliable VR sprayer, using inexpensive sensors and automated VR controllers for real-time SA of agrochemicals in the wild blueberry cropping system.

CHAPTER 3

MATERIALS AND METHODS

3.1 Development of a Prototype VR Sprayer

The prototype VR sprayer was developed for spot-application (SA) of herbicides on weeds/grasses and fungicides on plant foliage in the wild blueberry cropping system. The VR sprayer consists of ultrasonic sensors and/or µEye digital color cameras, computerized 8-channel VR controller (VRC), Land Manager II controller (LMC), handheld Pocket PC (PPC) with operating software, servo valve, flow meter, solenoid valves, nozzles and a tank capacity of 209 L (Fig. 3-1). The VR sprayer was mounted on an all-terrain vehicle (ATV). The 6.1 m sprayer boom was divided into eight sections (76.2 cm each section) and mounted behind the ATV at 1.0 m above the ground. This boom height was adjustable so that weed sensing area and spray could be fine-tuned to crop conditions. Eight solenoid valves and nozzles (one valve and one nozzle in each section) were mounted on the boom with a uniform (76.2 cm) interval between them. The nozzles were flat fan Teejet TP8004E (Spraying Systems Co., Wheaton, IL, USA). Using a series of T joints, the line connecting the distribution valve to each section was then connected to each solenoid valve to which a nozzle was fitted as closely as possible. The model 2201A solenoid valve (Delware Pump and Parts Limited, Delware, ON, Canada) was operated with 12 V and consumed only 13 W. The feed line from the pump went through a flow valve and flow meter then separated into two lines, each line (left and right) feeding four sections of the boom. The pump was operated by a Honda gas engine (Honda Inc., NS, Canada).

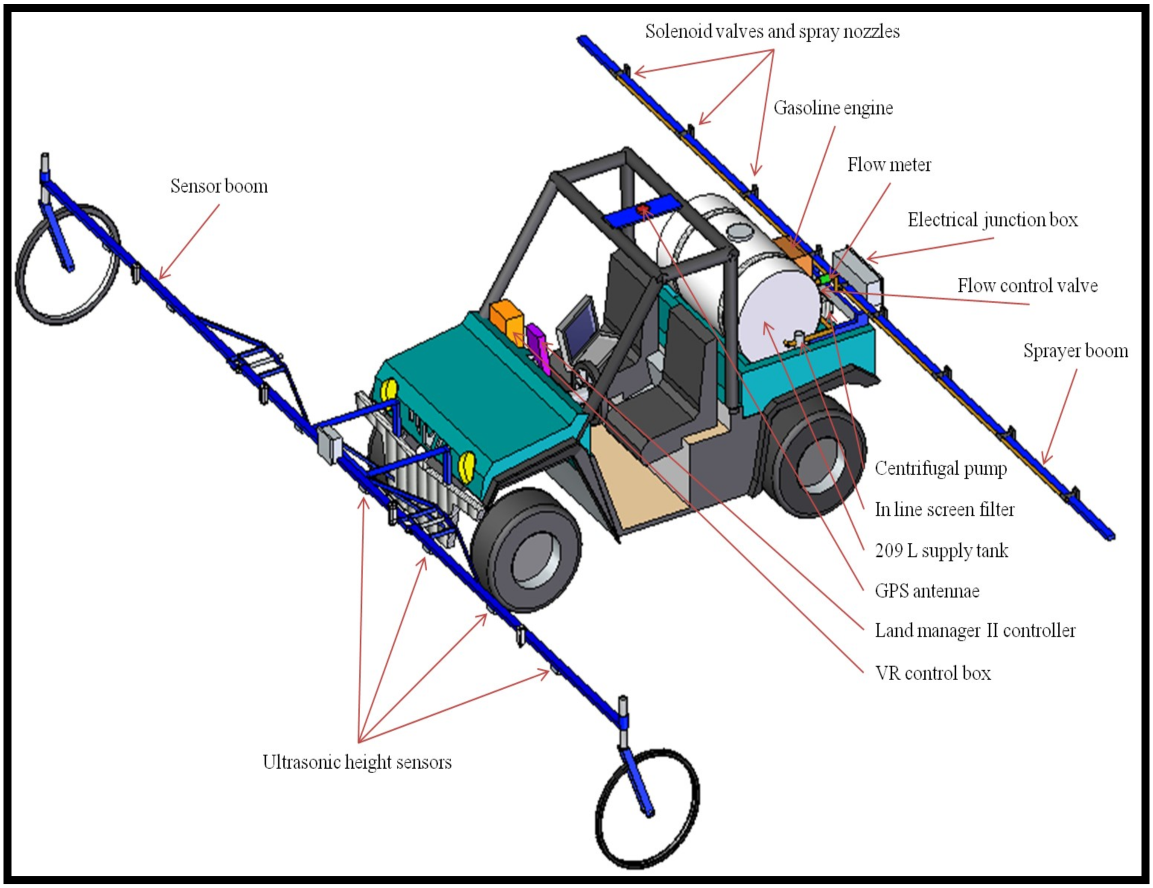


Figure 3-1 Schematic diagram of automated prototype VR sprayer for SA of agrochemicals using ultrasonic sensors.

3.2 LMC Flow Rate Evaluation

An experiment was conducted at the NSAC to evaluate the performance accuracy of the LMC for flow rate measurements from the nozzles mounted on the sprayer boom (Fig. 3-2). The volume of water from each nozzle and then from different combinations of nozzles was recorded from the LMC and also at the same time volume was measured manually with graduated cylinders for comparison. The experiment was replicated three times and volume measurement readings were recorded. The differences between LMC volumes and manually measured volumes were used to characterize the performance of the LMC.

Figure 3-2 Dickey John Land Manager II Controller (Dickey-john Corporation).

3.3 VR Sprayer with Ultrasonic Sensors for Tall Weed Detection

Eight wide angle beam, long range and fast measurement cycle Maxbotix LV-MaxSonar-EZ1 Sonar Module ultrasonic sensors (Robotic Inc., Boisbriand, QC, Canada) were incorporated vertically into individual boom sections to detect weeds taller than blueberry plants in real-time for use in wild blueberry fields (Fig. 3-1). The 6.1 m long sensor boom was mounted in front of the ATV at 0.90 m height above ground surface. The sensors were connected to the VRC (Chemical Containers, Inc., Lake Wales, FL, USA). The VRC consists of electronic hardware with internal firmware and matching Windows Mobile 6.0 software on a PPC. The VRC was interfaced to a PPC and could be operated easily from a PPC using wireless Bluetooth® radio. The VRC received target (weeds taller than blueberry plants) detection signal from the sensor and opened the valve in a specific section of boom where the target had been detected. The plant height typically ranged from 12 cm to 27 cm at time of application. The VRC was installed in the ATV cab and was connected to LMC (DICKEY-John Corporation, Auburn, IL, USA). After receiving the target detection information from the sensor the VRC automatically communicated with the LMC. The LMC regulated the discharge of the nozzles in specific sections of the boom where the target had been detected based on ground speed obtained from a WAAS enabled DGPS (Garmin International Inc. Olathe, KS, USA) through a Dickey John (DJ) servo valve and DJ flow meter (Fig. 3-3).

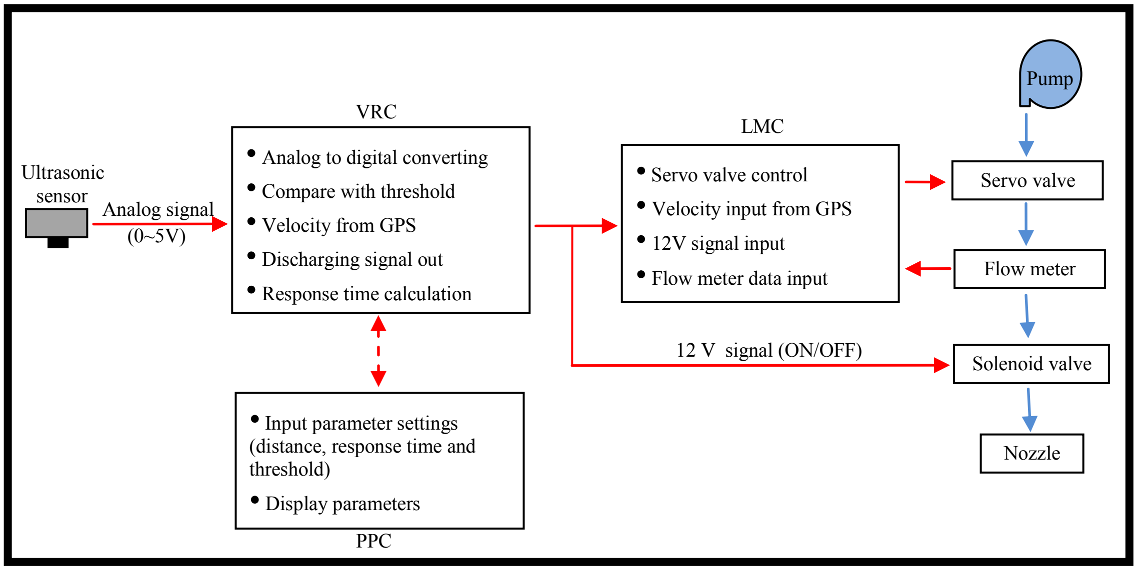


Figure 3-3 Flow chart showing the complete process from tall weed detection to spray discharge using ultrasonic sensors.

3.3.1 Ultrasonic Sensor Calibration

Ultrasonic sensors were calibrated in the metal shop at Nova Scotia Agricultural College (NSAC), Truro, NS, Canada to measure the distance from the sensor to the target. The distances (from sensor to the target; cardboard) were measured three times at ~12.7 cm intervals up to 152.4 cm with a measuring tape. The corresponding voltages were recorded using a digital multimeter at the time of distance measurements for comparison. The voltages were digitized from analog to digital to make them compatible with the program software installed in the PPC. The measured distances (from sensor to target) and voltage were compared by linear regression using Microsoft Excel software (Microsoft, WA, USA) to examine the performance accuracy of the ultrasonic distance measurements. The calibration equation was incorporated into the program software installed in the PPC.

The ultrasonic sensors were calibrated to measure the distance from the ultrasonic sensor to the weeds in a wild blueberry field. The maximum height (from the ground surface) of selected weeds was 30 cm. The distances (from sensor to the weeds) were measured three times at ~10 cm intervals up to 140 cm with measuring tape. The multimeter was connected to a sensor. The corresponding voltages were recorded using a digital multimeter at the time of distance measurements for comparison. The measured distances (from sensor to weeds) and voltage were compared by linear regression using Microsoft Excel software to examine the performance accuracy of the ultrasonic distance measurements. The developed calibration curve was installed in the VRC for proper targeting of tall weeds in wild blueberry fields (Fig. 3-4).

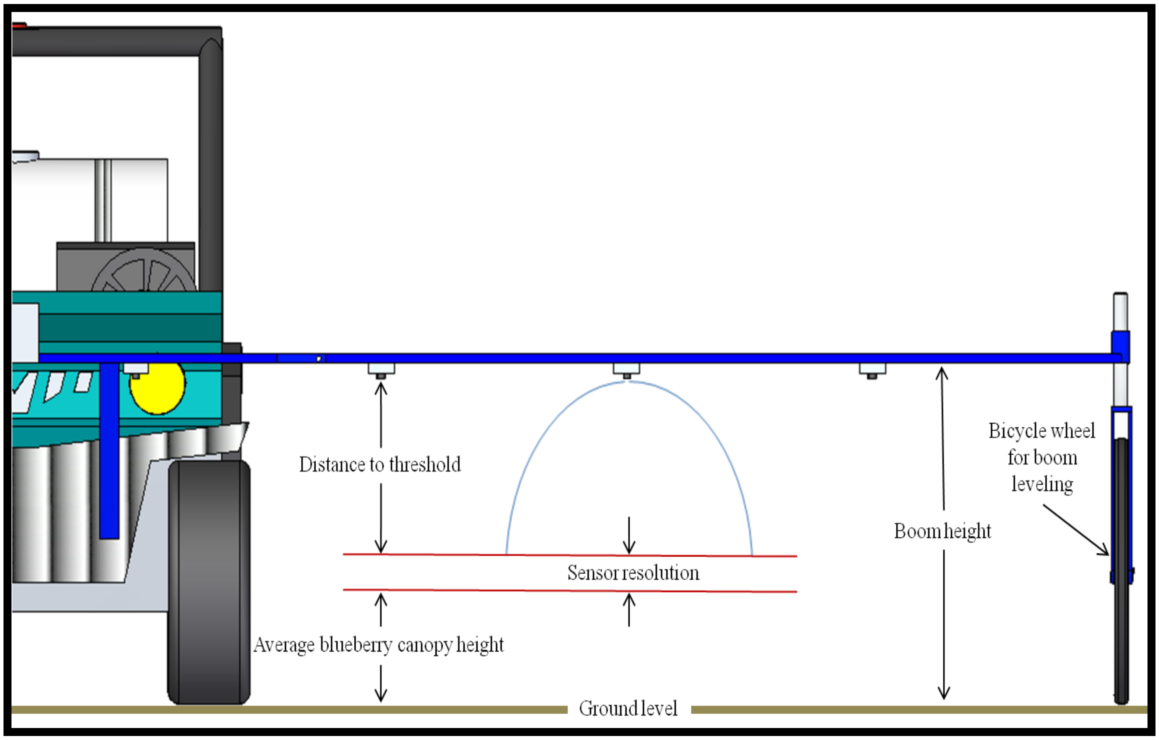


Figure 3-4 Front view of VR sprayer right boom section showing threshold height from sensor to target and sensor target zone for spray.

3.3.2 VRC Response Time for Precise Targeting using Ultrasonic Sensors

An experiment was conducted in the metal shop at NSAC to calculate the response time (i.e., lag time between sensor detection and target spray) for the VRC to open the valve at the correct target after receiving target detection information from the sensor. The time to build up the cone after the discharge is started has been added in calculating response time for precise real-time spray at correct target. An LED bulb was wired into switch #8 on VRC. A µEye camera (UI-1220SE/C, IDS Imaging Development System Inc., Woburn, MA, USA) was positioned in front of the spray nozzle (nozzle #8) to record the video. The bulb was placed within 5.8 cm of the camera lens so that it could be seen in the centre of the video frame (Fig 3-5). The video was recorded with 149 frames s^{-1} when the sensor detected the target and bulb was ON until the controller opened the valve to spray at the target. The test was repeated ten times and video images were analyzed with V1 HOME 2.0 software (Interactive Frontiers, Inc., Plymouth, MI, USA), allowing for a frame by frame analysis of response time between sensor detection and target being sprayed.

Figure 3-5 VRC response time experimental setup.

3.4 VR Sprayer with μEye Digital Color Cameras for Weed and Blueberry Plant Detection

Four, cost-effective μEye digital color cameras (UI-1220SE/C, IDS Imaging Development System Inc., Woburn MA, USA) were incorporated on the boom in front of the ATV at a height of 1.2 m (Fig. 3-6). Each camera covered two sections of the boom (0.762 m each section). Cameras were attached using USB cables to a ruggedized laptop (Latitude E6400 XFR, Dell Inc., Round Rock, Texas, USA) on the ATV. The camera lenses (LM4NCL, Kowa Optimed Inc., Torrance, CA, USA) had 3.5 mm focal length and were set up with fixed aperture (f/4.0) and infinity focus. Exposure time and digital gain were automatically controlled by auto exposure shutter/ auto gain control (AES/ AGC) to adjust for variable outdoor light conditions. The maximum auto exposure shutter was set to 2 ms to prevent picture blurring during field operations.

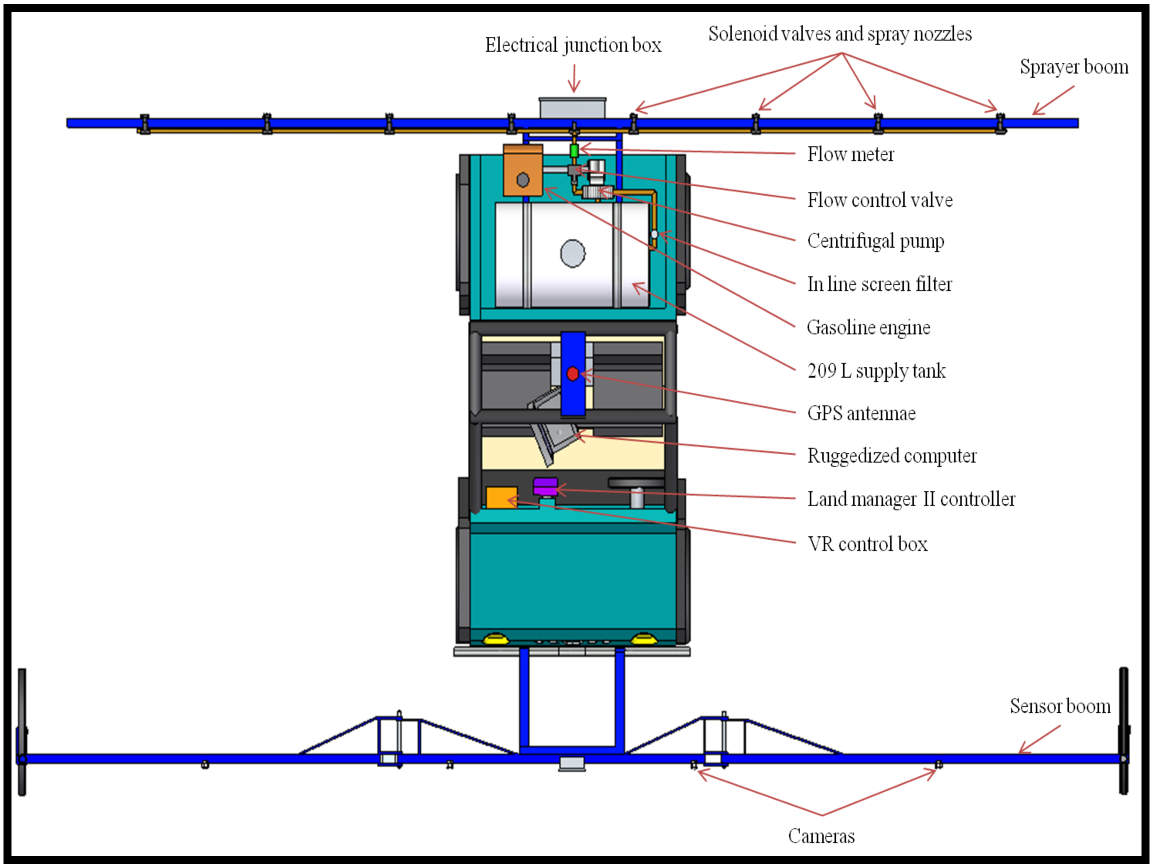


Figure 3-6 Schematic diagram of automated prototype VR sprayer for SA of agrochemicals using digital color cameras.

Custom image processing software installed in a computer was capable of processing images to differentiate between bare spots and foliage (wild blueberry plants and weeds) in real-time and send ON/OFF commands to a U3-HV (LabJack Corp., Lakewood, CO, USA) i/o unit. The U3-HV sends ON/OFF signals (5 V DC) to the VRC. The VRC has user programmable inputs from PPC such as a before and after buffer for precise overlapping, distance between front boom and sprayer boom and response time, and is able to automatically compensate the signal delay based on vehicle ground speed from a WAAS-enabled DGPS (Garmin International Inc. Olathe, KS, USA). The VRC converts ON/OFF signals from 5 VDC to 12 VDC and sends to the LMC and each solenoid valve. The LMC regulates the flow with a DJ servo valve and a DJ flow meter based on the status of solenoid valves and ground speed obtained from WAAS-enabled DGPS (Fig. 3-7).

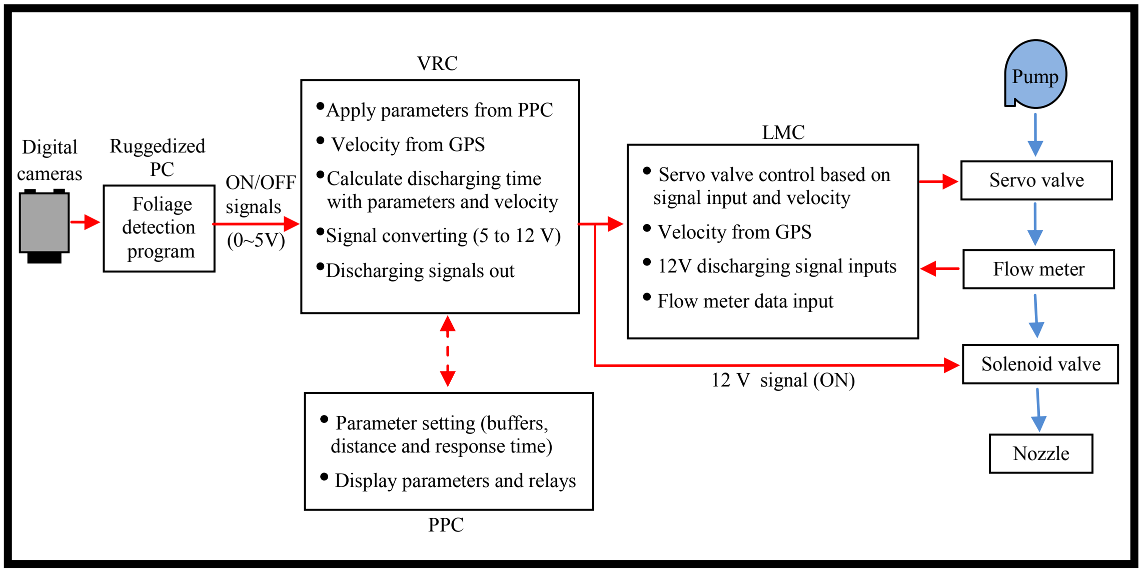


Figure 3-7 Flow chart showing complete process from foliage detection to spray discharge using digital color cameras.

3.4.1 Software Development

Real-time foliage detection software for SA of fungicide was developed in C++ using Visual Studio 2010 (Microsoft, Redmond, WA, USA). The real-time foliage detection software acquires 24-bit RGB 752 × 128 images corresponding to a 1.52 × 0.31 m area of interest from each camera and processes the data to discriminate foliage from bare spots. Two interrupt routines (DGPS reading and 50 ms timer) were built into the program to acquire the image from the camera and transfer onto the ruggedized laptop for image processing. The digital color images taken by the cameras were processed in real-time to differentiate bare spots from wild blueberry plants in RGB color space. The ratio used was (G × 255)/ (R + G + B), and a manually obtained threshold (> 85) adequately discriminated the apparent foliage green pixels from the remaining pixels in all images.

Small clusters of pixels in the image were incorrectly identified as foliage due to specular reflection but these were easily removed by applying an erosion filter. The final result of foliage detection converted 5 V DC signal, in each image and sent it to the VRC for spraying in the specific section of the boom where the foliage had been detected (Fig. 3-8).

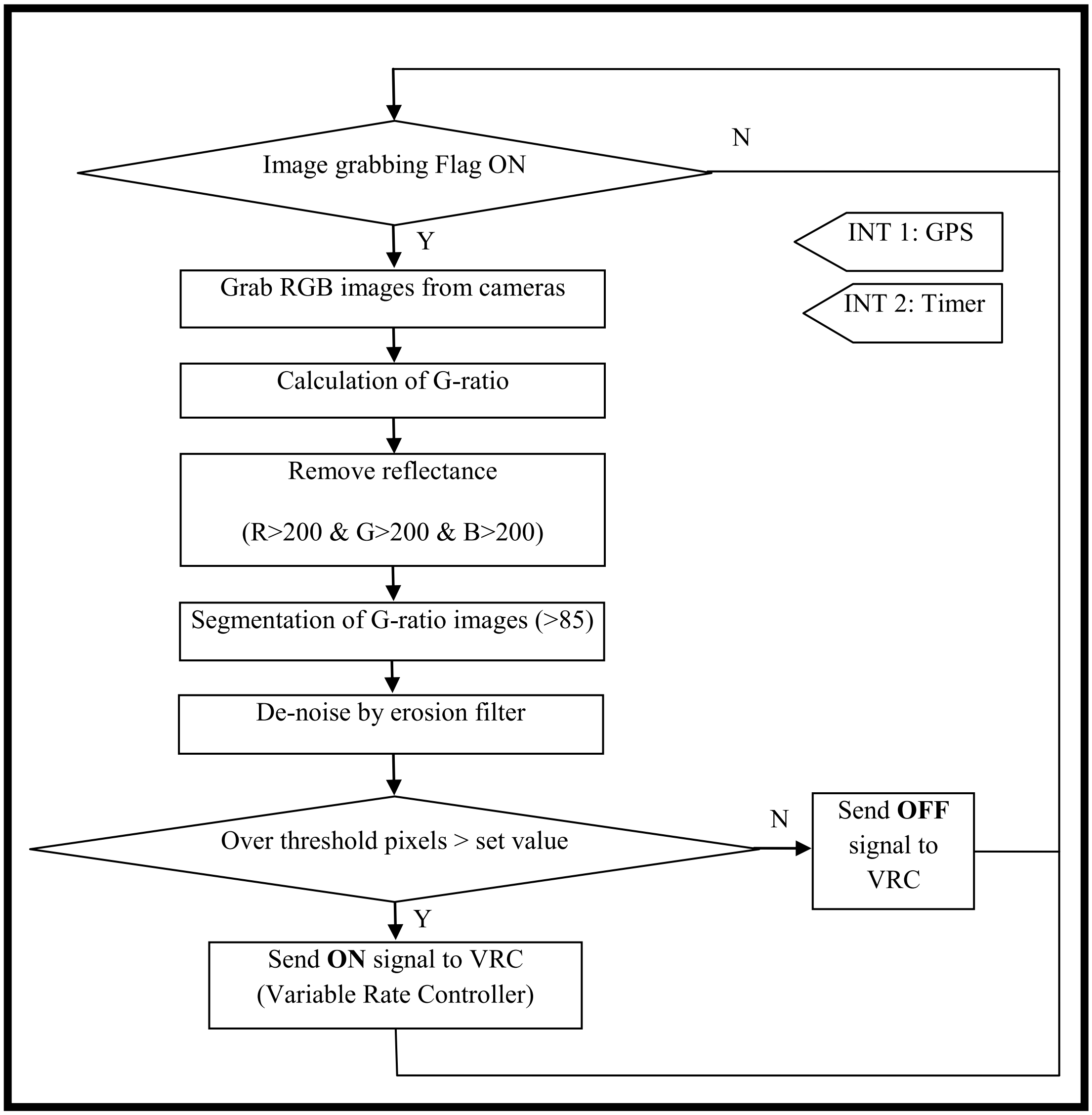


Figure 3-8 Image capture, processing and signal transfer algorithm.

3.4.2 VRC Response Time for Precise Targeting using Digital Color Cameras

An experiment was conducted in the metal shop at NSAC to calculate response time (i.e. lag time between camera image acquisition and spray discharge) for the VRC to open the valve at the correct target. Camera image acquisition time combined with image processing time was determined using a millisecond-timer function built into the custom software. An LED bulb was wired into a switch on the VRC. A μEye camera (UI-1220SE/C, IDS Imaging Development System Inc., Woburn MA, USA) was positioned in front of the spray nozzle to record the video. The video was recorded with 149 frames per second when the VRC receives targeting information from the computer and the bulb was ON until the controller opens the valve to discharge. The test was repeated ten times and video images were analyzed with V1 HOME 2.0 software (Interactive Frontiers, Inc., Plymouth, MI, USA), allowing for a frame by frame analysis of response time between VRC triggering signal and spray discharge. The total response was calculated as follows:

$$T_{rt} = T_{ic} + T_{ip} + T_{vd}$$

Where:

T_{rt} = Total response time
T_{ic} = Time taken by camera for image acquisition
T_{ip} = Image processing time for plant or bare spot detection and time from computer (sending signal) to VRC
T_{vd} = Time from VRC to spray discharge

3.5 Real-time Field Test using Ultrasonic Height Sensors

Three wild blueberry fields were selected in central Nova Scotia to test the performance accuracy of the VR sprayer for SA of agrochemicals. Kaolin clay and water mixture was applied to Fields 1 and 2 for application mapping and Callisto® was applied to Field 3. The selected sites were the Carmel Field (Field 1; 45.471101°N, 63.645816°W), Cattle Market Field (Field 2; 45.364850°N, 63.212783°W) and Cooper

Field (Field 3; 45.480573°N, 63.573471°W). Carmel and Cattle Market Field were in their sprout vegetative year of the biennial crop production cycle in 2009 at time of application, having been in the crop year in 2008 while, Cooper Field was in sprout year in 2010 during VR spray testing. The fields had been under commercial management over the past decade and received biennial pruning by mowing for the past several years along with conventional fertilizer, weed, and disease management practices. The main weed species, in competition with wild blueberry were goldenrod (*Solidago* sp.) in Carmel and Cooper Field, and black bulrush (*Scirpus atrovirens* Willd.), dogbane (*Apocynum androsaemi-folium* L.) and bracken fern (*Pteridium aquilinum* L.) were more in Cattle Market Field. The average blueberry plant height was 24 cm and weed height ranged from 50 cm to 70 cm. Meteorological conditions were same for both UA and SA during the field experiment.

Two tracks (100 m × 6.1 m each) were selected in both Carmel and Cattle Market Field to test the accuracy of VR sprayer for detecting weeds and spraying at the correct targets. The boundaries of selected tracks were mapped with real time kinematics-global positioning system (RTK-GPS) (On GRADE Inc., Dartmouth, NS, Canada) in each field. Twelve water sensitive papers (WSPs) were stapled at randomly selected weed spots in each track in Carmel and Cattle Market Field (Figs. 3-9 and 3-10). The weed patches were not equally distributed in the fields. There were very few weeds at the West part in Carmel Field. The WSPs were orientated parallel to the ground and selected targets were marked with RTK- GPS for mapping in ArcView3.2 GIS software (ESRI, Redlands, CA, USA). The water was sprayed on SA mode and WSPs were collected after drying. WSPs were stapled again and water was sprayed with a uniform application (UA) for comparison. The WSPs were scanned and processed to calculate PAC of the sprayed targets with both SA and UA using WinRHIZO image analysis system (Regent Instruments Inc., Canada). The paired t-test was performed to examine whether the percent area coverage (PAC) of the sprayed targets with SA were different from the PAC of the targets with UA. The heights of selected targets (weeds) were measured manually with a meter stick at the time of application during the experiments. The linear regression method in Microsoft Excel was used to test the relationship between target height and PAC of the sprayed targets with both methods UA and SA.

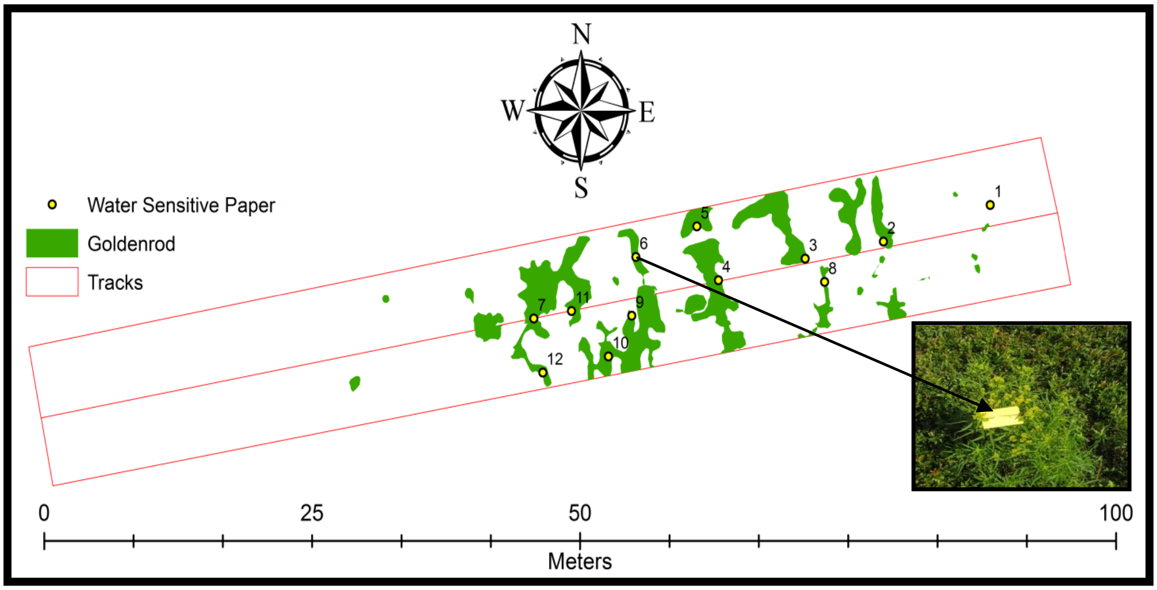


Figure 3-9 Map showing targets (WSPs) selected for spray applications with prototype VR sprayer in each track of Carmel Field 1.

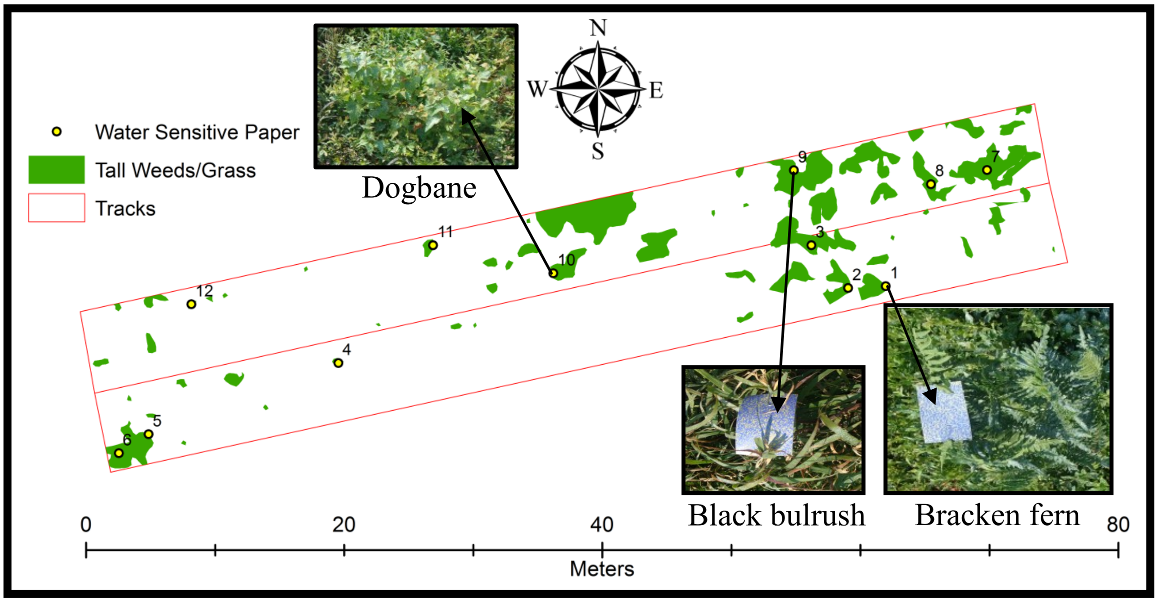


Figure 3-10 Map showing targets (WSPs) selected for spray applications with prototype VR sprayer in each track of Cattle Market Field 2.

The Cooper Field was divided into 18 equal tracks (80 x 6.1 m) and the experiment laid out following completely randomized block design (CRBD) with three treatments and six replications. The treatments were: i) Control (CN); No application, ii) SA of Callisto®, and iii) UA of Callisto®. Chemical saving analysis was also performed comparing SA technique to the conventional UA. The boundaries of selected tracks were mapped with RTK-GPS and twelve WSPs (targets) were stapled at randomly selected weed spots in a SA track and UA track (6 WSPs in each) (Fig. 3-11). The weed patches were randomly distributed but there seemed to be larger patches in the south half of the field. The WSPs were orientated parallel to the ground and selected targets were marked with RTK- GPS for mapping in ArcView3.2 GIS software. Callisto® was sprayed in each SA and UA track in the field and the WSPs were collected after drying. The WSPs were scanned and processed to calculate PAC of the sprayed targets with both SA and UA using WinRHIZO image analysis system. The paired t-test was performed using

Minitab statistical 15 software (Minitab Inc., NY, USA) to examine whether the PAC of the sprayed targets with SA different than the PAC of the targets with UA. A percent Callisto® savings was also calculated for the six SA tracks in the field.

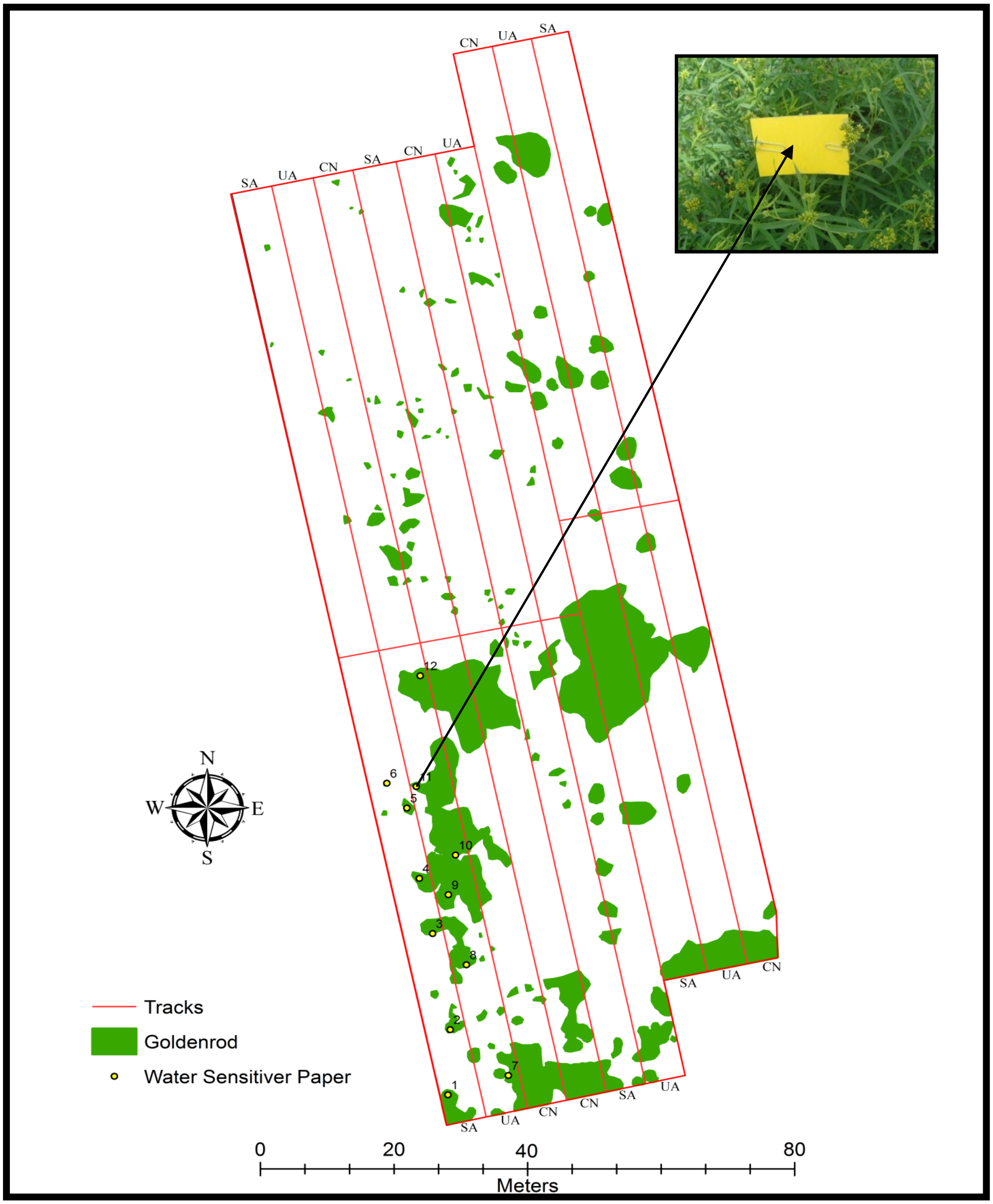


Figure 3-11 Map showing targets (WSPs) selected for spray applications with prototype VR sprayer in each track of Cooper Field 3.

The ground speed during the field operations was 6 ± 0.2 km hr^{-1}. Threshold distance from the sensor to weed canopy was set at 58 cm height to detect the weeds accurately in the selected fields. The buffer, before and after the target, was adjusted at 25.4 cm for precise overlapping of Callisto® application on targets. The response time and other constant parameters, threshold height from the sensor to weed canopy and buffer before and after the target, were stored in a non-volatile flash memory on the main microcontroller for accurate spray on correct targets. The stored operating parameters could be easily retrieved and activated by linking the VRC with a PPC using wireless Bluetooth® radio and editing or selecting values on the setup screen with Windows Mobile® compatible software. The application rate was setup at 187.0 L ha^{-1} in LMC.

3.6 Prototype VR Sprayer Setup using Digital Color Cameras

Growers apply herbicides during the growing season (Velpar® for pre-emergence control of grasses and perennial broadleaved weeds in April, Callisto® a post-emergence for control goldenrod and other annual broadleaf weeds in June and propyzamide (Kerb™) in the fall to control fescue grasses and sheep sorrel). Herbicide can be saved by utilizing a system employing digital color photography technology however, testing with actual herbicide is not recorded in this thesis but will rather focus on the proper application of fungicides in wild blueberry fields. Fungicides are applied for control of floral blights (*Monilinia* and *Botrytis)* and leaf diseases (*Septoria* and rust) on foliage only, and insecticides for fruit fly in July. The blueberry plants, grasses and weeds are not tall enough to sense using ultrasonic sensors in April and October. The digital color cameras with custom software, using the advanced image processing techniques, and fast processors are used to differentiate weeds, bare spots and blueberry plants real-time in the field. The weed or plant detection information is sent to the controller to spray agrochemical in the specific boom section where the weeds or plants have been detected.

The automated prototype VR sprayer consisted of µEye color cameras, ruggedized PC, VRC, LMC, PPC, solenoid valves, DJ servo valve, DJ flow meter and TeeJet nozzles (Fig. 3-12). The VR sprayer was mounted on an ATV (Yamaha Motor Canada Ltd., Toronto, ON, Canada). The 6.1 m sprayer boom was divided into eight sections (0.762 m each section). Section 3.1 describes the details of sprayer design for SA in wild blueberry fields.

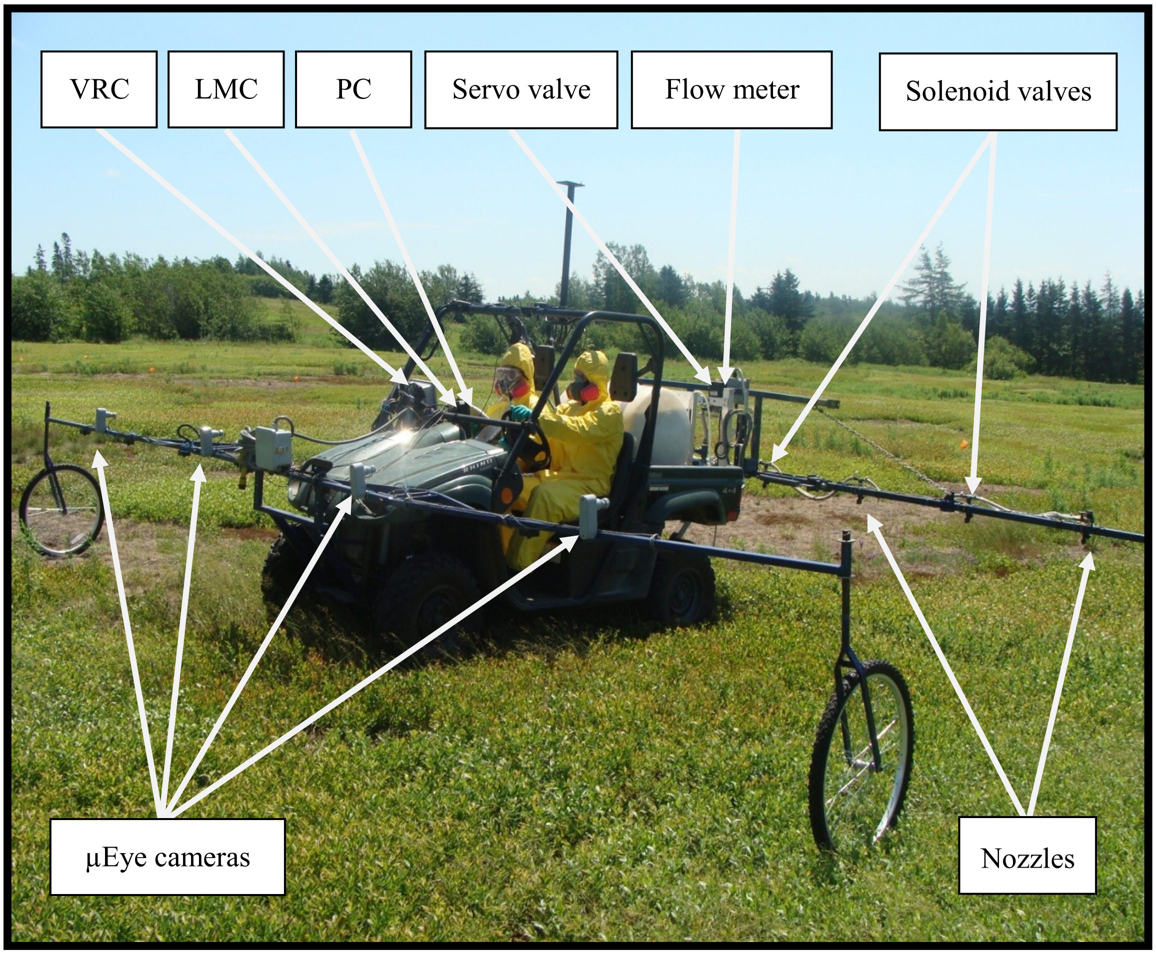


Figure 3-12 Prototype VR sprayer with µEye digital cameras, ruggedized PC, VR controller (VRC), land manager flow controller (LMC).

3.7 Field Setup for SA using Vision Technology

The Cooper Field in Londonderry, Nova Scotia (45.480573°N, 63.573471°W) was selected to test the performance accuracy of the VR sprayer for SA of Bravo® in July of 2010. The selected wild blueberry field was in the vegetative sprout year of the biennial crop production cycle, having been in crop during the previous summer of 2009. The field has been commercially managed while in production over the past decade. Conventional rates of herbicides for weed management, insecticides for insect control and fungicides for minimizing disease pressures were applied.

The ground speed during the field operations was 6.0 ± 0.2 km hr^{-1}. The buffer, before and after the target, was adjusted at 25.4 cm for precise overlapping of agrochemical applications on targets. The response time, buffer before and after the target and other constant parameters were stored in non-volatile flash memory on the main microcontroller. The stored operating parameters could be easily retrieved and activated by linking the VRC with a PPC using wireless Bluetooth® radio and editing or selecting values on the setup screen with Windows Mobile® compatible software. The application rate was setup at 187.0 L ha^{-1} in LMC.

Tracks (6.1 m wide each) were selected in the field to test the accuracy of the VR sprayer for detecting bare spots and spraying at correct targets. Boundaries of 18 selected tracks were mapped with RTK-GPS in the selected field. Bravo® was applied at grower's rate of 7.2 L ha^{-1} on foliage (blueberry plants and weeds). The field was laid out following a CRBD with three treatments and six replications. The treatments were: i) CN; ii) SA, and iii) UA (Fig. 3-13).

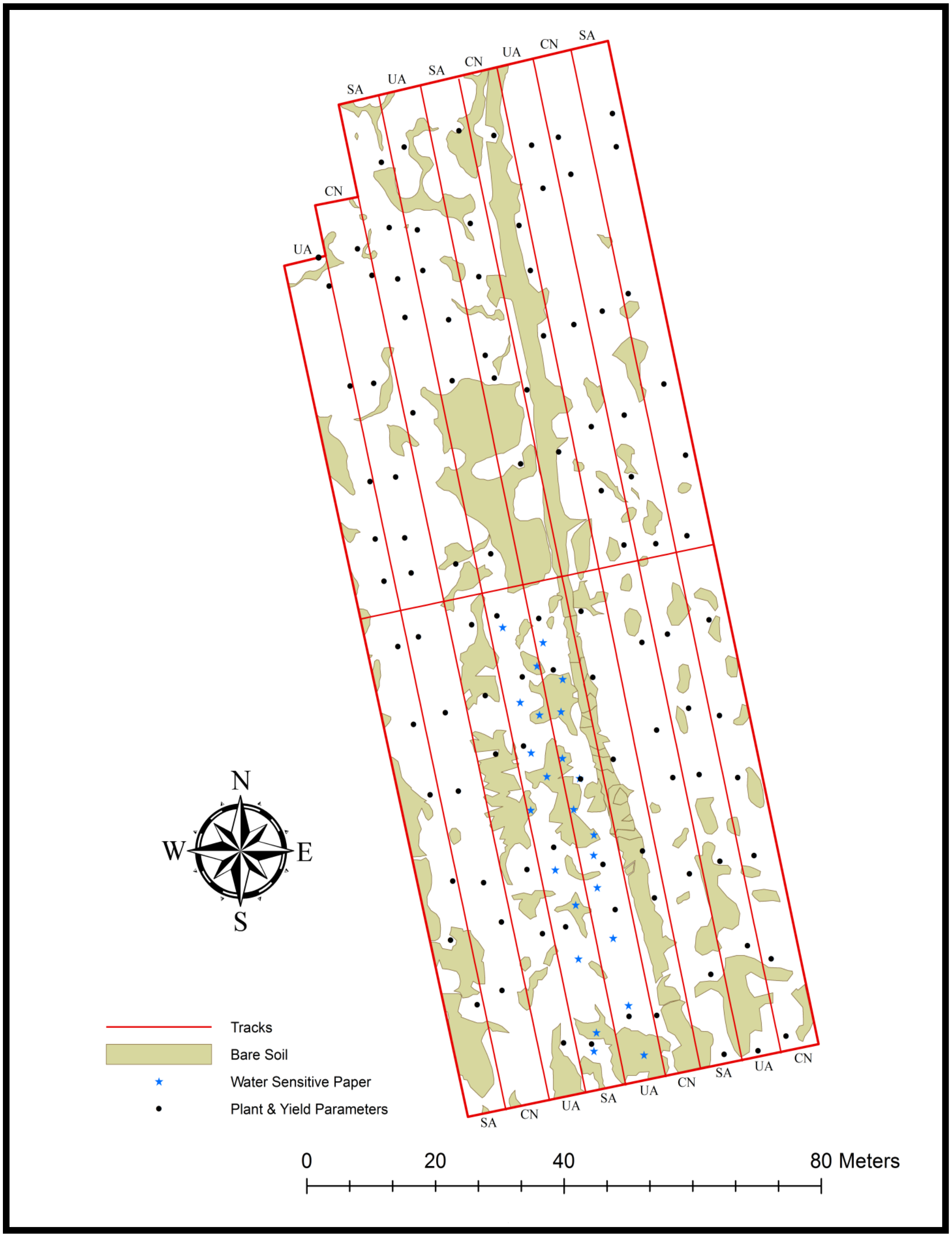


Figure 3-13 Cooper Field layout for VR application of Bravo®. Map shows locations for selected plant growth and fruit yield parameter data (•) and water sensitive paper locations for SA and UA in bare spots and plant foliage areas (*).

3.7.1 WSP Field Experiment and Estimated Fungicide Savings

WSPs were fastened at six randomly selected plant foliage areas and six bare spot areas in one SA track and the same procedure with a UA track (Fig. 3-13). The WSPs were orientated parallel to the ground and selected targets were marked with the RTK-GPS. Tracks were sprayed with SA and UA of Bravo® for comparison. The WSPs were collected after drying. The WSPs were scanned and processed to calculate their PAC in both blueberry plant foliage and bare spot areas for comparison. Classical statistics analysis was performed to calculate minimum, maximum, mean and standard deviation of PAC targets for both SA and UA using Minitab 15 statistical software (Minitab Inc., NY, USA). The paired t-test was performed to examine whether the PAC of targets with SA is different from the PAC of the targets with UA.

A chemical savings analysis was performed to compare SA technique with UA of Bravo® in wild blueberry fields. Sprayed areas were mapped using the RTK-GPS and imported into ArcGIS 9.3 computer software (ESRI, Redlands, CA, USA), to evaluate the performance of VR sprayer (Fig. 3-14). The chemical savings was calculated from the sprayed area and the track size using the following formula:

$$Chemical\ Savings\ (\%) = 100 - \frac{Sprayed\ Area}{Total\ Area} * 100\ \%$$

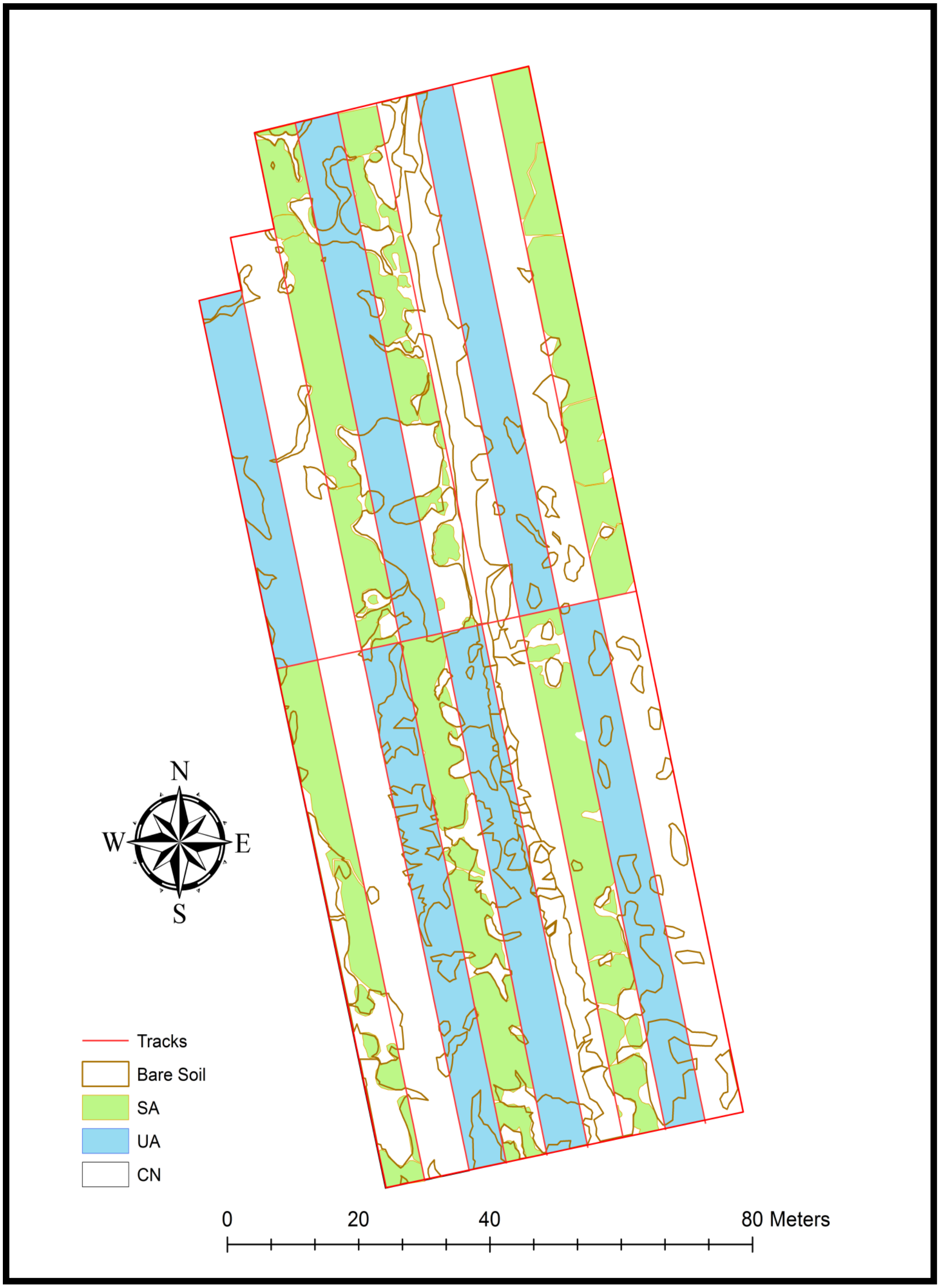


Figure 3-14 Cooper Field layout for SA and UA of Bravo® as well as CN tracks. Map shows application tracks and shows bare spot areas.

3.7.2 Blueberry Plant Growth, Health and Yield Measurements

Plant growth and yield parameters were measured from six randomly selected sampling plots in each track (SA, UA and CN) to assess the effect of Bravo® (Fig. 3-13). A steel quadrat measuring 0.15 × 0.15 m was used to mark out the area for plant density measurements. Six blueberry stems from each 0.15 × 0.15 m sample area were randomly cut using a knife to measure the height, number of branches and number of floral buds. The 6 recordings taken from each quadrat were averaged to show number of branches and number of floral buds per stem. A 0.5 × 0.5 m steel quadrat was used to collect and measure the yield from each of the 108 data collection plots. The yield was manually harvested using a 36 tooth hand rake collecting blueberries from the vine as well as any blueberries that dropped onto the ground. The collected yield and leaf debris samples were packaged in a sealed plastic bag and later separated and weighed in the lab. The plant density, stem height, number of branches and number of floral buds were counted in December 2010 of the sprout year while the fruit was harvested in Mid-August of 2011. Classical statistics was used to calculate minimum, maximum, mean and standard deviation using Minitab 15 statistical software (Minitab Inc. NY, USA). Analysis of variance (ANOVA) and post hoc LSD method with 95 % confidence interval was performed using SAS statistical software (SAS Institute, Cary, NC) to examine and compare the effect of Bravo® on the plant parameters with SA, UA and CN.

An 8.1-megapixel Sony Cyber-shot digital camera (Sony of Canada Ltd., Toronto, ON, Canada) was mounted on a tripod and pointed downwards at each of the six selected sample plots in each track at 1.0 meter height above ground (Fig. 3-15). On October 04 of 2010, blueberry foliage images were collected at each of the 108 different sample locations. A 0.5 × 0.5 m steel frame quadrat was constructed and placed at these selected locations on the ground to identify the area of interest. The image exposure and other camera settings were on automatic mode for this experiment. The images were imported into a laptop computer for further processing.

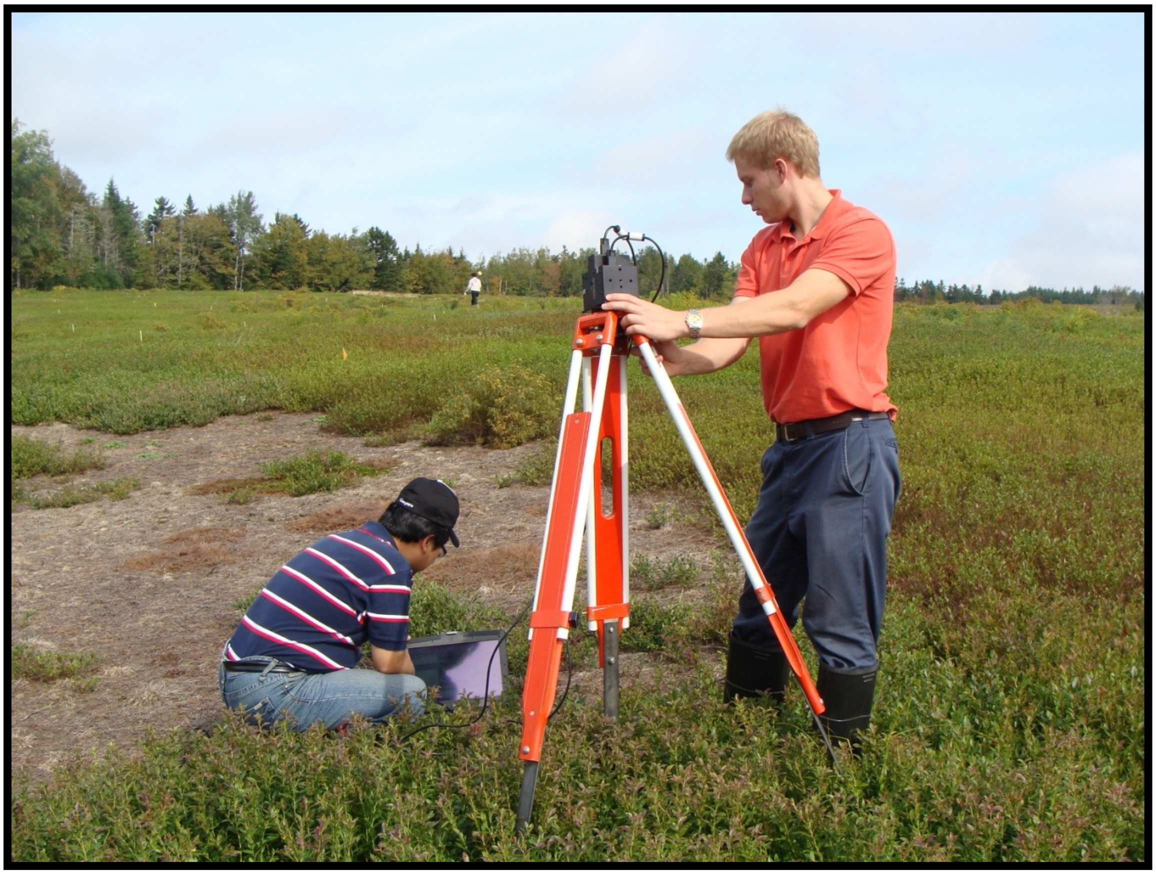


Figure 3-15 Image acquisition at selected points in Cooper Field.

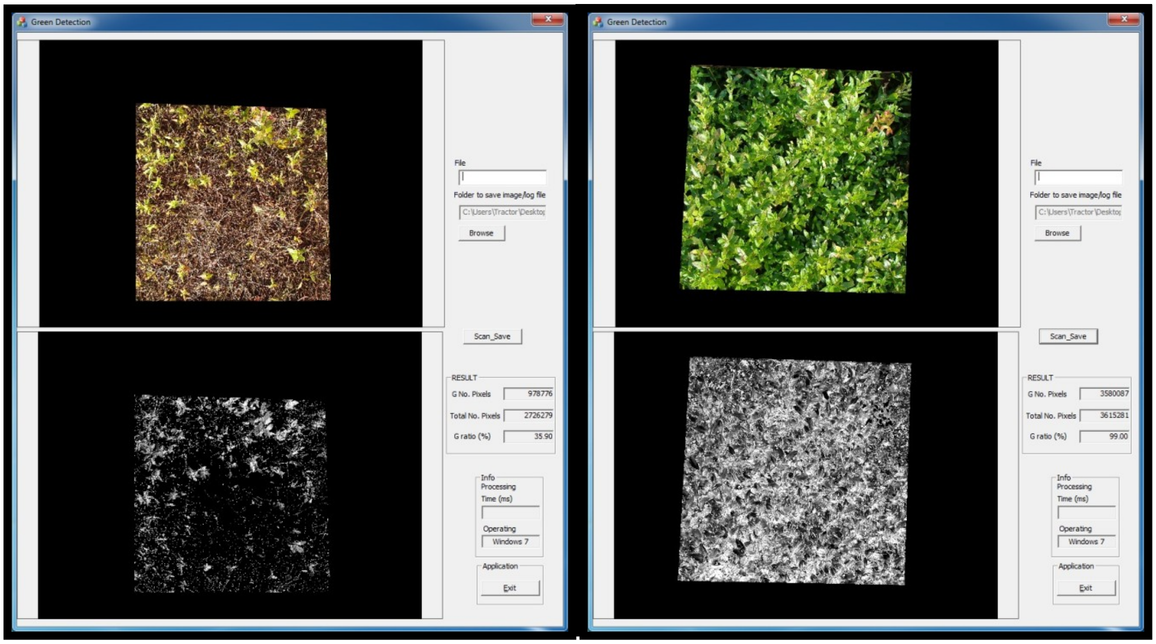
A custom image analysis program was used to determine the percentage of green pixels of the images taken from all application rates (SA, UA, CN) at each quadrat for comparison to quantify the effect of Bravo® on plant growth and leaf retention (Fig. 3-16). The software was used to enhance and count the mostly green pixels in the quadrat region of each image, using RGB pixel ratios, and expressing the result as the total green quadrat pixels.

$$Green\ Ratio = \frac{255 \times G}{R + G + B}$$

A manually obtained threshold of > 85 adequately discriminated the apparent foliage from the remaining pixels in all images. The percent of green ratio was calculated using the following formula and ANOVA and post hoc least significant difference (LSD) statistical procedure with 95 % confidence interval was performed using CoStat statistical software (CoHort Software, CA, USA) to compare the percent of green ratio of the selected areas with respect to the three application methods.

$$\%\ of\ Green\ Ratio = \frac{Total\ of\ Over\ 85\ pixels}{Total\ Pixels} \times 100$$

Most of the functions of the image analysis program are same to real-time foliage program except omitted interrupts, sending signals to VRC and image grabbing routines and added image reading and display routines.



Folder to save image/log file: C:\Users\Tractor\Desktop
G No. Pixels: 978776
Total No. Pixels: 2726279
G ratio (%): 35.90
Operating: Windows 7

Folder to save image/log file: C:\Users\Tractor\Desktop
G No. Pixels: 3580087
Total No. Pixels: 3615281
G ratio (%): 99.00
Operating: Windows 7

Figure 3-16 Image processing with custom percentage of green pixels software. Original image (top), conversion to calculate percentage of green pixels (bottom).

3.8 Expected Outcome

The expected outcome of the project is the development of equipment which will reduce the amount of agrochemicals applied to wild blueberry fields by applying a SA. The equipment consists of a VR sprayer with look-ahead vision technology which open and close spray nozzles in the specific locations as required. It features easy user-friendly setup with no complicated switches. Wireless convenience for operating parameter setup is possible even at some distance from the controllers via Bluetooth. There is automatic compensation for changing ground speed with no need to manually readjust sensors with the ability to input a manual speed in case of GPS signal outage. Adjustable front and back edge distance buffers are used for precise overlapping of agrochemical applications on targets. The outcome will increase agrochemical input use efficiency, reduce the cost of production and reduce environmental contamination. The research will also help to identify potential problems and future improvements required to make the prototype sprayer a commercial reality.

3.9 Project Benefits and Impacts

Wild blueberry producers and processors are the immediate beneficiary of this proposed research. In total, there are over 2,500 wild blueberry producers in Atlantic Canada, Quebec, and Maine who can benefit from the research. The large horticultural industry in eastern Canada will also benefit from this technology as it can be modified for other high value horticultural crops. The VR sprayer technology will also have a target audience including engineers involved in the design and manufacturing of sensors and controllers for precision agriculture. Other audiences that may benefit from the proposed research include the high bush blueberry and cranberry industries in North America.

This project has the potential to improve the competitiveness and profitability of the blueberry industry, reduce the environmental impact of existing wild blueberry production systems, and enhance the sustainability of rural life in Eastern Canada. The environmental impact will be positive as it is anticipated that the amount of current agrochemicals being used in the wild blueberry industry will be reduced and better targeted by SA of agrochemicals. This coincides with the desire of blueberry producers association and leading wild blueberry producers and processors, Oxford Foods Group to reduce agrochemical use by 40 %, increase harvestable yields by 33 % and to improve product quality and safety; and an overall need in the NS agri-food industry to develop site-specific farm management practices.

This technology could be very useful to (i) reduce agrochemical use, improve product quality and environmental stewardship, enhance production sustainability, reduce agrochemical usage and the overall cost of production; (ii) add value and enhance the efficiency, competitiveness and market position of eastern Canada’s blueberry industry; (iii) fill the growing market for environmentally friendly, safe, and healthy foods; and (iv) facilitate the continued conversion of the agri-food industry to a knowledge-based industry.

CHAPTER 4

DEVELOPMENT OF A PROTOTYPE VR SPRAYER FOR SMALL SCALE SPOT-APPLICATIONS IN WILD BLUEBERRY FIELDS

4.1 Introduction

Weeds are the major yield-limiting factor in wild blueberry fields (Yarborough, 2006). Weed flora in blueberry fields traditionally consisted of slow spreading perennial species whereas many of the new species invading blueberry fields are common annual weeds of arable fields that produce large number of seeds and require control with herbicides both in prune and production year (Jensen and Yarborough, 2004; McCully et al., 1991). Traditionally, herbicides are applied uniformly in wild blueberry fields, but weeds are not distributed uniformly within fields. In these situations, spatial information management systems hold great potential for allowing producers to fine-tune the locations, timings, and rates of herbicide application.

Many researchers have attempted to develop VR technologies for various crops (Rockwell and Ayers, 1994; Giles and Slaughter, 1997; Steward and Tian, 1999; Tian, 2002; Carrara et al., 2004; Miller et al., 2005; Zaman et al., 2005, Schumann et al., 2006a; Dammer et al., 2008) to date little attention has been paid to wild blueberry production systems. Michaud et al. (2008) developed a VR prototype sprayer to deliver pesticides based on prescription maps, developed in GIS software, using aerial spectral scans of wild blueberry fields. The system was sensitive to positional error caused by GPS and obtaining up-to-date aerial photography was expensive, the quality was quite variable, and data processing for weed detection was also intensive and difficult.

Several machine vision systems have been developed to detect weeds in different cropping systems (Sui et al., 1989; Shearer and Holmes, 1990; Zhang and

Chaisattapagon, 1995; Tian et al., 1997; Zhang et al., 2009), because real-time weed detection at the time of spot spraying could be very valuable for lower chemical usage and reducing environmental contamination. However, these vision systems, based on morphological or textural weed detection methods, generally needed a relatively high image resolution, and the detection algorithms were quite complicated and computationally expensive (Meyer et al., 1998; Zhang et al., 2009). There is a need to develop spot-specific herbicide application technologies that do not require high resolution image processing techniques, but rely on sensors or digital color cameras with fast image processing to sense the weed in real-time and provide the weed detection information to fast VR controllers for spray at correct targets.

Ultrasonic sensors are widely accepted for quantification of plant heights (Sui et al., 1989; Schumann and Zaman, 2005). Swain et al. (2009) developed and tested low-cost ultrasonic system for weeds (taller than plants) and bare spot mapping in real-time within wild blueberry fields during growing season. They reported that ultrasonics performed well to detect tall weeds (taller than plants) and bare spots in wild blueberry fields.

Advances in sensing technology and VR control systems have offered new opportunities for detecting weeds and SA of agrochemicals in a specific section of the VR sprayer boom where the weeds have been detected. Many commercial controllers have been developed to deliver agrochemicals on site-specific basis using GPS guided prescription maps within field (DICKEY-John Land Manager II: DICKEY-john Corporation, Auburn, IL; MidTech Legacy 6000 controller: Midwest Technologies, Spring- field, IL; Raven 660 controller: Raven Industries Inc., Sioux Falls, SD).

Schumann and Hostler (2009) with the partnership of a machinery manufacturer (Chemical Containers, Inc., Lake Wales, FL, USA) developed an 8-channel computerized VR controller consists of electronic hardware with internal firmware and matching Windows Mobile 6.0 software on a handheld pocket PC (PPC). A computerized 8-channel VR controller is linked with PPC using wireless Bluetooth®. Typically this controller does not use prescription maps, but relies on sensors to provide real-time weed information which is used to dispense the correct herbicide rate for the weed eradication within field. Reliable and fast ultrasonics/digital color cameras and VR controllers could be used to develop a VR rate sprayer for in-season, spot-application (SA) of agrochemicals in the wild blueberry cropping system.

In this study, an automated VR prototype sprayer consisting of ultrasonic sensors, digital color cameras, 8-channel computerized VR controller (VRC), Land Manager II controller (LMC), solenoid valves, PPC with operating software was developed and performance tested.

4.2 Materials and Methods

4.2.1 Development of a Prototype VR Sprayer using Ultrasonic Sensors

The automated prototype VR sprayer developed for SA of herbicides on tall weeds/ grass consists of ultrasonic sensors, 8-channel computerized VRC, LMC, PPC with operating software, solenoid valves, servo valve, flow meter and nozzles. The 6.1 m sprayer boom is divided into eight sections (97 cm each section) with an independent solenoid valve and nozzle for each section. Ultrasonic sensors were incorporated vertically into individual boom sections of the sprayer to detect tall weeds and grass in real-time within wild blueberry fields. The sensor boom was 6.1 m in width at a height of

0.90 m above the ground surface. The sprayer and front look-ahead sensor boom was mounted on an ATV. The stored operating parameters (buffer, response time and threshold height) were retrieved and activated, by linking the VRC with a handheld PPC using wireless Bluetooth and editing or selecting values on the setup screen with Windows Mobile compatible software. The VRC receives signals from the sensors and communicates at the same time automatically to both the LMC and the individual solenoid valves. The LMC regulates the flow rate based on ground speed obtained from WAAS-enabled DGPS through a servo valve. The total applied chemical information will be stored and later imported from the LMC.

4.2.2 Development of a Prototype VR Sprayer using µEye Cameras

Two cost-effective µEye digital color cameras were incorporated on each side of the boom because blueberry plants, grasses and weeds were not tall enough to sense using ultrasonic sensors in spring and fall. Each camera is able to cover two sections of the boom (97 cm each section). Cameras were attached using USB cables to the computer on the ATV. Custom software, installed on the computer, capable of processing the images to detect weeds, bare spots and blueberry plants in real-time sends weed or plant triggering signals through a Labjack digital i/o (LabJack Corp., Lakewood, CO) and data acquisition device to the VRC. The VRC had user programmable inputs such as a before and after distance buffer, response time and ground speed correction. The VRC sent a 12 V DC power signal to the LMC which automatically adjusted the flow rate based on the number of nozzles on at a specific time and also actuated the corresponding solenoid valve to spray agrochemical in the specific boom section where the weeds or plants were detected.

4.2.3 Testing and Performance Evaluation of the Prototype VR Sprayer

Major components of the prototype VR sprayer (VRC, sensors/ digital color cameras, and LMC) were tested at the Nova Scotia Agricultural College (NSAC) for accurate target detection and spraying. The performance of SA with the prototype VR sprayer was evaluated in wild blueberry fields.

An experiment was conducted at the NSAC to evaluate the performance accuracy of the LMC for flow rate measurements from the nozzles mounted on the sprayer boom. The volume of water from each nozzle and then from different combinations of nozzles were recorded from the LMC and also at the same time volume was measured manually using graduated cylinders for comparison. The experiment was replicated three times and output volume measurement readings were averaged in Excel and the percent difference was determined between manually measured readings and the LMC digital readout. The differences found between manually measured volumes and LMC volumes were used to characterize the performance accuracy of the LMC.

Ultrasonic sensors were calibrated to measure the distance from the sensor to the target in the metal shop at NSAC. The corresponding voltages were recorded using a digital multimeter at the time of distance measurements for comparison. The measured distances (from sensor to target) and voltage were compared in Microsoft Excel by linear regression to examine the performance accuracy of the ultrasonic distance measurements. The calibration equation was incorporated into the software program installed in the PPC.

An experiment was conducted in the metal shop at NSAC to calculate response time (i.e. lag time between sensor detection and spray discharge time) for the VRC to open the valve at the correct target after receiving target detection information from the sensor. An LED bulb was wired into a switch on the VRC. A µEye camera was positioned in front of the spray nozzle to record the video. The video images were recorded with 149 frames per second when the sensor detected the target and the bulb was ON until the controller opened the valve to discharge. The test was repeated ten times and video images were analyzed with V1 HOME 2.0 software (Interactive Frontiers, Inc., Plymouth, MI, USA), allowing for a frame by frame analysis of response time between sensor detection and full spray discharge.

4.3 Results and Discussion

4.3.1 LMC Flow Rate Evaluation

The LMC performed reliably and rapidly to regulate the flow rate in each nozzle through the servo valve and flow meter with a maximum of ≤ 3.7 % difference from manual flow measurements during calibration test and (Table 4-1). Therefore, the principle components of the VR sprayer could be used to further develop the sprayer to detect targets (weeds taller than plants) and SA of agrochemicals at correct targets reliably to reduce cost of production and protect environment.

Table 4-1 Comparison of LMC discharge measurement with manually measured discharge from the nozzle(s) in different sections of the sprayer boom.

Nozzle(s) open	1	1,2	1,2,3	1,2,3, 4	1,2,3, 4,5	1,2,3, 4,5,6	1,2,3, 4,5,6, 7	All 8
Manually Measured (L min^{-1})	12.0	13.3	14.9	18.6	18.9	18.9	18.6	36.9
LM Controller (L min^{-1})	11.7	13.3	15.2	19.0	19.4	19.6	19.0	37.4
Difference (%)	+2.5	0.0	-2.0	-2.1	-2.6	-3.7	-2.1	-1.4

4.3.2 Ultrasonic Sensor Calibration

The principal components of the VR sprayer (sensors and controllers) were successfully calibrated and tested in the metal shop at NSAC for target sensing and spraying at correct target in a specific section of the sprayer boom where the target has been detected. Ultrasonics were calibrated for distance measurement and the linear calibration model showed that distance measured from sensor to cardboard was correlated highly significantly with the voltage ($R^2 = 0.99$; $P < 0.001$). The ultrasonic sensor was also calibrated for distance measurement in a wild blueberry field and the linear regression results indicated highly significant correlation between distance measured from sensor to weeds and voltage ($R^2 = 0.99$; $P < 0.001$). The ultrasonic sensor calibration equation for distance measurement (Figs. 4-1 and 4-2) was incorporated into software installed in PPC to permit the sensor of target detection accurately.

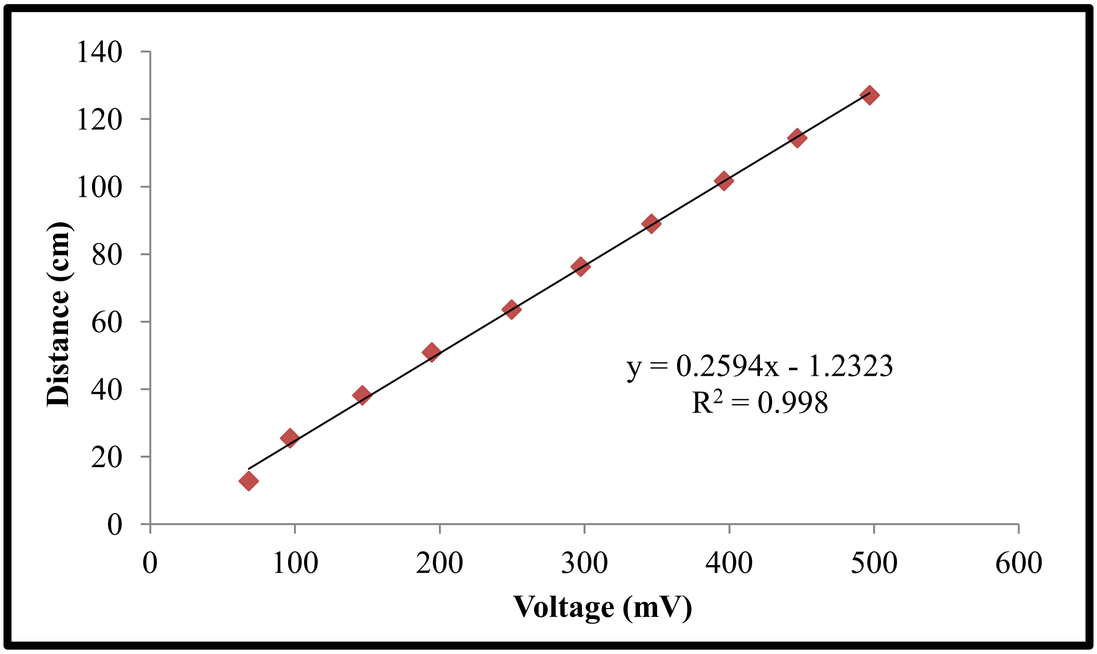


Figure 4-1 Relationship between voltage obtained from voltmeter connected to ultrasonic sensor and actual distance measured from sensor to target (cardboard) with measuring tape for calibration of ultrasonic sensor to measure target heights.

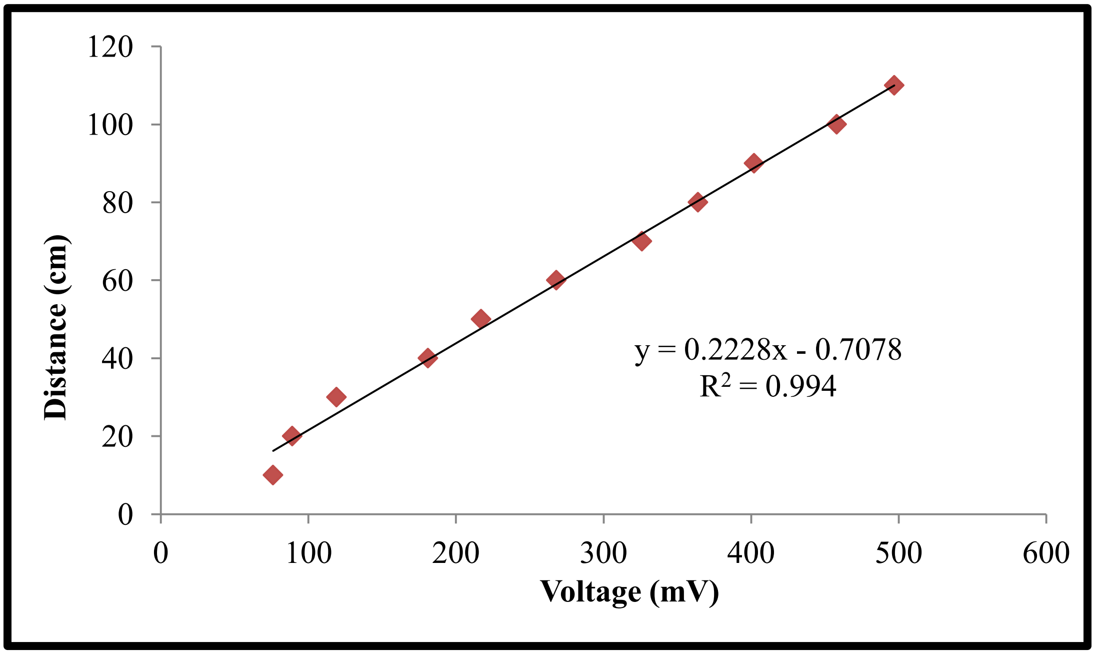


Figure 4-2 Relationship between voltage obtained from voltmeter connected to ultrasonic sensor and actual distance measured from sensor to target (weeds) with measuring tape for calibration of ultrasonic sensor to measure target heights.

4.3.3 VRC Response Time for Precise Targeting using Ultrasonic Sensors

Results indicated that VRC was operated easily from PPC using wireless Bluetooth radio with Windows Mobile compatible software. VRC was fast and accurate enough to open the valve at correct target with response time 0.050 ± 0.003 s (Table 4-2) after receiving the sensor target detection information.

Table 4-2 Response time for 8-channel computerized VRC to open valve and spray in a specific section of the boom where the target has been detected.

Trial	Camera start time (s)	Spray time (s)	Difference (s)	Average response time (s)
1	3.497	3.544	0.047	0.050 ± 0.003
2	7.946	7.993	0.047	
3	12.329	12.376	0.047	
4	16.765	16.819	0.054	
5	21.087	21.141	0.054	
6	25.490	25.537	0.047	
7	29.564	29.618	0.054	
8	33.564	33.618	0.054	
9	37.336	37.390	0.054	
10	41.282	41.336	0.054	

4.3.4 Image Processing and VRC Response Time with µEye Digital Color Cameras

The total response time (0.131 s) was programmed into the VRC and the front boom was spaced far enough ahead of the rear sprayer boom to compensate for the time lag needed to take the image, process the image with computer, send triggering signal to the control and then send power to the corresponding solenoid valve opening the nozzle and spraying (Table 4-3). The VR sprayer was able to spray at the target location while travelling at 6 km hr^{-1} during field operation without response time issues.

Table 4-3 Response time for 8-channel computerized VRC to open valve in the specific section of the boom where the target detected.

Trial	Image acquisition time (s)	Processing time (from camera to VRC) (s)	Camera start time (s)	Spray time (s)	Difference (s)	Average response time (s)
1	0.015	0.064	3.497	3.544	0.047	0.131 ±0.003
2			7.946	7.993	0.047	
3			12.329	12.376	0.047	
4			16.765	16.819	0.054	
5			21.087	21.141	0.054	
6			25.490	25.537	0.047	
7			29.564	29.618	0.054	
8			33.564	33.618	0.054	
9			37.336	37.390	0.054	
10			41.282	41.336	0.054	

4.4 Summary and Conclusions

The LMC performed reliably and rapidly to regulate flow rate in each nozzle through servo valve and flow meter with ≤ 3.7 % difference from manual flow measurements during calibration test with four nozzles open. Ultrasonics were calibrated for distance measurement and the linear calibration model showed that distance measured from sensor to cardboard and sensor to weed was correlated highly significantly with the voltage ($R^2 = 0.99$; $P < 0.001$) and ($R^2 = 0.99$; $P < 0.001$) respectively. Results indicated that the VRC was operated easily from PPC using wireless Bluetooth® radio with Windows Mobile® compatible software. Using the ultrasonic sensors the VRC was fast and accurate enough to open the valve at the correct target with a response time of 0.050 s after receiving the sensor target detection information. Therefore, the principal components of the VR sprayer could be used to develop the sprayer to detect targets (weeds taller than plants) and SA of agrochemicals at correct targets reliably to reduce cost of production and protect environment.

With μEye digital color cameras the total response time (0.131 s) was programmed into the VRC and the front boom was spaced far enough ahead of the rear sprayer boom to compensate for the time lag needed to process and spray allowing the ATV to travel 6 km hr^{-1} without response time issues. Therefore, The VR sprayer could be used to further expand the spray capabilities and allow for SA of herbicides and fungicides only where needed within field saving in bare spot areas or non weed infested areas during all times over the two-year production cycle.

CHAPTER 5

PERFORMANCE EVALUATION OF THE PROTOTYPE VR SPRAYER WITH ULTRASONIC SENSORS FOR SPOT-APPLICATION OF HERBICIDES ON TALL WEEDS IN WILD BLUEBERRY FIELDS

5.1 Introduction

Wild blueberry producers apply agrochemicals to minimize weed, grass and disease pressures within fields to maintain high yielding crops (Percival and Dawson, 2009, Yarborough and Jemison, 1997). Perennial weeds that have a life cycle of greater than two years are the most difficult to control in wild blueberry fields (Wild Blueberry Factsheet, 1997). Fields developed from woodland, often have to be treated with herbicides to control tree seedlings, perennial bushes and shrubs. However, fields developed from abandoned hayfields or pastures typically have to be treated for control of grasses and perennial weeds (Wild blueberry factsheet, 1997).

Hexazinone has been used heavily in wild blueberry production since 1983 to suppress competing weed cover (Yarborough and Jemison, 1997). As a result, hexazinone increases blueberry stem density, length, and number of buds maximizing yields up to threefold (Yarborough and Bhowmik, 1989, Yarborough and Jemison, 1997). Eaton (1993) found that wild blueberries react slowly to herbicide and fertilizer applications, and that much of the yield increases are from the effect of herbicides rather than from fertilizers. Hexazinone is known for leaching into ground water from wild blueberry fields because of the mostly sandy loam soils and the herbicide's chemical composition (Yarborough and Jemison, 1997). As a result, hexazinone has been applied at a reduced rate resulting in an increased weed pressures within wild blueberry fields (Yarborough and Marra, 1997). Pre-emergent application of herbicide is one of the most effective methods in controlling weeds, while later post-emergent applications are effective but can cause serious foliar damage to the crop (Jensen, 1985). The Nova Scotia wild blueberry network information centre suggests farmers to follow a list of best management practices for wild blueberry production. Producers need to scout their fields and spray only when and where necessary (Wild Blueberry Factsheet, 1997). Yarborough and Marra, (1997) found it does not pay to control common weeds found in wild blueberry fields until one-fourth to one-half of the field is infested with the weeds. If SA technologies were to be used it would allow for growers to apply herbicides to fields with any given percentage of weed coverage without worry of wastage of chemical that would increase production cost and pollute the environment.

Prior to the registration of pre-emergent herbicides, cutting and hand-wiping or herbicide rollers were used to control the growth of taller weeds (Yarborough, 2006). However, cutting is not effective and wiping could result in injury to the blueberry plant. Both cutting and wiping methods are laborious and time consuming. Newer post-emergent innovations such as the wick master wiper, sideswipe hockey stick wiper, sproutless weeder and clean cut applicator are readily available, effective and cause less damage to the plant however, they are still laborious and time consuming to operate (Yarborough, 2006).

Precision agriculture brings technologies together to make agriculture more economically and environmentally efficient (Al-Gaadi et al, 1999; Castro et al, 2011; GopalaPillai et al, 1999). One of the newest innovations in precision agriculture is the real-time VR sprayer. Motivation for the development of this type of VR sprayer is increased field performance and lower chemical use and costs (Mooney et al, 2009). This type of VR sprayer does not use prescription maps, but relies on sensors to provide real-time weed and bare spot detection information to the controller for spraying the correct targets. Although research programs throughout North America have concentrated on the development of VR technologies for different crops to date, little attention has been put towards wild blueberry production systems. In this study the developed VR sprayer with ultrasonic sensors is performance tested in selected wild blueberry fields in central Nova Scotia.

5.2 Materials and Methods

5.2.1 Field Tests Using Ultrasonic Sensors

Three wild blueberry fields were selected in central Nova Scotia to test the performance accuracy of the VR sprayer for SA during the summer. The selected fields were in the vegetative sprout year of the biennial crop production cycle. The predominant weed species, in rivalry with the wild blueberry were black bulrush (*Scirpus atrovirens* Willd.), dogbane (*Apocynum androsaemi-folium* L.) and bracken fern (*Pteridium aquilinum* L.) in the Cattle Market Field (45.364850°N, 63.212783°W) and goldenrod (*Solidago* sp.) in Carmel (45.471101°N, 63.645816°W) and Cooper Field (45.480573°N, 63.573471°W). The average blueberry plant height was 24 cm and weed height ranged from 50 cm to 70 cm. Meteorological conditions were same for both SA and UA during the field experiment.

5.2.1.1 Carmel Field

The Carmel Field was broken into two test tracks (100 x 6.1 m wide) that were marked to investigate the accuracy of the VR sprayer for detecting weeds and spraying at the correct targets. The boundaries of selected tracks were mapped with a RTK-GPS.

TeeJet® water sensitive papers (WSPs) (Spraying Systems Co., Wheaton, IL, USA) were fastened at randomly selected weed spots in each track. The WSPs were used for performance testing using the percent area coverage (PAC) and comparing SA to UA technique The paired t-test was performed with Minitab statistical 15 software (Minitab Inc., NY, USA) to examine whether the PAC of the sprayed targets with SA were different from the PAC of the targets with UA. The heights of selected targets (weeds) were measured manually with a ruler at the time of water application during the experiment. The linear regression method was used to test the relationship between target height and PAC of the sprayed targets with both SA and UA methods.

5.2.1.2 Cattle Market Field

Two tracks (100 m x 6.1 m each) were selected within the Cattle Market Field to test the accuracy of the VR sprayer for detecting weeds and spraying at the correct targets. The boundaries of selected tracks were mapped with a RTK-GPS. Weed patches were mapped with a RTK-GPS in test tracks of the selected field before and after kaolin clay spray application to evaluate the performance accuracy of the VR sprayer in the wild blueberry field. The sprayed map was superimposed on the weed map in ArcGIS 9.3 computer software (ESRI, Redlands, CA, USA) for comparison. The area of each track before and after application of chemical was measured with RTK-GPS. The data was analyzed for chemical savings.

5.2.1.3 Cooper Field

The Cooper Field was selected in Londonderry, Nova Scotia to test the performance and accuracy of the VR sprayer for SA of a post-emergence herbicide (Callisto®) for control of annual broadleaf weeds (goldenrod) during June. The field was divided into 18 equal plots and the experiment was laid out following completely randomized block design (CRBD) with three treatments and six replications. The treatments were: i) Control (CN); No application, ii) SA of Callisto®, and iii) Uniform-application (UA) of Callisto®. A Cost saving analysis was performed.

5.3 Results and Discussion

Results of this study indicated that LMC regulated the flow correctly through DJ servo valve and flow meter in specific nozzle of the boom section where the weeds had been detected during the operation with SA (Fig. 5-1). The paired t-test for UA versus SA targets PAC indicated that there was no significant bias in the SA and that the SA was accurate. It is observed that LMC automatically compensated the changes in nozzle flow rate caused by variation in ground speed during operation by monitoring the flow valve position. On a conventional chemical broadcast application sprayer, the nozzle spacing and the boom height chosen mainly depend on the overall spray pattern uniformity requirement. For the new VRC, the sensing system spatial resolution was considered as the major factor in the nozzle spacing selection (Fig. 3-6). For each individual nozzle to be controlled separately, the size of the section which one nozzle covered was equal to, or slightly larger than the detection zone of the sensing system.

5.3.1 Carmel Field

5.3.1.1. Water and Kaolin Clay Spray Application

Tall weeds remain a serious threat for the growth of wild blueberry as well as for smooth mechanical harvesting causing fruit losses. Results of this study indicated that automated identification of taller weeds in real-time and SA of herbicides using ultrasonic and fast VRC would help in monitoring their growth in wild blueberry fields.

Paired t-test for UA versus SA targets PAC with a 95 % confidence interval indicated that there was no significant bias in the SA and that the SA technique was to apply chemicals at selected targets (Table 5-1). Visual observation also revealed that VR sprayer performed reliably during the field experiments, permitting real-time target (weed) sensing and SA at correct targets in a specific section of sprayer boom where the weeds have been detected (Fig. 5-1). Therefore, it is important to develop VR sprayer using ultrasonics and VRC for in-season SA of agrochemicals in wild blueberry fields in order to increase net economic returns.

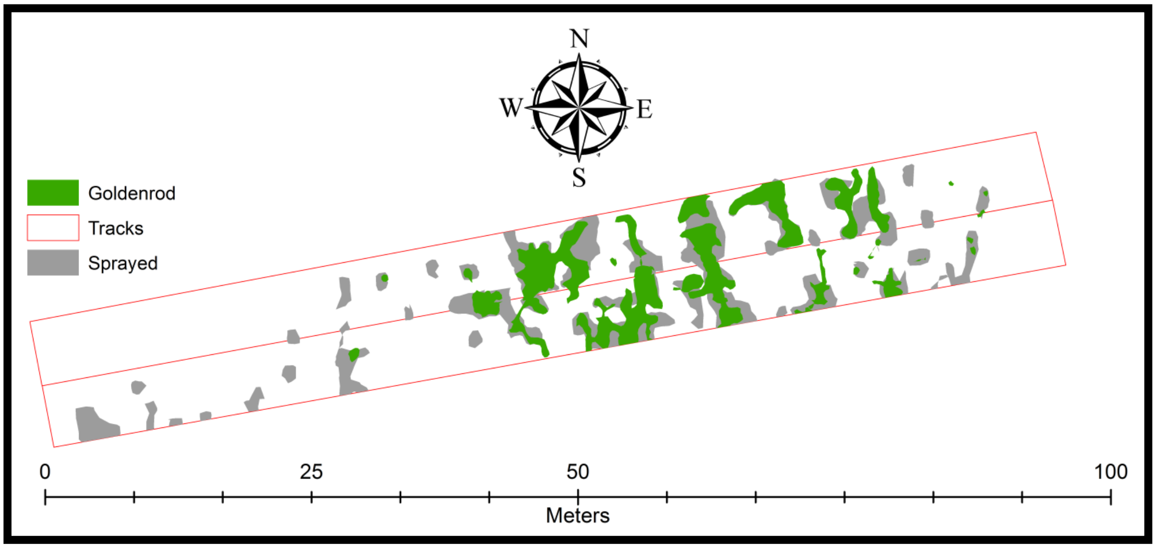


Figure 5-1 Map showing weeds and sprayed patches with prototype VR sprayer in each track of Carmel Field 1.

5.3.1.2 Goldenrod Targeting using WSPs

As expected, all WSPs were targeted with UA (Fig 5-2). Using SA technique all WSPs were also able to be all targeted (Fig 5-3). The VR sprayer performed well to target proper locations in the field where goldenrod was growing and open the nozzle in the specific section of the boom.

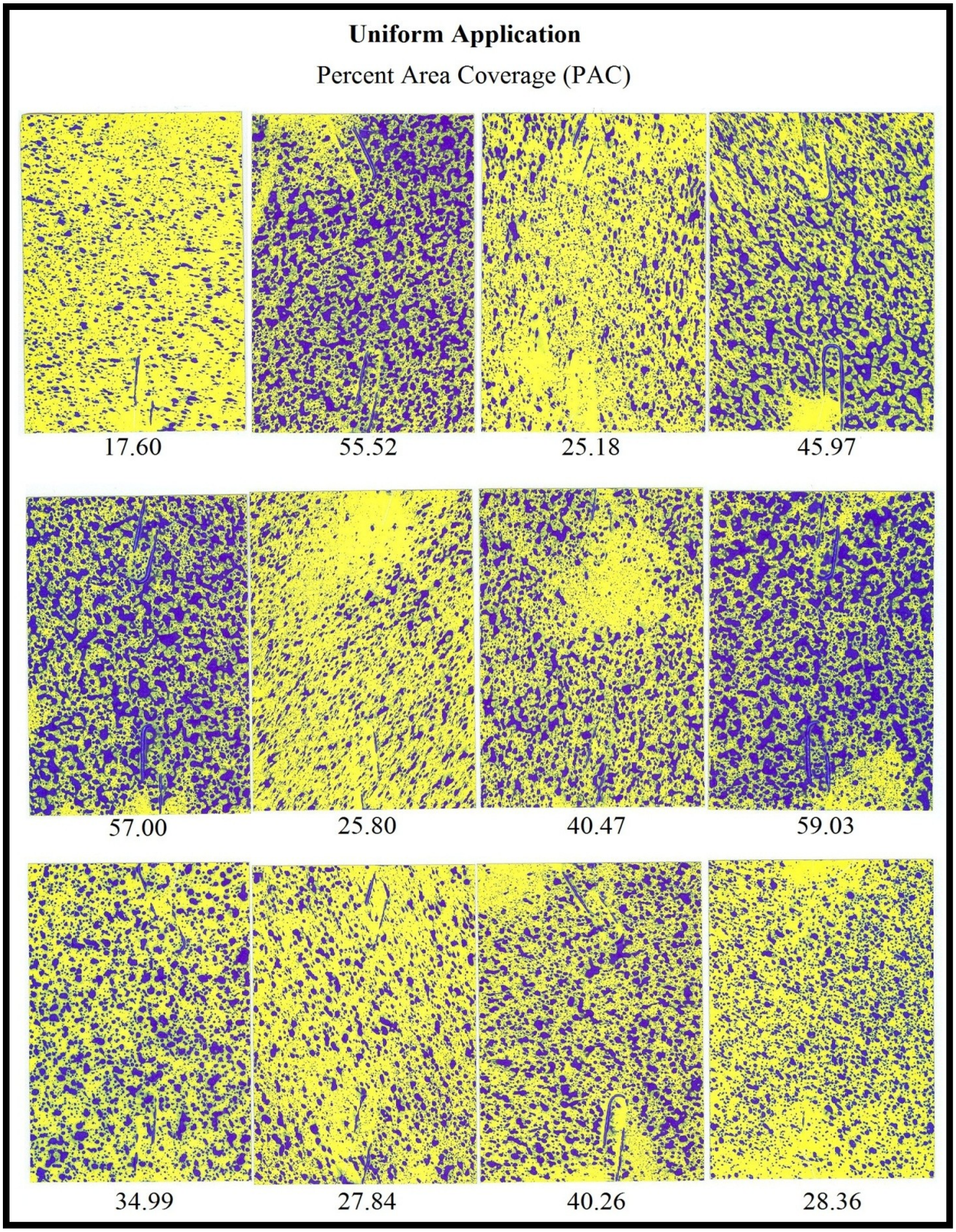


Figure 5-2 Showing the targets (WSPs) sprayed with water and PAC of the sprayed targets for UA in Carmel Field using prototype VR sprayer.

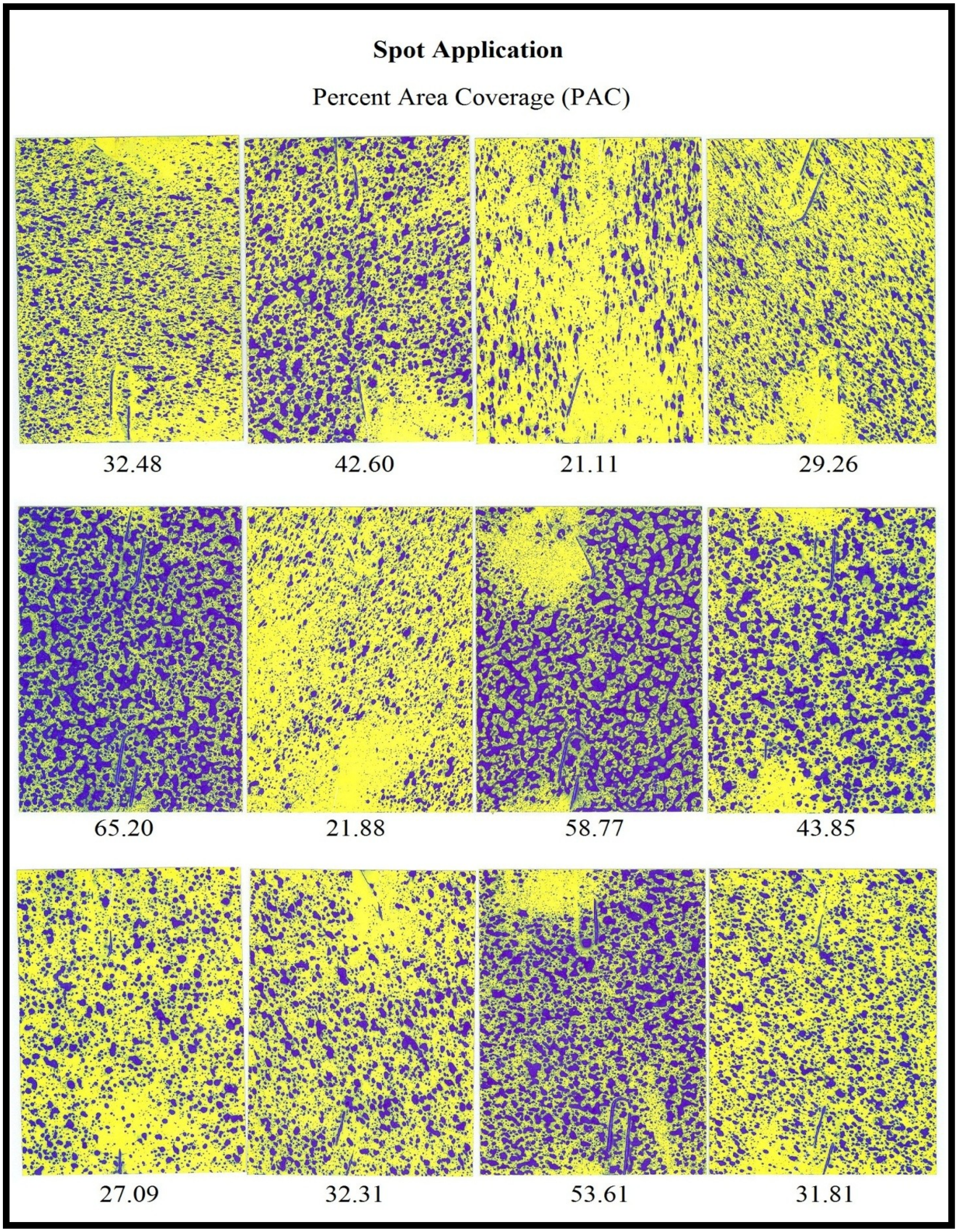


Figure 5-3 Showing the targets (WSPs) sprayed with water and PAC of the sprayed targets for SA in Carmel Field using prototype VR sprayer.

The PAC of the sprayed targets ranged from 17.6 to 59.03 % and from 21.11 to 65.20 % UA and SA, respectively (Figs. 5-2 and 5-3). The reason of variation in PAC might be due to the designed boom height for the VR sprayer. Wind also has an effect on spray patterns and on August 13 of 2009, the wind speed was 6 km hr^{-1} directed to the West (National Climate Data and Information Archive, 2009).

Table 5-1 Summary statistics of PAC of the sprayed targets for determining the precision of SA technique relative to the UA with prototype VR sprayer at selected points in each track.

Track (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
UA(12)	17.60	59.03	38.17	13.88	0.955
SA (12)	21.11	65.20	38.33	14.49	

The height of the targets that were measured in selected tracks ranged from 50.80 to 66.04 cm. Linear regression analysis results showed that weed heights were correlated (R^2 ranged from 0.76 to 0.82) with PAC for SA and UA respectively (Fig. 5-4). The results indicated that the VR sprayer performed well for < 55 cm tall weeds with the existing arrangements. It is proposed that herbicide should be applied at the early stage of weed growth (weed height ranged from 30 cm to 55 cm and plant height ranged from 12 cm to 27 cm) for appropriate application with these specific VR sprayer arrangements.

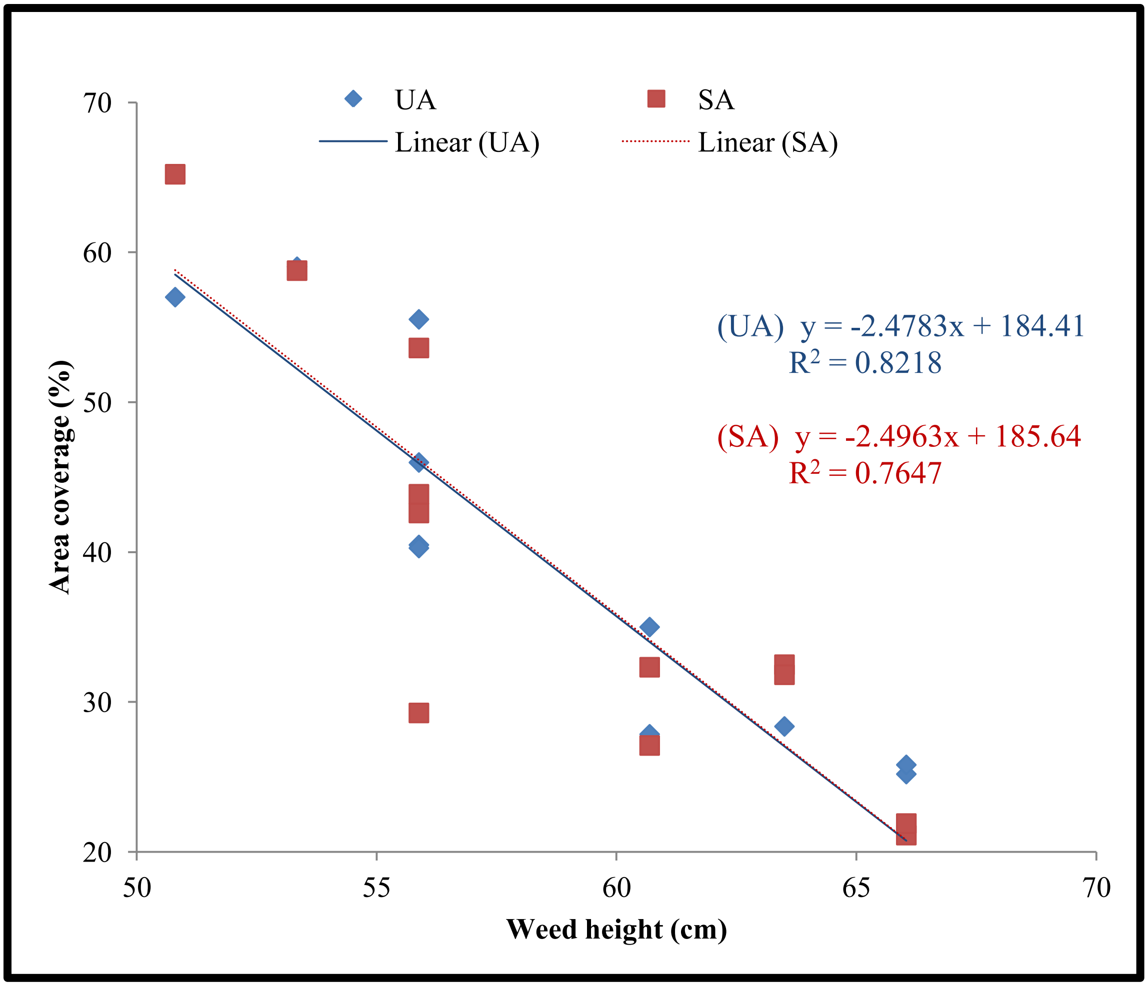


Figure 5-4 Relationship between PAC of sprayed targets with target height for both UA and SA at selected points in both tracks of Carmel Field.

5.3.2 Cattle Market

5.3.2.1. Water and Kaolin Clay Spray Application

The sprayed map superimposed on the weed map shows the performance accuracy of the VR sprayer for SA (Fig. 5-5). Visual observation revealed that VR sprayer performed reliably during the field experiment, permitting real-time target (weed) sensing and SA at correct targets in a specific section of sprayer boom where the weeds had been detected (Fig. 5-5).

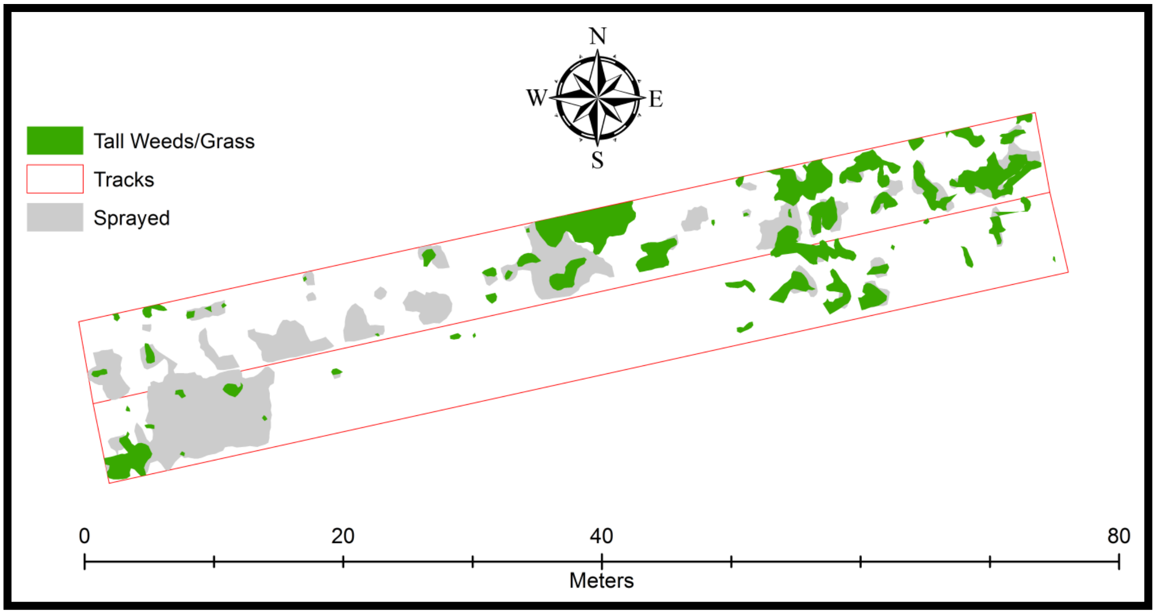


Figure 5-5 Cattle Market Field layout showing weeds and sprayed patches with prototype VR sprayer in each track.

5.3.2.2 Tall Weed Target Performance Testing using WSPs

The PAC of the sprayed WSPs ranged from 12.91 to 71.29 % and 5.39 to 72.67 % using SA and UA technique, respectively (Table 5-2, Figs. 5-6 and 5-7). The reason of variation in PAC might be due to spray drift caused by wind speed. On August 19 of 2009, the temperature ranged from 25 to 29 °C and relative humidity from 59 to 61 %, and wind speed was 15 km hr^{-1} directed to the West (National Climate Data and Information Archive, 2010). Using the paired t-test method with Minitab and a 95 % confidence interval there was no significant difference between SA and UA techniques applying to tall weed areas with a P-value of 0.698. Based upon the results of this study the VR sprayer performed well for SA on tall weeds in wild blueberry field.

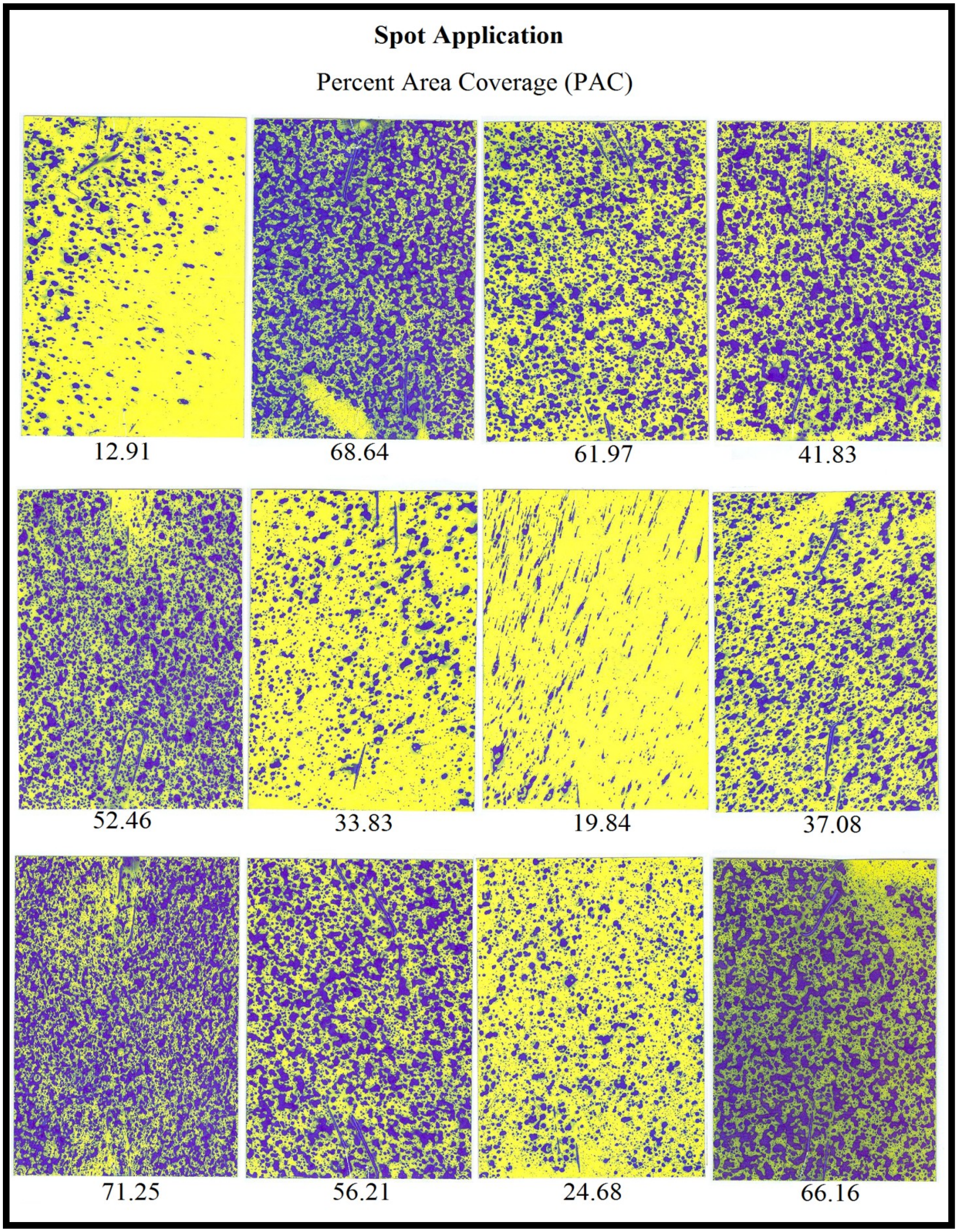


Figure 5-6 Showing the targets (WSPs) sprayed with water and PAC of the sprayed targets for SA in Cattle Market Field using prototype VR sprayer.

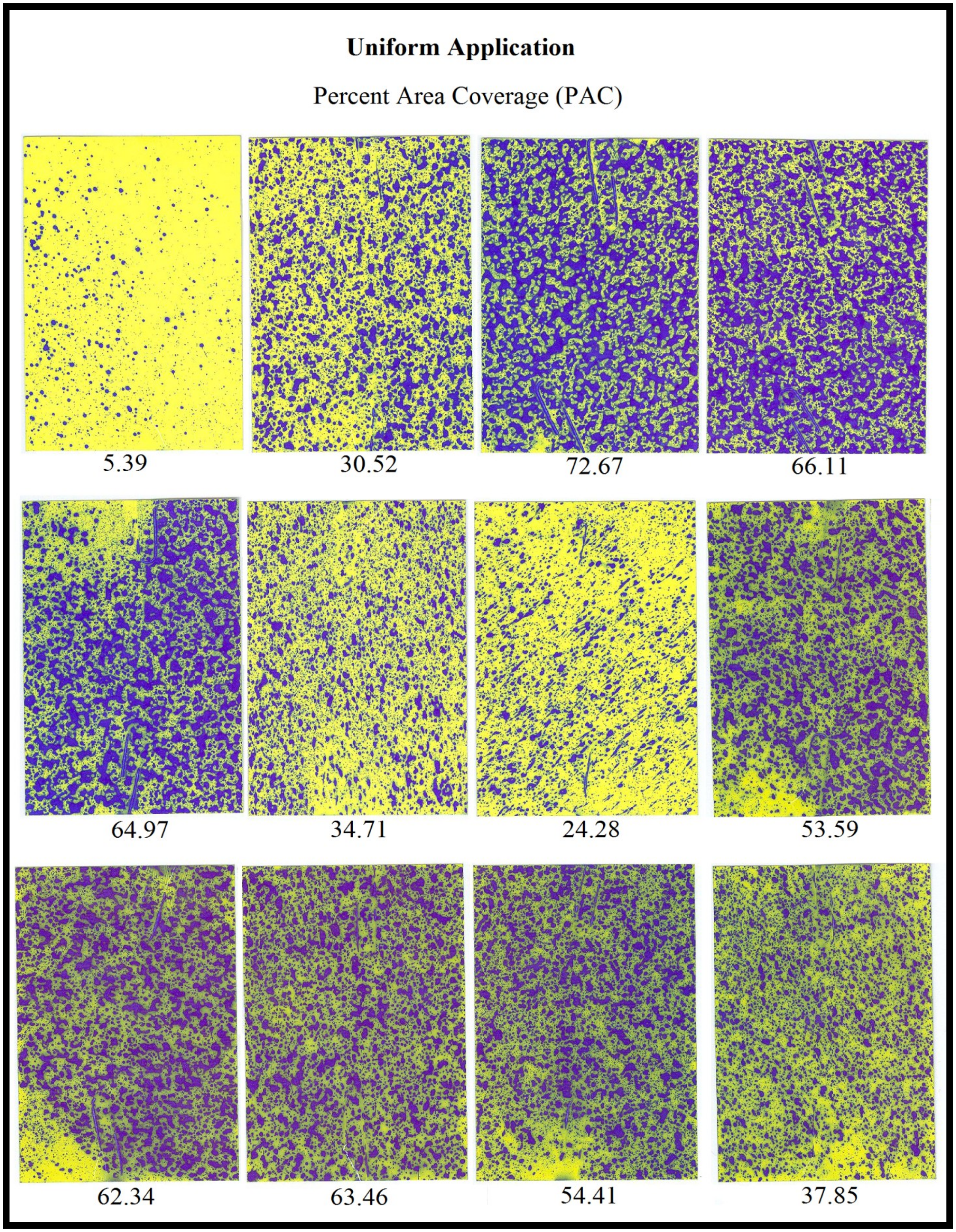


Figure 5-7 Showing the targets (WSPs) sprayed with water and PAC of the sprayed targets for UA in Cattle Market Field using prototype VR sprayer.

Table 5-2 Summary statistics of PAC of the sprayed targets for determining the precision of SA technique relative to the UA with prototype VR sprayer at selected points in each track.

Track (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
UA(12)	5.39	72.67	45.57	20.68	0.698
SA (12)	12.91	71.29	47.52	20.08	

The height of the targets was measured in selected tracks ranged from 48.26 to 68.58 cm in the Cattle Market Field. Linear regression analysis results showed that weed heights were reasonably correlated (R^2 ranged from 0.54 to 0.67) with PAC for SA and UA, respectively (Figs. 5-8).

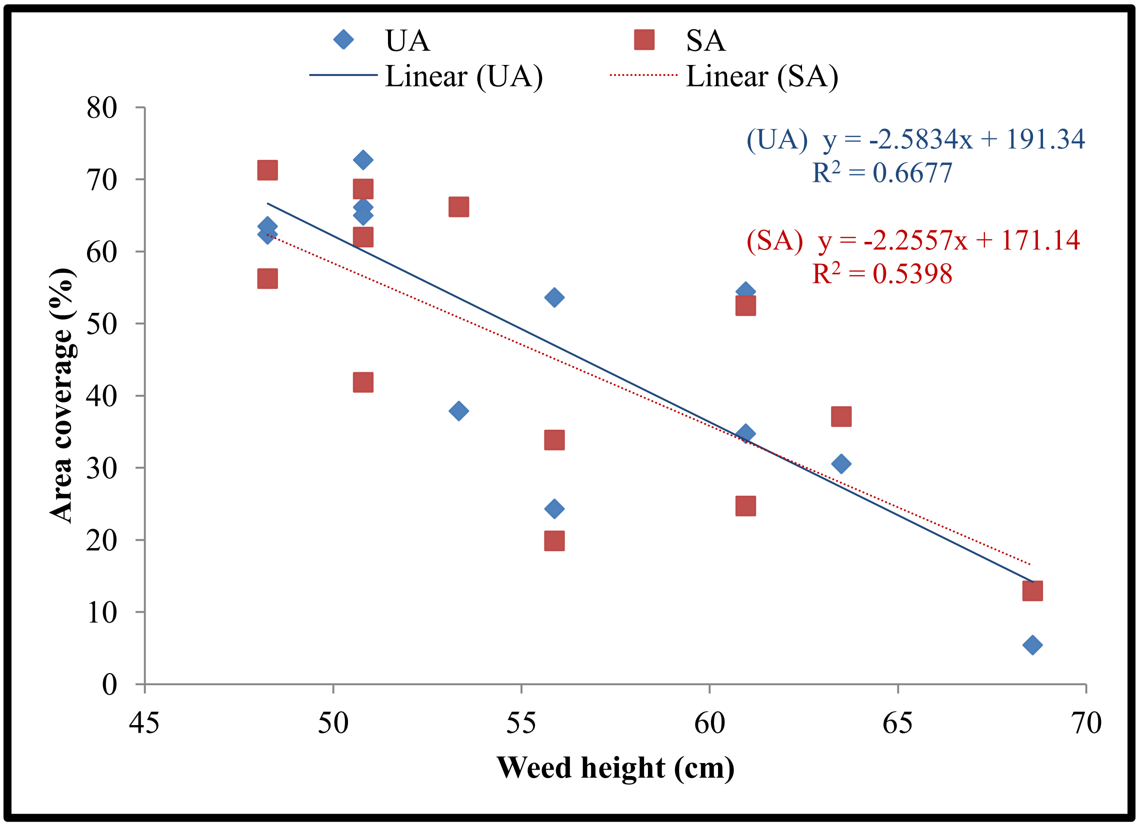


Figure 5-8 Relationship between PAC of sprayed WSPs with weed height for both UA and SA at selected points in both tracks of Cattle Market Field 2.

In both the Carmel and Cattle Market Fields the data sets (area coverage and height) were combined to examine the relationship. The height of the targets within both fields were observed to range from 48 to 68 cm. Linear regression analysis results showed that weed heights were reasonably correlated (R^2 ranged from 0.63 to 0.74) with PAC for SA and UA, respectively (Fig. 5-9). Therefore, one equation can be used for all sites to describe the relationship between height and PAC. The results indicated that the VR sprayer performed well for < 55 cm tall weeds with the existing arrangements. It is proposed that herbicide should be applied at the early stage of weed growth (weed height ranged from 30 cm to 55 cm and plant height ranged from 12 cm to 27 cm) for appropriate application with these specific VR sprayer arrangements.

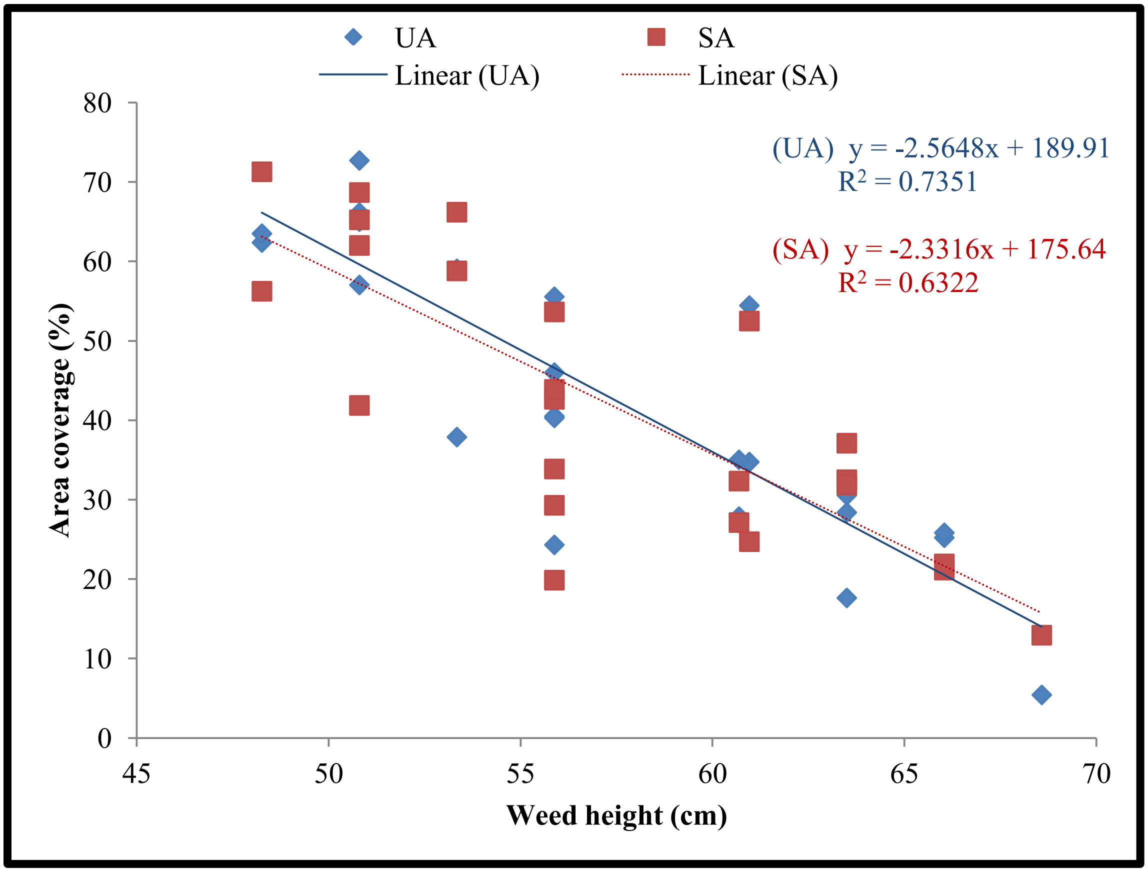


Figure 5-9 Relationship between PAC of sprayed WSPs with weed height for both UA and SA at selected points in both Carmel and Cattle Market Fields.

5.3.3 Cooper Field Callisto® Herbicide Spray Application

5.3.3.1 Goldenrod Targeting using WSPs

The PAC of the sprayed WSPs ranged from 18.70 to 76.60 % and 25.80 to 81.80 % using SA and UA technique, respectively (Table 5-3 and Figs. 5-10 and 5-11). The reason of variation in PAC might be due to spray drift caused by high wind speed. On July 04 of 2010, the temperature ranged from 24 to 28 °C and relative humidity from 44 to 47 %, and wind speed was 15 km hr^{-1} directed to the West (National Climate Data and Information Archive, 2010). Using the paired t-test method with Minitab and a 95 % confidence interval there was no significant difference between SA and UA techniques applying Callisto® on goldenrod patches with a P-value of 0.693. One month after Callisto® application visual observation of the CN tracks showed more goldenrod as compared to both SA and UA tracks, despite the windy conditions during spray application. Based upon the results of this study the VR sprayer performed well for SA of Callisto® on foliage in wild blueberry field.

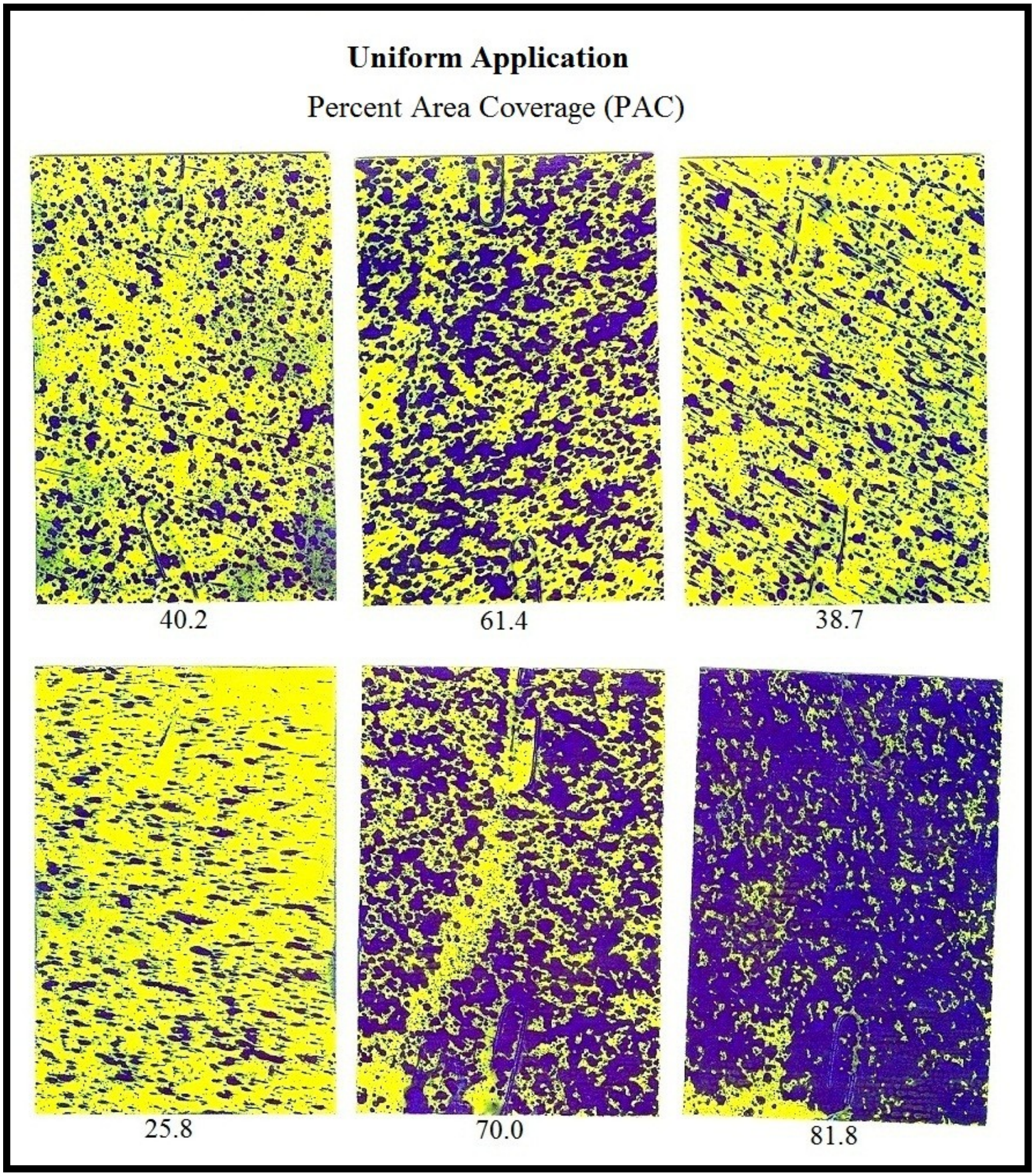


Figure 5-10 Showing the targets (WSPs) sprayed and PAC of the sprayed targets for UA in Cooper Field.

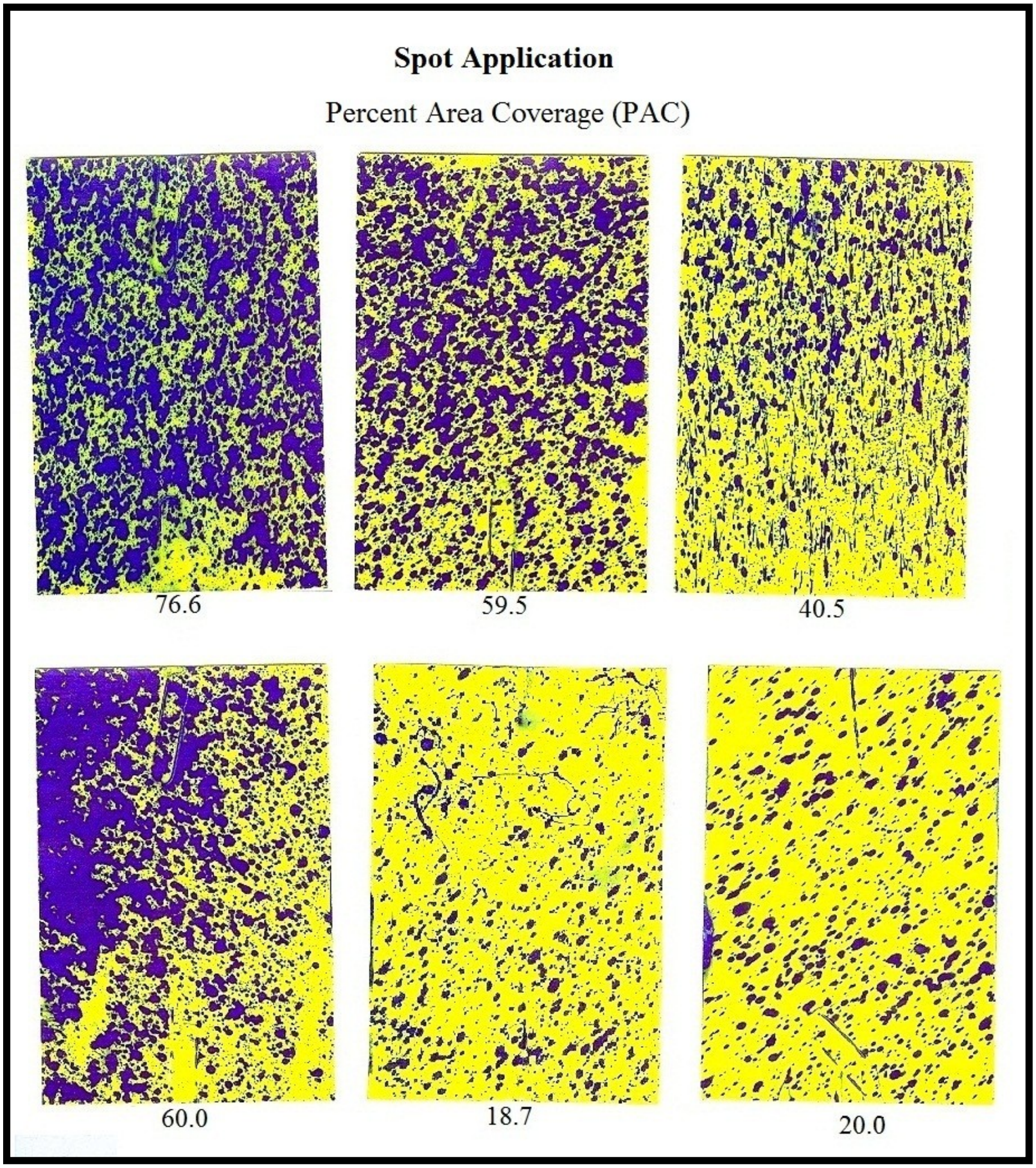


Figure 5-11 Showing the targets (WSPs) sprayed and PAC of the sprayed targets for SA in Cooper Field.

Table 5-3 Summary statistics of PAC of the sprayed targets for determining the precision of SA technique relative to the UA with prototype VR sprayer at selected points in each track.

Track (n)	Min (%)	Max (%)	Mean (%)	S. D. (%)	P-value
UA(6)	25.80	81.80	52.98	21.43	0.693
SA (6)	18.70	76.60	45.88	23.52	

The VR sprayer savings of Callisto® using SA ranged from 64 to 98 % based on bare spot areas within the selected field (Table 5-4). The chemical savings will lower the cost of production as well as having lower environmental impact. Also, fewer trips back to the water truck to refill the sprayer tank would save time, labor and fuel.

5.3.3.2 Chemical Savings Analysis

Table 5-4 Prototype VR sprayer chemical savings with SA technique compared UA.

Plot #	Total Area (m^2)	Weed Area (m^2)	Sprayed Area (m^2)	Chemical Savings (%)
1	476	40	45	90
5	462	32	58	87
7	488	170	177	64
10	466	3	5	98
13	500	4	35	93
18	442	16	54	88

5.4 Summary and Conclusions

The VR sprayer proved very efficient for in-season SA of herbicides to eradicate tall weeds < 55 cm (taller than plants) in wild blueberry fields. The PAC of the sprayed targets with SA and UA was limited on taller weeds in both test fields. Chemical application is only necessary during early weed growth stage allowing for a more consistent PAC. Visual observation revealed less goldenrod in SA and UA tracks as compared to CN tracks after Callisto® application. Windy conditioned affected the spray coverage on targets more when using SA than UA, probably due to off-target drifting of the precision spray plume.

This VR sprayer could be used for a variety of precision farming applications including site-specific liquid fertilization in plant areas, fungicide/ insecticide spraying on foliage only in wild blueberry cropping systems. Further research and experimentation are needed to determine the optimal chemical input amount for different weed coverage, CN zone size, and timing combinations. The knowledge of agricultural engineers, agricultural economists, weed scientists, and agrochemical experts must be brought together in order to develop the high performance expert system required for a VR sprayer.

CHAPTER 6

PERFORMANCE EVALUATION OF THE PROTOTYPE VR SPRAYER WITH DIGITAL COLOR CAMERAS FOR SPOT-APPLICATIONS OF FUNGICIDE IN WILD BLUEBERRY FIELDS

6.1 Introduction

The wild blueberry (*Vaccinium angustifolium*) industry is rapidly growing with over 86,000 ha in production (Yarborough, 2009). Unlike many other agricultural crops, wild blueberries are managed rather than planted; the crop cannot be rotated nor the fields cultivated. Wild blueberry yields are highly dependent on fungicides for adequate disease control. The two most common foliar diseases found in wild blueberry fields are *Septoria* leaf spot (*Septoria*) and blueberry rust (*Thekopsora minima*) (Percival and Dawson, 2009). *Septoria* leaf spot prevails in late June and rust in late July of the vegetative development stage of the biannual crop production cycle (Wild Blueberry Factsheet, 2009). Both diseases cause visual reductions in green leaf area and leaf area duration and cause reduction in carbohydrate supply to develop floral buds (Percival and Dawson, 2009). Growers apply fungicides during both the vegetative and cropping year to reduce disease pressures and increase floral bud counts and harvestable yields (Percival and Dawson, 2009). Chlorothalonil (Bravo®) for *Septoria* leaf spot and blueberry rust during vegetative year, propiconazole (Topas® 250E) for *Monilinia* blight (*Monilinia vaccinii-corymbosi*), cyprodinil/fludioxonil (Switch™) for *Botrytis* (*Botrytis cinerea*), and Pristine™ (boscalid/pyraclostrobin) for valdensinea (*Septoria* spp.) leaf spot and rust during crop year. Traditionally fungicides are applied uniformly without considering significant bare spots (30-50 % of the total field area; Zaman et al., 2008), that exist within fields. The repeated and excessive use of fungicides in bare spots has resulted in an increased cost of production. The wrong or over use of fungicide is also dangerous for the environment, for humans, for the native pollinators, and for the plants. Chlorothalonil, the active ingredient in Bravo® is a fungicide that is heavily used in eastern Canada and has led to significant aquatic contamination (Ernst, 1991; Pariseau et al., 2009). With given the high proportion of bare spots in typical wild blueberry fields, there is a large fungicide savings potential expected in the wild blueberry industry. Therefore, there is an urgent need to use an affordable and reliable automated variable rate (VR) sprayer for spot-application (SA) of fungicides in wild blueberry cropping systems.

This study was designed to (i) evaluate the performance of prototype VR sprayer for SA of fungicides in blueberry fields and (ii) determine the effect of Bravo® on plant growth, health and fruit yield parameters using VR technology.

6.2 Materials and Methods

6.2.1 Field Test using µEye Digital Color Cameras

An experiment was conducted in the Cooper Field in Londonderry, Nova Scotia to test the performance accuracy of the VR sprayer for SA of Bravo® fungicide. The selected wild blueberry field was in the sprout vegetative year of the biennial crop production cycle at the time of application. The objective of the project was to save fungicide by only applying in plant foliage areas and saving in bare spot zones within field. The field experiment was divided into 18 equal tracks and the experiment was laid out following a completely randomized block design (CRBD) with three treatments and six replications. The treatments were: i) CN, ii) SA, and iii) UA. The potential fungicide savings were calculated comparing SA to UA technique.

6.2.2 Crop Growth Parameters and Fruit Yield

The plant growth parameters were measured from six randomly selected sampling areas in each track (SA, UA, and CN) to assess the effect of Bravo® on plant height and the number of flower buds. A steel quadrant measuring 0.15 × 0.15 m was used to mark out the area for the plant growth measurements. Blueberry stem height, stem density, number of branches, number of blueberry fruit buds and fruit yield was averaged at each plot location. Analysis of variance (ANOVA) and post hoc LSD statistical analysis using SAS (SAS Institute, Car, NC) was performed on the results to examine the effect of Bravo® on the plant growth and fruit yield with SA, UA and CN techniques.

6.2.3 Percentage of Green Pixels Calculation of Blueberry Plants

A 10-megapixel 24-bit digital color camera was mounted on a tripod, pointing downwards to take photographs from six randomly selected sample areas in each track at 1.0 m height above ground. A steel frame measuring 0.5 × 0.5 m was placed on the ground to identify the area where images will be taken. Custom image processing software was utilized to determine the percentage of green pixels of the images taken from all application rates (SA, UA and CN) for comparison to quantify the effect of Bravo® on plant growth and leaf retention. ANOVA was performed using CoStat statistical software (CoHort Software, CA, USA) comparing the three application techniques using post hoc LSD method and a 95 % confidence interval.

6.3 Results and Discussion

6.3.1 Performance Evaluation of VR Sprayer using WSP and the Potential Saving of Fungicide

The total response time 0.131 s was programmed into the VRC and the front boom was spaced far enough ahead of the rear sprayer boom to compensate for the time lag needed to process and spray. The ATV was driven at 6 km hr^{-1} ground speed. The principal components (digital cameras, ruggedized PC, VRC, LMC and solenoid valves) performed well to detect and spray on foliage areas in the field. Non-significance of the paired t-test for SA versus UA targets PAC indicated that there was no significant bias in the SA and that the SA technique was accurate to apply fungicide at selected targets in the field (Table 2 and Fig. 6-1). Visual observations also revealed that the VR sprayer performed reliably during the field experiment permitting proper detection of plant foliage in real-time and spraying exactly on the foliage.

The PAC of the sprayed WSPs ranged from 45.17 to 66.42 % and 22.47 to 70.22 % using SA and UA technique respectively (Table 6-1 and Fig. 6-1). The reason of variation in PAC might be due to spray drift caused by high wind speed. On July 08 of 2010, the temperature ranged from 26 to 27 °C and relative humidity from 18 to 19 %, and wind speed was 20 km hr^{-1} directed to the West (National Climate Data and Information Archive, 2010). The PAC of sprayed WSPs with SA technique ranged from 0.25 to 3.19 % in bare spot areas. The cause of the small PAC areas could have resulted from spray drift from adjacent nozzles or from the spray drifting from the front or back edge of the bare spot patch. Using the paired t-test method with 95 % confidence interval there was no significant difference between SA and UA techniques applying Bravo® to plant canopy areas with a P-value of 0.38. There is a highly significant difference

(P-value < 0.01) when comparing SA and UA for Bravo® applications on bare spot areas (Table 6-1). Based upon the results of this study the VR sprayer performed well for SA of Bravo® on foliage in wild blueberry field.

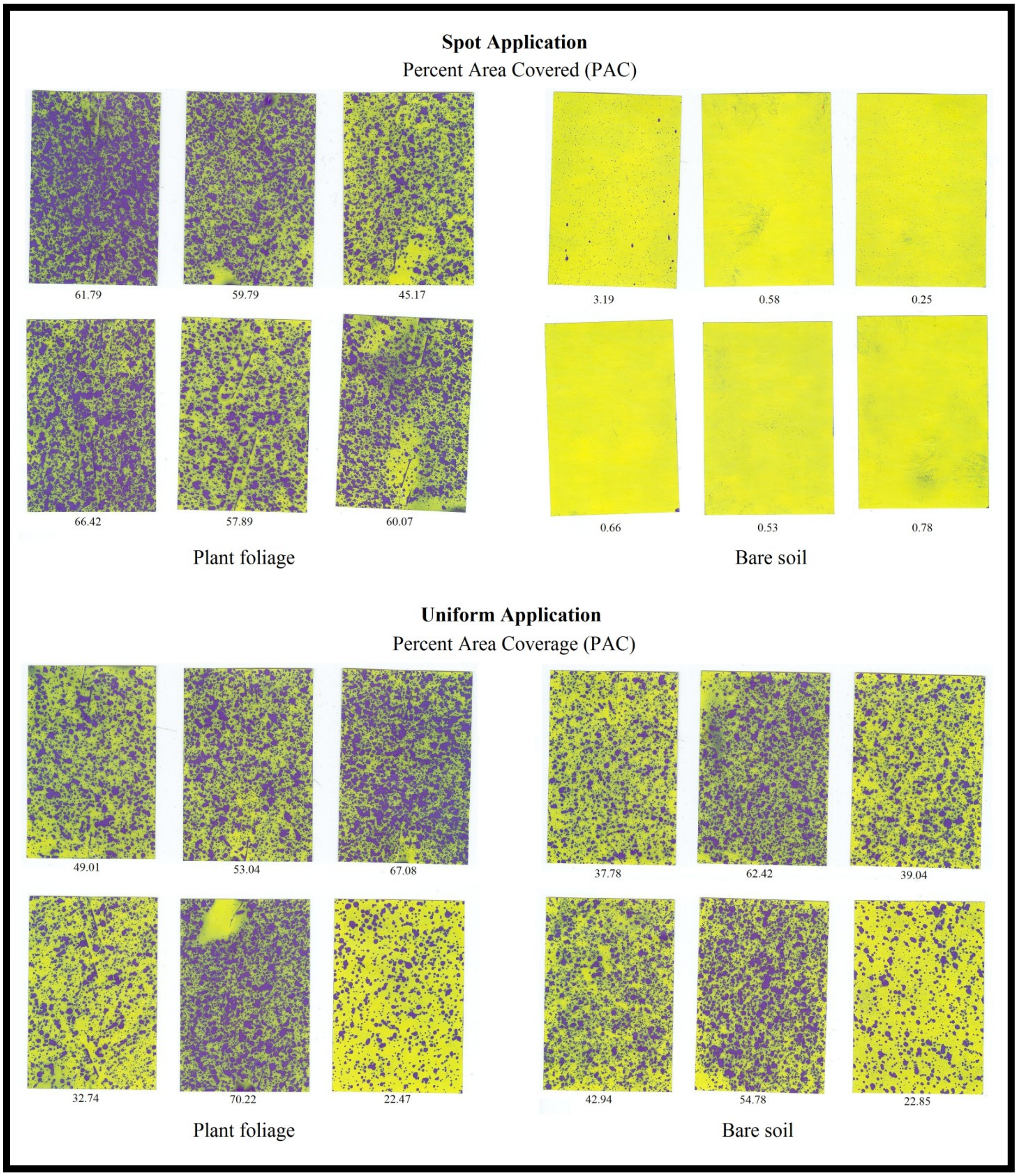


Figure 6-1 Showing the targets (WSPs) sprayed with Bravo® and PAC of the sprayed targets for both SA and UA in the Cooper Field using prototype VR sprayer.

Table 6-1 Summary statistics of PAC of the WSPs for determining the precision of SA technique relative to the UA with prototype VR sprayer at selected points in each track.

Track (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
SAP (6)	45.17	66.42	58.52	7.10	0.38
UAP (6)	22.47	70.22	49.09	18.77	
SAB (6)	0.25	3.19	1.00	1.09	<0.01
UAB (6)	22.85	62.42	43.30	13.89	

SA of Bravo® in plants (SAP)
UA of Bravo® in plants (UAP)
SA of Bravo® in bare spots (SAB)
UA of Bravo® in bare spots (UAB)

VR sprayer SA of Bravo® savings ranged from 9.90 to 51.22 % based on bare spot areas within the selected field (Table 6-2). The chemical savings will lower the cost of production as well as having lower environmental impact. Also, fewer trips back to the water truck to refill the sprayer tank would save time, labor and fuel.

Table 6-2 Prototype VR sprayer Bravo® fungicide savings with SA technique compared to UA

Track #	Total Area (m^2)	Bare Spot (m^2)	Sprayed Area (m^2)	Chemical Savings (%)
1	467.89	160.78	306.73	34.44
4	487.86	133.90	355.45	27.14
7	484.08	117.17	367.22	24.20
12	472.15	95.88	373.86	20.31
14	462.54	236.91	224.87	51.22
18	447.76	44.35	402.23	9.90

6.3.2. Evaluation of Effect of VR Technology

6.3.2.1 Blueberry Plant Parameters

By early December of the sprout year, mean values of 655, 691 and 645 plants per square meter was consistent in SA, UA and CN tracks respectively (Table 6-3). This could be the result of the new blueberry stems being already formed in early spring of the sprout year (McIsaac, 1997). ANOVA method shows there was no significant difference between mean stem heights 0.239, 0.235 and 0.231 m in SA, UA and CN tracks, respectively. A similar trend was observed for mean number of blueberry branches per stem in SA, UA and CN. The results from the plant growth parameters suggest that Bravo® does not have any significant effect on plant density, stem height and number of branches per stem. The results coincide with Percival and Dawson (2009) who found Bravo® applications to only effect floral bud number and harvestable yields.

Table 6-3 Summary statistics and ANOVA comparison of plant density (PD), stem height (SH) and number of branches (NB) for determining the precision of SA technique relative to the UA with the prototype VR sprayer applying Bravo®. Reference was made to CN tracks.

Application (n)	Plant growth parameter	Min	Max	Mean	S.D.	P-value
SA (36)	PD (stems m^{-2})	304	1260	655	186	0.473
UA (36)	PD (stems m^{-2})	391	1090	691	152	
CN (36)	PD (stems m^{-2})	391	1000	645	161	
SA (36)	SH (m)	0.170	0.337	0.239	0.040	0.682
UA (36)	SH (m)	0.157	0.297	0.235	0.034	
CN (36)	SH (m)	0.157	0.322	0.231	0.042	
SA (36)	NB (# branches $stem^{-1}$)	1.50	7.00	3.86	1.46	0.893
UA (36)	NB (# branches $stem^{-1}$)	1.33	9.33	3.90	1.85	
CN (36)	NB (# branches $stem^{-1}$)	1.33	6.17	4.02a	1.11	

Means followed by different letters are significantly different

6.3.2.2 Plant Foliage Health using Percentage of Green Pixels

Results indicated Bravo® greatly improved leaf retention and leaf area duration (Fig. 6-2). The percentage of green pixels varied from 87.14 to 99.03 % in the SA tracks, 81.21 to 99.06 % in the UA tracks and 21.83 to 73.82 % in the CN tracks in the field (Table 6-4). The SA and UA of Bravo® increased the percentage of green pixels by 130 and 128 % more than the CN, respectively. ANOVA statistical analysis and post hoc LSD method showed that there was no significant difference between the means of the SA and UA. However, there was a significant difference between CN and both SA and UA (Table 6-4). The cause of the significant difference between the CN and both the SA and UA techniques may be due to the Bravo® ability to reduce foliage disease keeping the plants green and healthy improving carbohydrate production for the developing floral buds (Percival and Dawson, 2009). The large variation in percentage of green pixels (S.D. = 12.06) with CN could have been caused by the natural variation of *Septoria* leaf spot and blueberry rust disease damage. Wild blueberry crop has several different species and clones, some of them may be more resistant against *Septoria* leaf spot and blueberry rust.

Table 6-4 Summary statistics and ANOVA comparison of percentage green pixels for SA and UA of Bravo®. Reference was made to CN tracks.

Track (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
SA (6)	87.14	99.03	96.08a	2.41	<0.001
UA (6)	81.21	99.06	95.31a	3.72	
CN (6)	21.83	73.82	41.80b	12.06	

Means followed by different letters are significantly different

Figure 6-2 Percentage of green pixels sample images for determining plant health. SA (right), UA (middle) and CN (left).

6.3.2.3 Blueberry Yield Parameters

The mean values of floral buds were 9.73, 9.56 and 6.45 per stem in SA, UA and CN, respectively (Table 6-5). There was no significant difference between number of floral buds between SA and UA. The number of floral buds in CN plots was significantly different than SA and UA. The SA and UA of Bravo® increased floral bud formation by 49 and 47 %, respectively over the CN (Table 6-5). Similar results were found by Percival and Dawson (2009).

Results from the harvest of 108 plots showed the mean blueberry fruit yield 0.690, 0.715 and 0.528 kg m^{-2} in SA, UA and CN, respectively. Fruit yield in CN plots was significantly lower than the fruit yield in SA and UA. SA and UA of Bravo® increased the harvestable yield by 31 and 35 %, respectively over the CN. These results were in agreement with the findings of Percival and Dawson (2009). The variance of the blueberry yield was higher than blueberry growth, health and other yield parameters. The possible reasons for variance in blueberry fruit yield could be other factors such as soil properties, disease and insect damage, weeds, pollination, winter kill and seasonal variations other than the Bravo® application. The findings suggest that floral bud formation in the fall of the vegetative year is important for harvestable yield in the cropping year.

Table 6-5 Summary statistics and ANOVA comparison of floral buds (FB) and blueberry yield (YD) for determining the precision of SA technique relative to the UA with the prototype VR sprayer applying Bravo®. Reference was made to CN tracks.

Application (n)	Plant yield parameter	Min	Max	Mean	S.D.	P-value
SA (36)	FB (# buds stem^{-1})	4.00	24.33	9.73a	4.88	0.013
UA (36)	FB (# buds stem^{-1})	1.67	36.00	9.56a	6.41	
CN (36)	FB (# buds stem^{-1})	1.50	21.17	6.45b	4.09	
SA (36)	YD (kg m^{-2})	0.104	1.26	0.690a	0.274	0.043
UA (36)	YD (kg m^{-2})	0.030	1.66	0.715a	0.438	
CN (36)	YD (kg m^{-2})	0.050	1.14	0.528b	0.281	

Means followed by different letters are significantly different

6.4 Summary and Conclusions

The µEye color cameras, ruggedized computer, LMC and 8-channel computerized VRC were fast and accurate enough to apply Bravo® fungicide effectively in the specific section of the boom where the foliage was detected. With an overall response time of 0.131 s the system was able to travel at a normal operating speed of 6 km hr^{-1} when applying fungicide. The Bravo® savings with SA ranged from 9.90 to 51.22 % based on bare spot coverage within field. Bravo® did not show any significant difference on plant density, stem height or number of stem branches. However, the percentage of green pixels was higher by 130 and 128 % for SA and UA, respectively over the CN. There was a considerable increase in floral buds with both SA (47 %) and UA (49 %) of Bravo® as compare to CN. There was a significant increase in harvestable yield by 31 and 35 %, respectively over the CN.

This VR sprayer can be used for a wider range of fungicides such as Topas® 250E for *Monilinia* blight, Switch™ for *Botrytis*, and Pristine™ for valdensinea leaf spot and rust. This innovative technology can be further developed to include VR herbicide and insecticide applications based on the producers' needs as per pervious chapters. This technology with modifications could be applied to other fruit and vegetable cropping systems to maximize farm profitability while minimizing environmental pollution.

CHAPTER 7

CONCLUSIONS

7.1 Objective of the Study

Wild blueberry fields rely on agrochemicals for proper weed, disease and pest control. Traditionally, herbicides, fungicides and insecticides are applied uniformly in wild blueberry fields even though weeds and blueberry plants are not distributed consistently within the fields. In these situations, spatial information management systems hold great potential for allowing producers to fine-tune the locations, timings, and rates of agrochemical application. The objectives of this project were to develop a prototype VR sprayer and evaluate the performance using ultrasonic sensors and digital color cameras for small scale SA in wild blueberry fields.

This project has the potential to improve the competitiveness and profitability of the blueberry industry, reduce the environmental impact of existing wild blueberry production systems, and enhance the sustainability of rural life in Eastern Canada. The environmental impact will be positive as it is anticipated that the amount of current agrochemicals being used in the wild blueberry industry will be reduced and better targeted by SA of agrochemicals.

7.2 General Discussion

The developed equipment consists of a VR sprayer with look-ahead sensing technology which opens and closes spray nozzles in the specific locations as required. It features easy user-friendly setup with no complicated switches. Wireless convenience for operating parameter setup is possible even at some distance from the controllers via Bluetooth. There is automatic compensation for changing ground speed with no need to manually readjust sensors and the ability to input a manual speed in case of GPS signal outage. Also, an adjustable front and back edge distance buffers are used for precise overlapping of agrochemical applications on targets.

The LMC performed reliably and rapidly to regulate flow rate in each nozzle through servo valve and flow meter with less than 3.7 % difference from manual flow measurements during calibration tests. Using the ultrasonic sensors the VRC was fast and accurate enough to open the valve at the correct target with a response time of 0.050 ± 0.003 s after receiving the sensor target detection information.

The VR sprayer proved very efficient for in-season SA of herbicides to eradicate tall weeds less than 55 cm (taller than plants) in wild blueberry fields. The µEye color cameras, ruggedized computer, LMC and 8-channel computerized VRC were fast and accurate enough to apply Bravo® fungicide effectively in the specific section of the boom where the foliage was detected. With an overall response time of 0.131 ± 0.003 s the system was able to travel at a normal operating speed of 6 km hr^{-1} when applying fungicide. The Bravo® savings with SA ranged from 9.90 to 51.22 % based on bare spot coverage within field.

7.3 Recommendations and Future Research

It is recommended that further research and experimentation is done to develop a larger commercial sized sprayer for SA of agrochemical in wild blueberry fields. An added light source would be beneficial for using the VR sprayer during early morning or late evening times when the natural light may not be sufficient for the camera vision system. This innovative technology could be further developed to include a variety of precision farming applications. Modifications could be made to the VR sprayer to apply the technology in other fruit and vegetable cropping systems to maximize farm profitability while minimizing environmental pollution.

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APPENDIX

January 17, 2012

Development of prototype automated variable rate sprayer for real-time spot-application of agrochemicals in wild blueberry fields

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