SMART SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICAL IN WILD BLUEBERRY FIELDS

by

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DEDICATION

This PhD thesis dissertation is dedicated to my wife, Karen, who has been an amazing source of support and encouragement. I am truly thankful for having you in my life. This work is also dedicated to my parents, Carl and Marion, whose hard work and guidance have allowed me to accomplish my goals.

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ABSTRACT

Agrochemical spray applications are currently being managed on a uniform field basis despite the significant variation that exists throughout many of the wild blueberry fields. The main objective of this study was to develop and evaluate a smart sprayer using machine vision and a custom control system to apply spot-applications of agrochemicals within wild blueberry fields. A commercial boom sprayer was retrofitted with smart sprayer components to allow for real-time nozzle specific weed and blueberry plant targeting.

Wild blueberry fields were selected and performance of the smart sprayer system was evaluated for spot-applications. Water sensitive papers were used in target and non-target locations in the test tracks to determine the targeting accuracy of the system. Plant parameters including stem density, stem height, stem diameter and number of branches were collected from selected plots for determination of spot-application treatment effects. Blueberry yield data including floral bud count and harvestable yields were collected from plots to determine the effectiveness of spot-applications as compared to uniform and control treatments. Weed and bare soil areas were mapped in selected fields using a global positioning system to quantify the amount of target and non-target areas in the selected fields. Agrochemical spray amounts were recorded to compare the spot-application savings with uniform applications, based on the target areas in the field.

The smart sprayer herbicide savings ranged from 69 to 82% within selected fields. Results revealed that the smart sprayer saved significant amount of fungicides by avoiding applications in bare soil and weed areas. Lights with added diffusers were used to maintain the lux within an acceptable range while targeting green weeds after dark with 65% potential agrochemical savings. Rear mounted machine vision was added for increased simplification and operator ease of use. An economic analysis of a swath control sprayer and smart sprayer system to a basic boom sprayer showed reductions of 12.3% and 44.5% input cost, respectively. This study can help to reduce the amount of agrochemical usage and guide the wild blueberry industry to adopt economic and environmentally sustainable options for production to increase farm profitability.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ABBREVIATIONS

A – Ampere

ABS – Acrylonitrile butadiene styrene

ANOVA – Analysis of variance

ATV – All-terrain vehicle

CAD – Computed aided design

CCD – Charged-coupled device

CIR – Color-infrared

cm – Centimeters

CN – Control

CPU – Central processing unit

DAL AC – Dalhousie University Agricultural Campus

DC – Direct current

dB - Decibel

DGPS – Differential global positioning system

FB – Floral bud

GB – Gigabit

GHz – Gigahertz

GIS – Geographical information system

GPS – Global positioning system

h – Hour

ha – Hectare

HID – High intensity discharge

HSV – Hue, saturation and value

kg – Kilogram

km – Kilometer

kPa – Kilopascal

L – Liter

LED – Light emitting diode

LS – Least squares

Lux - Illuminance

m – Meter

min – Minute

MLC – Midtech Legacy Controller

mm – Millimeters

ms – Milliseconds

n – Number of samples

NB – Number of branches

P – Probability

PA – Precision agriculture

PAC – Percent area coverage

PC – Personal computer

PD – Plant density

PPC – Pocket personal computer

RAM – Random access memory

RGB – Red green blue

RTK – Real time kinematics

s – Second

SA – Spot-application

SAS – Statistical analytical software

SATA2 – Serial advanced technology attachment

SD – Stem diameter

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

USB – Universal serial bus

V – Volt

VAC – Volts alternating current

VDC – Volts direct current

VR – Variable rate

VRC – Variable rate controller

W – Watt

WASS – Wide area augmentation system

WSP – Water sensitive paper

YD – Yield

°C – Degree Celsius

® – Registered

™ – Trade mark

μ – Micro

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

1.1.1 Weeds in the Wild Blueberry Cropping System

Weeds in the wild blueberry cropping system are any plant growing in a location where they are un-wanted. Weeds typically are damaging to the wild blueberry crop and limit harvestable yields as they compete for water, nutrients, sunlight and space. Weeds are classified as either annuals, biennials or perennials (Radosevich et al. 1997). Annuals have the ability to produce seed quickly and in large quantities over a one-year lifespan. Biennial weeds grow their roots and leaves in the first year. After entering dormancy in the colder winter months they produce flowers/seeds during the second summer. Perennials are typically the hardest type of weed to eradicate because they continue to grow each year (Mulligan and Findlay 1969).

Weeds have been a major yield limiting factor for the wild blueberry industry (Metzger and Ismail 1976; Yarborough 2006). Weeds can cause a variety of issues to the final harvested crop if left unhindered including; reduced yield, inability to harvest crop, product contamination or off flavors. In some extreme cases the processing facility may even refuse to accept the harvested crop due to poor quality. The presence of weeds also poses a difficulty in mechanical harvesting of wild blueberries as the picking teeth get clogged with debris and weeds, resulting in an additional fruit loss of 10 to 30% (Trevett and 1972). More competitive weed species can reduce harvestable wild blueberry yields by more than 80%, if not properly managed. Other weed species that are less damaging would likely reduce yields by 5% if not managed (Gianessi and Sankula 2003). In Maine, USA, a research study compared the organic and conventional wild blueberry farms revealing 75% lower yield for organic wild blueberry when compared with conventional (Marra 1995). Gianessi and Sankula (2003) found that proper herbicide use in wild blueberry increased yield up to 200%. Research in other cropping systems have found a similar reduction trend in yields due to damaging contributions from different weed species (Beckett et al. 1988; Edward-Jones 2008; Gianessi and Sankula 2003; Cooper and Dobson 2007).

1.1.2 Herbicides for Weed Control

Originally weeds have been removed from competing agricultural crops by hoeing manually or with an implement towed behind a horse or tractor. Edward-Jones (2008) states that pesticides offer a variety of advantages over other control methods including ease of use, rapid weed control, consistency of control and significantly higher yields. Herbicides are now the most commonly used (60%) type of pesticide since weeds are the major yield limiting factor in many crops (Gianessi and Sankula 2003). Herbicides damage plants by interfering with the normal function of one or more of their vital processes including photosynthesis, amino acid, protein synthesis, lipid synthesis, respiration, cell division and maintenance of membrane integrity (Gianessi and Sankula 2003). Synthetic pesticides are among the most widely used chemicals in the world (Yao et al. 2008). Contact herbicides kill the parts of the weed that come in direct interaction with the herbicide. Systemic herbicides kill by getting absorbed into the root system of the target weed usually with the water or nutrients, which are used by that particular weed. Timing of herbicide application is broken into two categories *i.e.,* pre-emergence and post-emergence. Pre-emergence herbicide is applied before the germination of the target weeds. Post-emergence herbicides are effective for the weeds that are already grown.

Pesticides are important for controlling pests and plant disease resulting in improved crop yields, increased crop quality, reduced fungal disease and improved shelf life (Cooper and Dobson 2007). Drummond et al. (2009) found that weeds compete with the wild blueberry plants for soil nutrients causing a reduction in yield if not managed. *Rumex acetosella L.* (red sorrel) is a common weed in wild blueberry fields (Fig. 1-1). Improper management and control of this weed results in decreased blueberry yields and lowers mechanical harvester picking efficiency (Kennedy 2009; Kennedy et al. 2011). Propyzamide (Kerb™) herbicide decreased red sorrel above ground shoot growth and ramet density (Hughes 2012).

Figure 1-1: Red sorrel infestation in a wild blueberry field.

Hair cap moss (Polytrichum commune) is the most common weed growing in many wild blueberry fields in Atlantic Canada (Percival and Garbary 2012). Moss competes with the wild blueberry plants and stays growing late into the fall season (Fig. 1-2). Percival and Garbary (2012) determined a fall application of Chateau® herbicide (flumioxazin) was an effective method to control hair cap moss pressures without damaging the wild blueberry plants.

Figure 1-2: Hair cap moss infestation in a wild blueberry field.

Regulations of herbicides is a common practice in North America limiting the amount and timing of the applications made as well as banning older herbicides that were found to be detrimental to the agriculture sector. Wilson and Tisdell (2001) found that farmers are required to use pesticides despite environmental risks, health and sustainability costs, due to the increased yield benefits. Benefits to the local community from the use of pesticides in agriculture include increased farm and agribusiness revenue, food safety, wider range of available crops and less pressure on uncropped land (Cooper and Dobson 2007). Without herbicides there would be an estimated $13.3 billion loss in farm income in the USA (Gianessi and Sankula 2003). Herbicides have been used on more than 90% of the acreage of most U.S. crops (Gianessi and Sankula 2003). However, herbicide use in Canada is more controlled by the authorities as Canadians are concerned about the quality of their water resources (Commissioner of the Environment and Sustainable Development 1999; Ontario College of Family Physicians 2004; Federation of Canadian Municipalities 2006).

Pesticides enter the Canadian environment primarily through agricultural practices (Murray et al. 2011). Pesticides are able to enter the atmosphere mainly through spray drift and post-application volatilization (Yao et al. 2006). Hashemi and Damalas (2011) found that farmer's perceptions of pesticide effectiveness should receive special attention by extension services as a critical point of intervention for rational pesticide use and adoption of an integrated pesticide management program. Maroni et al. (1999) developed a risk assessment and management of occupational exposure tool for proper pesticide use.

1.1.3 Fungicides for Disease Control

Annis and Stubbs (2004) showed significant variation in wild blueberry yield with the incidence of stem and leaf spot diseases. However, a significant reduction in fruit production did occur in stems with disease as compared to healthy plants. Foliar diseases *Septoria* leaf spot and blueberry rust have caused a reduction in wild blueberry yields (Percival and Dawson 2009). The application tank mix of chlorothalonil (Bravo®) and

Boscalid/pyraclostrobin (Pristine™) fungicide have found to lower *Septoria* leaf spot and blueberry rust. This application resulted in an increased harvestable yields of 13.3% over the non-treated control (Percival and Dawson 2009). Percival and Burnham (2013) found that proper fertilizer and fungicide use prolonged wild blueberry leaf retention and suppressed foliar pathogens resulting in an increased harvestable yield. In Georgia more than 80% of the blueberry producers frequently apply fungicides to control disease resulting in increased yields (Scherm et al. 2001).

Gradish et al. (2012) reported many pesticides used for wild blueberry production to be harmful to the alfalfa leaf cutting bee, which is an important wild and managed pollinator in Atlantic Canada. Insect-mediated cross-pollination is essential for wild blueberry fruit set (Melathopoulos et al. 2014). Drummond and Groden (2000) found biological control of insect pests that attack lowbush blueberry can be an effective method resulting in lower pesticide application. Results also showed that pollination success was also strongly dependent upon the pest and disease management. Pruning the wild blueberry plants by burning has found to be an effective method of reducing the presence of mummery berry blight and leaf spot disease incidence compared to fields that are pruned by flail mowing. Burning destroys many of the mummy berries that over-winter on the surface of the soil under the leaf debris.

1.1.4 Pesticides and the Environment

Present environmental concerns related to agrochemical spraying include emissions of volatile organic compounds, runoff that allows pesticides to enter waterways, and spray drift onto non-target areas (Giles et al. 2011). An increasing population growth (80 million per year) requires more efficient use of non-renewable resources (Azadi et al. 2011a).

Tilman et al. (2002) determined the need of new incentives and policies to be implemented for ensuring the sustainability of agriculture and ecosystem services to meet the demand of improving yields without compromising the environmental integrity or public health. Azadi et al. (2011b) emphasize the need of introducing law and regulation coupled with tax incentives and agricultural subsidies to meet the goal of sustainable agriculture.

Organic agriculture has been highlighted with the ability to reduce many negative impacts associated with pesticide (Pelletier et al. 2008). Organic farmers do not use herbicides and have reported that weed control is their leading implication causing reduced yields as compared to conventional practice of using herbicides to control the weed pressures (Gianessi and Sankula 2003). Given the low productivity of organic agriculture, conventional methods of agricultural inputs are required to sustain the current food demand (Azadi et al. 2011b).

1.1.5 Agrochemical Sprayers

Sprayers have revolutionized the agriculture industry by allowing the famers to control weeds, disease and pests resulting in increased harvestable yields (Razali 2012). Three general spraying methods are being implemented for agriculture use: broadcast, band, and targeted spraying (Hong et al. 2012). Broadcast is the most commonly used method of spray application that covers the entire field with a blanket agrochemical application. Band spraying is used for row crops where only selected strips in the field need application. Targeted spraying is the most difficult method of application because it requires sensors to determine the locations that need application of agrochemicals. Target spraying can lower the amount of agrochemical spray by 60 – 70%, allowing for a substantial cost reduction for farmers (Hong et al. 2012). Target spraying can also minimize the environmental risk to ensure a sustainable agriculture sector.

Cayley et al. (1987) tested the effectiveness of different spraying systems. They found that rotary atomisers gave the greatest control of target organisms except for when applying herbicides. Smart spraying systems use selective spraying methods in which crop, plant, weed and disease information is obtained by sensors to control nozzles for real-time spot-spraying. The control systems typically make decisions based on input from the sensors and adjusts the output spray based on a computer algorithm. Smart sprayer technology has benefits such as; uses water more efficiently, less agrochemical wasted in non-target areas, more environmentally friendly (from less agrochemical being applied), reduction in soil erosion and potential for an increased yield.

Spot-application of agrochemical using a smart sprayer has a great potential to achieve high yield, with potentially lower risk to the environment compared to conventional spraying methods. A variety of smart spraying methods for spot-specific herbicide application have been developed and tested to reduce production costs and to ensure environmental sustainability. WeedSeeker® (NTech Industries, Inc., Ukiah, CA, USA) is a common spraying system that is able to target and spray green foliage, however, it is limited to use with the detection of green foliage (Rizzardi et al. 2007). Percival et al (2014) used WeedSeeker® Model 650 sensors mounted on a 6.1 m wide boom sprayer to target and spray weeds during spring pre-emergence and fall post-emergent herbicide applications within wild blueberry fields. The sprayer was also used to apply fungicide saving 16.7 to 26.7% agrochemical by shutting off nozzles in bare-soil areas.

Changxing et al. (2012) developed an intelligent robot sprayer that significantly reduced pesticide use by 60%. Ahmed et al. (2007) built a real-time machine vision weed control system using Microsoft Visual C++ that detected both broad and narrow leaf weed locations. The developed algorithm classified images with little to no weeds with 100% accuracy and narrow and broad leaf weeds with 90% accuracy. Ahmed et al. (2008b) used a video camera and successfully (>95% accuracy) developed a selective spraying system for selective weed control. Similarly, Ahmed et al. (2008a) developed an advanced control system that used edge based real-time weed recognition system for selective herbicide treatment. Cooke (1996) developed a sprayer system using photo-sensors and was able to detect green weeds (as small as 0.02 m in diameter) and shutoff nozzles in soil areas for use in soybean fields. Herbicides savings reported with this system ranged from 50 to 85%.

Bajwa and Tian (2001) successfully mapped weed density using color-infrared (CIR) digital aerial images in the early stages of crop growth for soybean fields. Results of their study reported significant spatial variations in weed density within field, demanding of spot applications on an as needed basis. Haq et al. (2007) developed a machine vision system to detect and discriminate crop and weed plants with >93.5% accuracy with over 200 sample images. However, Haq et al. (2007) found only one species of weed which could be detected at any one-time resulting in limited commercial application. Ishak and Rahman (2010) developed an automated weedicide sprayer system to locate the existence and intensity of weeds using red-green-blue (RGB) images in real-time to spray automatically with precision. Ishak and Rahman (2010) also reported that variable lighting conditions negatively affected the quality of the acquired images. Naeem et al. (2007)

differentiated between broad leaf and narrow leaf weeds using a machine vision system on a prototype sprayer with an accuracy of 97%.

Zheng et al. (2004) developed a precision pesticide application method suitable to recognize the image from each softwood tree and automatically apply the proper amount of agrochemical. Giles et al. (2011) used a target-sensing smart sprayer to reduce pesticide application rates in almond and prune orchards by 15 – 40%, providing significant environmental and economic benefits. Ishak et al. (2011) developed a variable rate (VR) sprayer using machine vision system and allocated three rates of nozzle output volume based on the level of weed infestation (0 – 2% weed coverage = nozzle off, 3 – 50% weed coverage = nozzle half rate, 51 – 100% = nozzle full rate). The aim of their study was to efficiently eradicate weeds by applying the optimum amount of herbicide in the precise locations on an as needed basis. Liu et al. (2015) developed an intelligent VR sprayer that could adjust spray output to match grapevine shape and size to maximize agrochemical input efficiency. The sprayer was successfully tested at speeds between 3.2 and 8.0 km h^{-1} with agrochemical savings of 50%. Tian (2002) developed a smart sprayer to estimate the weed density and size in real-time and effectively spray herbicide spot-specifically. This sprayer was specially designed to work under variable outdoor lighting conditions. Instead of using high spatial resolution images and individual plant recognition, low resolution (large view area) images were used. Swain et al. (2009) developed a self-guided robot that could travel at speeds of 0.1 m s^{-1} and apply liquid agrochemical with 3.1 mm target accuracy. However, the accuracy decreased significantly at higher traveling speeds. Further testing was also required with different illumination sources in field conditions for accurate targeted applications.

Esau et al. (2013) developed and tested a prototype VR sprayer with a machine vision sensor boom located in front of an all-terrain vehicle (ATV) for small scale spot-applications of fungicide in wild blueberry fields using a 6.1 m wide sprayer boom mounted behind the ATV. Esau et al. (2014a) developed and tested a prototype VR sprayer with a machine vision system located in front of a farm tractor for large scale spot-application of herbicides in wild blueberry using a 12.2 m wide sprayer boom mounted behind the tractor. Esau et al. (2014b) modified a smart sprayer to operate with a machine vision system mounted on the rear sprayer boom and compared the target detection and spraying accuracy with the older version of sprayer equipped with front mounted sensor boom. The authors suggested that the rear mounted machine sensor boom was a superior system with reduced positioning error and lower construction and material costs and should be tested for a wider range of agrochemical applications.

1.2 OBJECTIVE AND GOALS

The overall objective is the development of an effective smart sprayer system for spot-applications of agrochemicals in wild blueberry fields. The detailed objectives of this study were to:

i) Develop a prototype variable rate sprayer for spot-application of agrochemicals in wild blueberry.

ii) Supplementary light source development for camera-based spraying in low light conditions.

iii) Rear mounted machine vision smart sprayer for spot-application of agrochemicals.

iv) Economic analysis for smart sprayer application in wild blueberry fields.

CHAPTER 2 PROTOTYPE VARIABLE RATE SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICALS IN WILD BLUEBERRY

A prototype VR sprayer was developed for spot-application of herbicides to the weeds. The boom was divided into 16 sections (0.76 m per section). The VR control system consisted of eight digital color cameras mounted on a separate boom in front of the tractor, a 20-channel MidTech Legacy 6000™ controller (MLC) (Midtech Technologies, Springfield, IL, USA), and two 8-channel VR controllers (VRCs) interfaced to a Pocket PC via wireless Bluetooth®. Cameras were connected via USB cables to a computer. The cameras were capable of capturing the images and custom software was developed for processing the images to detect weeds in real-time. The triggering signals were sent to the VRC to open the specific nozzles where the weeds had been detected.

The VR sprayer performed well and adequately sprayed propyzamide on red sorrel and flumioxazin on moss within the selected wild blueberry fields. T-test from experiment 1 indicated that the percent area coverage (PAC) of water sensitive papers (WSPs) in target and non-target areas after the flumioxazin application was significantly different indicating spot-application technique using the VR sprayer applied the flumioxazin on targets. Spot-application from experiment 2 resulted in a 69% reduction in propyzamide use with 25 cm before and after target buffer and 28% cover of red sorrel.

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2.1 INTRODUCTION

Wild blueberry (*Vaccinium angustifolium* Ait.) yields are highly dependent on agrochemicals (herbicides, fungicides, and insecticides) for adequate weed, floral blight, leaf disease, and insect control (Yarborough, 2006). Traditionally, these agrochemicals are applied uniformly without considering significant bare spots and weed patches that exist within fields. The repeated and excessive use of agrochemicals not only increases the cost of production but it is also impacting the environment, for humans, for the native pollinators, and for the blueberry plants. Chemically-polluted runoff from fields can cause contamination to the surface and ground water (Tardiff, 1992; Pimentel and Lehman, 1993). This situation emphasizes the urgent need to develop an affordable, reliable, real-time VR sprayer, using cost-effective sensors/cameras and controllers for spot-specific application of agrochemicals in the wild blueberry cropping system.

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., 2006; Dammer et al., 2008) to date. Michaud et al. (2008) developed a VR prototype sprayer to deliver pesticides based on prescription maps developed in geographical information system (GIS) software using aerial spectral scans of the wild blueberry fields. The system was sensitive to positional error caused by the global positioning system (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. Zaman et al. (2011) developed an automated prototype VR sprayer for real-time tall weed detection and spot spraying in wild blueberry fields. The concern with using this technology is that grasses and weeds are not tall enough to sense using ultrasonic sensors in the sprayer during the spring and fall. Automated ground measurements using a digital photography technique for weed and bare spot detection were thought to overcome these limitations of ultrasonic sensors.

Automated yield monitoring systems using digital color photography were developed and evaluated to map wild blueberry yield (Zaman et al., 2008, 2010; Chang et al., 2012a; Farooque et al., 2013). Chang et al. (2012b, 2014) developed several algorithms and incorporated them into an automated real-time weed detection system for wild blueberry fields. Zhang et al. (2010) developed color image-based machine vision technology to detect and map bare spots for site-specific application of agrochemicals within wild blueberry fields. Esau et al. (2013) developed and tested a prototype VR sprayer for small scale spot-application of fungicide for wild blueberry. These technologies could also be used to detect weed and plant information and send triggering signals to the controller to spray agrochemicals in the specific boom section where the weeds have been detected. The digital color cameras with custom software, using advanced image processing techniques, and fast processors can be an option to differentiate weeds, bare spots and blueberry plants real-time in the field.

Advances in sensing technology and VR control systems have offered new opportunities for detecting weeds and spot-application of agrochemicals on as needed basis. Many commercial controllers have been developed to deliver agrochemicals on a site-specific basis using GPS guided prescription maps within fields. Schumann and Hostler (2009) with the partnership of a machinery manufacturer (Chemical Containers, INC, Lake Wales, Fla.) developed an 8-channel VRC. The controller is linked with a pocket personal computer (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. Therefore, a prototype commercial VR sprayer with digital cameras and controllers could be developed and used for in-season, spot-application of agrochemicals in the wild blueberry cropping system. In this study, the performance of an automated prototype VR sprayer was evaluated for real-time weed detection and spot spraying in wild blueberry fields.

2.2 MATERIALS AND METHODS

2.2.1 Development of a Prototype Smart Sprayer

2.2.1.1 Smart Sprayer Hardware Components

The prototype VR sprayer is operated with a John Deere 6430 (Deere & Company, Moline, Ill.) farm tractor. Components of the prototype VR sprayer included eight µEye digital color cameras (UI-1220SE/C, IDS Imaging Development System Inc., Woburn Mass.), a rite-height auto-boom leveling system, two 8-channel VRCs, MLC, desktop computer (PC) with custom image processing software, servo valve, flow meter, 16 solenoid valves and nozzles (Fig. 2-1). The 12.2 m MS 1135E sprayer boom (MS Spray Inc., Drummondville, Quebec, Canada) was divided into 16 sections with 0.76 m in each section. One solenoid valve and one nozzle were installed on each section of the boom. A series of tee joints connected the distribution valve to each section. The tee joints were connected to a solenoid valve to which a nozzle was fitted as closely as possible. Each nozzle was able to spray in a 0.76 m wide section of the 12.2 m sprayer boom (Fig. 2-1). The boom height above the ground surface was 1.1 m.

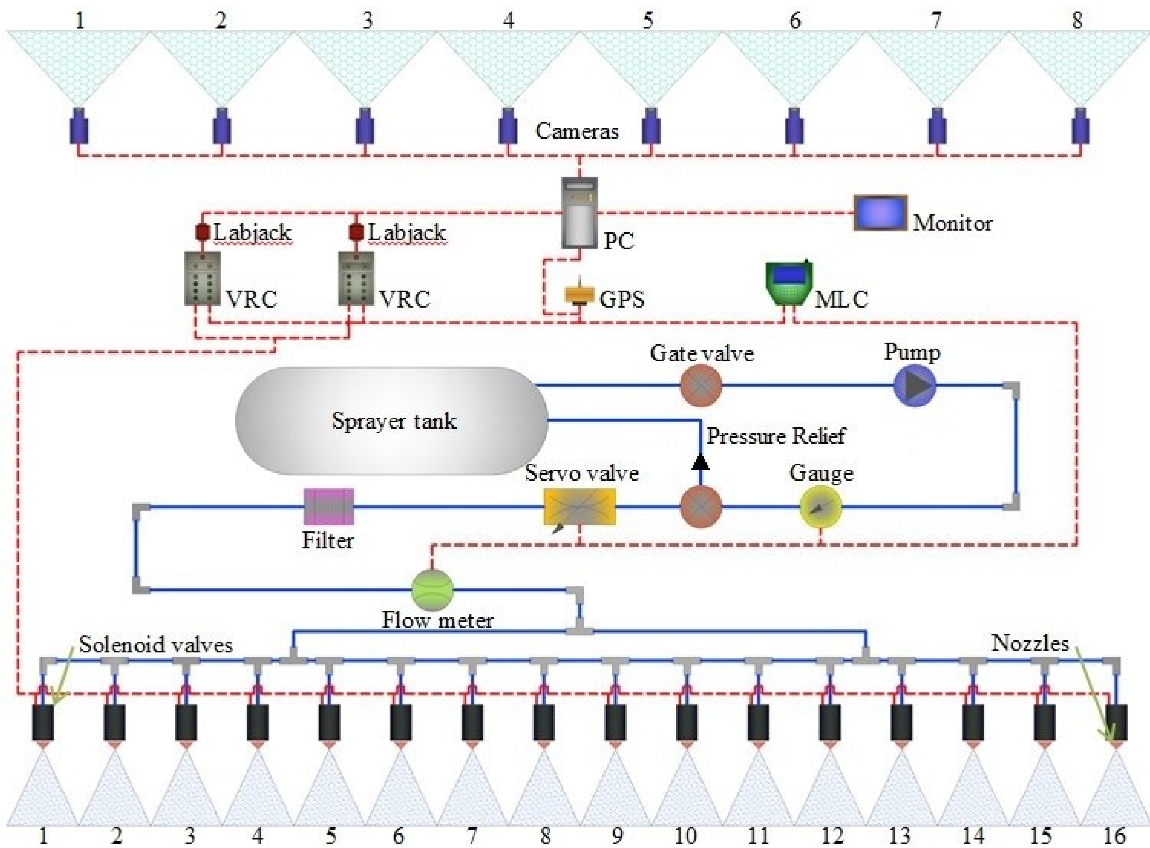


Figure 2-1: Schematic diagram showing the main components of the machine vision system and individual nozzle section flow control setup.

The sensor boom, with 12.2 m width at 1.1 m height above ground surface, was mounted in front of the tractor (Fig. 2-2). Eight digital color cameras were incorporated on both sides of the front boom (Fig. 2-2). Each camera covered two sections of the boom (0.76 m each section). Cameras were attached using USB cables to the PC in tractor cabin (Fig. 2-1). Custom software was used which was capable of processing the images to detect weeds, bare spots, and blueberry plants in real-time and send weed or plant triggering signals through two Labjack digital i/o and data acquisition devices (LabJack Corp., Lakewood, Colo.) that both feed 8-channels on each of the VRCs. The VRC consists of electronic hardware with internal firmware and matching Windows Mobile® software on a handheld PPC that had user programmable inputs such as a before and after distance buffer, delay time, and ground speed correction. These stored operating parameters could be easily retrieved and activated by linking the VRC with the PPC using wireless Bluetooth® and editing or selecting values on the setup screen with Windows Mobile® compatible software. The VRCs were designed to send 12 V direct current (DC) power signals to the 16 solenoid valves to open and close the nozzle at the specific time interval when needed. The VRCs also send triggering signals to the MLC which automatically adjusts the flow rate using a servo valve and in-line flow meter based on the number of nozzles operating and tractor speed at the time of application. The ground speed was obtained in real-time from a wide area augmentation system (WASS) enabled differential GPS (DGPS) to compensate changes in flow in the nozzles to maintain a consistent application rate of 187 L ha^{-1}. The PC in the tractor cabin was operated using a touchscreen monitor that was mounted in clear view while sitting in the operator's seat. The monitor also displays the custom software user interface where camera and program settings can be easily modified.

The sprayer tank size was 1128 L. The Comet BP125 3 pistons diaphragm pump (Comet Industrial Pumps, Burnsville, Minn.) was powered by the tractors power take off. The feed line from the pump went through a flow valve, particle filter and flow meter. The line was then separated into two sections, each line feeding eight segments of the boom (Fig. 2-1). The nozzles were TeeJet TP8004 flat fan nozzles (TeeJet Technologies, Springfield, IL, USA).

Computer and controller

Solenoid valves & nozzles Self-leveling boom height sensor µEye cameras

Figure 2-2: The experimental setup showing the cameras out in front of the tractor and the individual nozzle section flow control setup.

2.2.1.2 Image Processing Hardware and Software Development

Real-time foliage detection hardware consisted of eight µEye cameras connected via 12.2 m length USB 2.0 active extension cables (Sabrent CB-USBXT, Miami, Fla.) to a 2.8-gigahertz (GHz) Intel® Core™ i7-860 central processing unit (CPU) and 4 gigabit (GB) random access memory (RAM) computer. Active extension USB cables were used to ensure proper connectivity over the extended distance (9.75 m). A 128 GB serial advanced technology attachment (SATA2) solid state disk flash drive was installed to ensure the durability and performance when operating in rough field conditions. A 1500 W 12 volt direct current (VDC) to 120 volt alternating current (VAC) power inverter was installed in the tractor cabin to power the PC. The wide angle field of view lenses (LM4NCL, Kowa Optimed Inc., Torrance, Calif.) had a 3.5 mm focal length and were set up with a fixed aperture (f/4.0) and infinity focuses. To adjust for the variable outdoor light conditions the exposure time and digital gain were automatically controlled by auto exposure shutter/auto gain control. To prevent picture blurring during image acquisition the maximum auto exposure shutter was set to 2 ms. Multiple selection foliage detection software was developed in C++ using Visual Studio 2010 (Microsoft, Redmond, Wash.) (Fig. 2-3). The software interface allows the user to choose the type of agrochemical being applied which then automatically adjusts the program for proper image processing settings. The software acquires 24-bit RGB 752 × 128 pixel images corresponding to a 1.52 × 0.31 m^2 area of interest from each of the eight cameras and processes the data to discriminate weeds from blueberry foliage and bare spots. The ratio used was $(G \times 255)\ (R + G + B)^{-1}$, and a manually obtained threshold (> 80) adequately discriminated the apparent foliage green pixels from the remaining pixels. The final stage of the foliage detection converted the 5 VDC signal, in each image and sent it to the VRC for spraying in the specific section of the boom where the target foliage had been detected. Detailed algorithm can be seen in Chang et al. (2014).

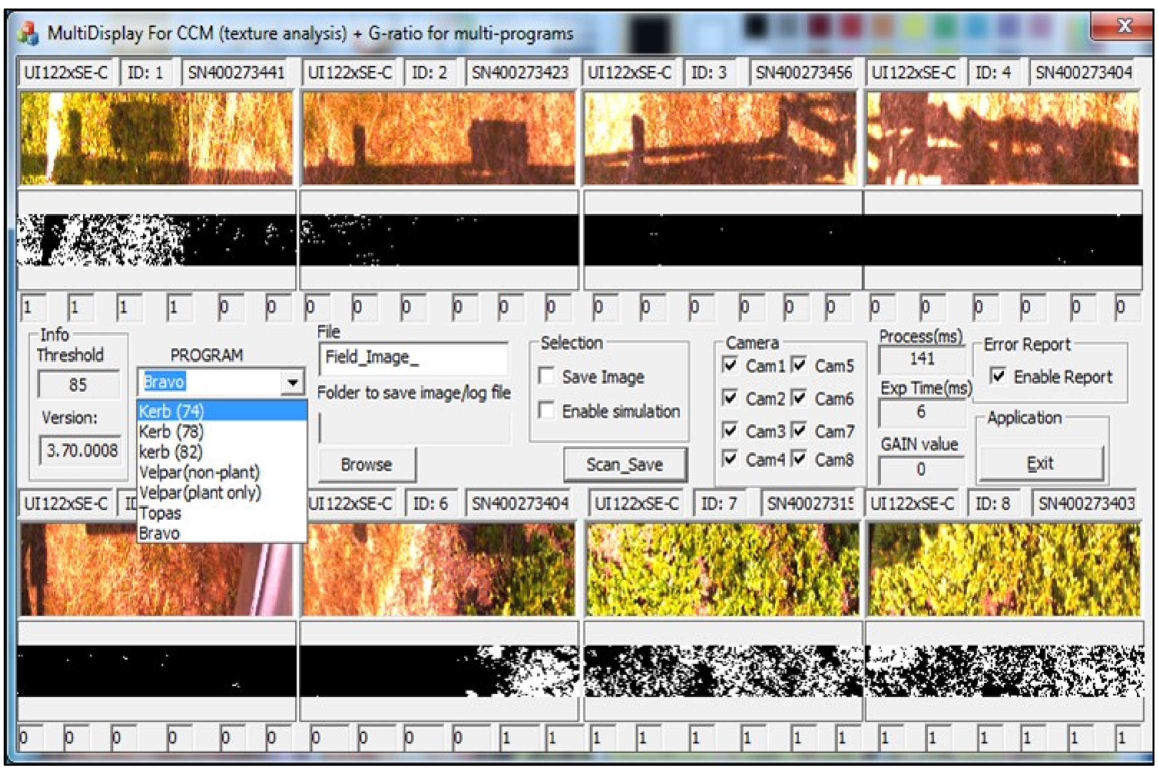


Figure 2-3: Custom image processing program user interface developed for use with a touchscreen monitor. The user can choose the appropriate program from a drop down window.

2.2.1.3 Custom Developed µEye Camera Case

The dimensions (length = 48.56 mm, width = 43.66 mm, height = 38.08 mm) of a µEye digital color camera and attached kowa lens (length = 39.04 mm, diameter = 30.99 mm) were measured using digital calipers. A custom designed ruggedized weather resistant case was drawn using SolidWorks® 2014 (Dassault Systemes SolidWorks® Corp., Waltham, MA, USA) computer aided design (CAD) software for exact fitment of the µEye digital color camera (Fig. 2-4). The designed camera case was water resistant and could allow easy access to the enclosed camera with the ability to be mounted directly to the sprayer boom. A rubber O-ring was used to seal the connection between the camera case and the removable cover. Rubber washers were used to seal water and dust from entering through the camera mounting screw holes on the back side of the case. A recessed lip on the bottom of the case was designed to install the clear camera lens cover that kept unwanted water and dirt from entering.

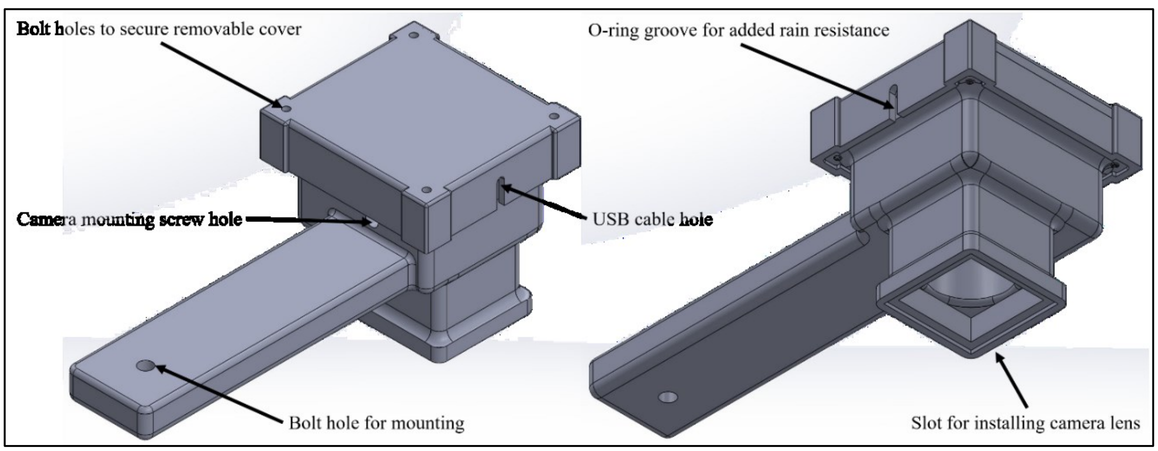


Figure 2-4: SolidWorks® CAD schematic showing custom designed weather resistant camera case.

3D Afinia V2.17 (Afinia, Chanhassen, MN, USA) software was used to import the SolidWorks® .STL CAD drawing to print the camera case on an Afinia H800 3D printer

(Afinia, Chanhassen, MN, USA). The Afinia H800 used a fully-automated platform leveling and height sensing system with ultra-fine 100-micron print resolution and print accuracy within 0.10 mm. Afinia natural acrylonitrile butadiene styrene (ABS) 1.75 mm filament was used as the printing material (AF-ABS-1.75-1K-NTL, Saelig Company, Inc., Fairport, NY, USA). The print resolution was set to fine detail to ensure maximum quality and water resistance. Approximately ten hours was required to print each camera case. Figure 2-5 shows the camera case 3D print stages. Following completion the rafting and supporting material used for printing the case was removed using needle nose plyers to reveal the final 3D printed product (Fig. 2-6).

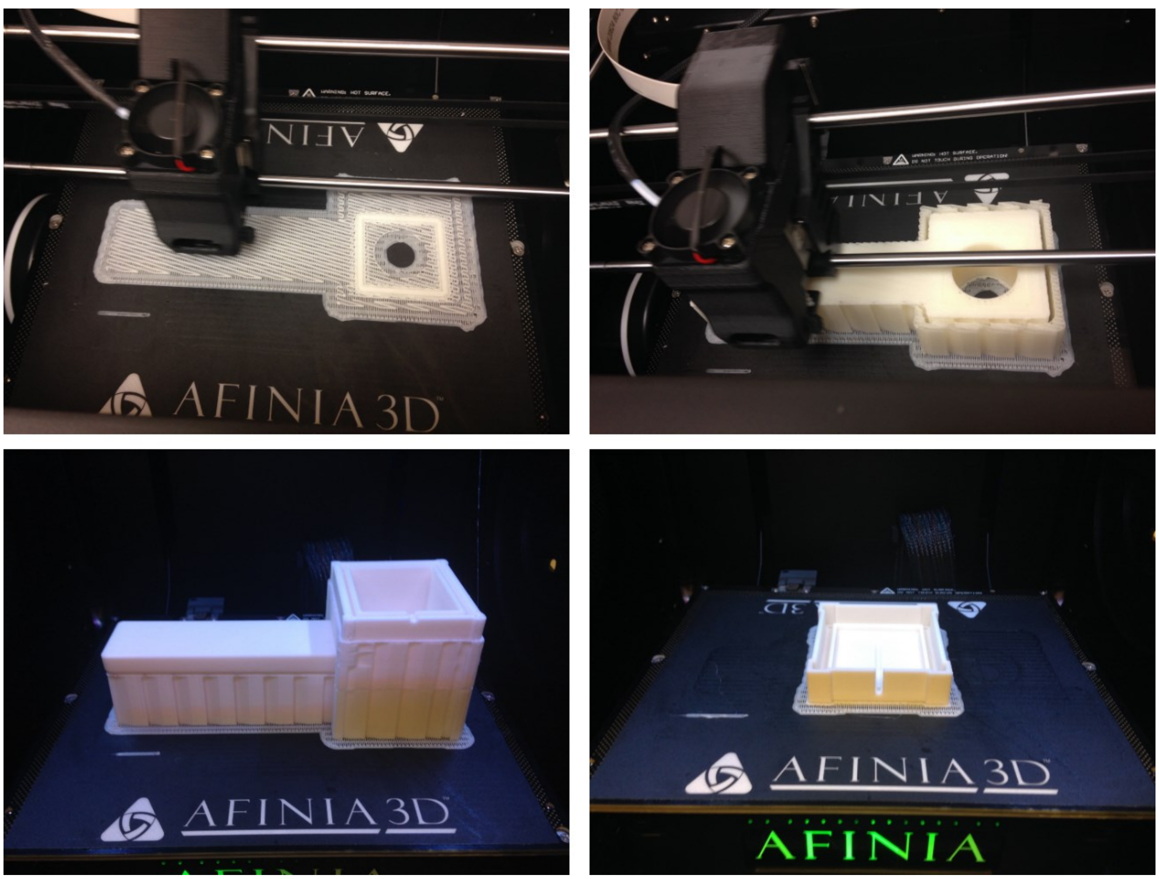


Figure 2-5: Custom camera case print stages using Afinia H800 3D printer.

Impact resistant clear polycarbonate lens (BLU-28853000, Air Liquide Inc., Montreal, QC, CA) were cut to size and fixed into the grove of the camera opening at the bottom of the case using quick dry epoxy. To insure the camera case stayed water resistant, white plastic spray paint (42320, Krylon Industrial, Cleveland, OH, USA) was used to fill the small pores of the surface that may be prone to water penetration (Fig. 2-6). The μEye camera was then installed in the camera case and mounted onto the sprayer boom of the tractor (Fig. 2-7).

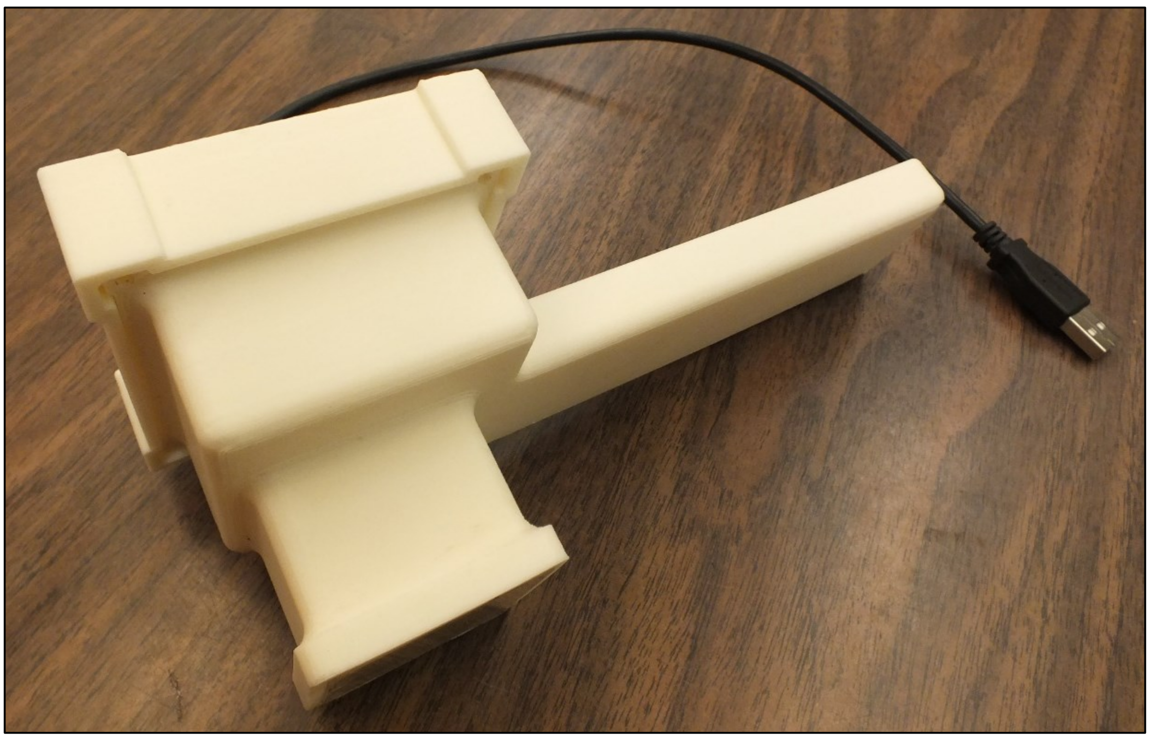


Figure 2-6: 3D printed ABS custom camera case with camera installed with attached USB camera.

Figure 2-7: Custom made weather resistant smart sprayer camera case painted white and mounted on smart sprayer boom.

2.2.2 Testing and Performance Evaluation of the Prototype Smart Sprayer

2.2.2.1 Lab Testing Components for Smart Sprayer

Major components of the prototype VR sprayer (VRC, digital color cameras, and MLC) were tested at the Dalhousie University Agricultural Campus (DAL AC) for accurate target detection and spraying. The performance of the prototype VR sprayer was evaluated in wild blueberry fields and the herbicide savings of using VR technologies was calculated.

An experiment was conducted at the DAL AC to calibrate and evaluate the MLC for accurate nozzle flow rates. The volume of liquid from single nozzles as well as different nozzle combinations was collected and measured using a graduated cylinder over a 1-min interval and compared with flow rates on the display screen of the MLC. The nozzle combinations were chosen to represent a wide range of flow groupings. The experiment was replicated three times and the results were displayed on a per nozzle basis. The percent difference between the MLC volumes and manually measured volumes were used to characterize the performance accuracy of the MLC to determine its feasibility for use with the on/ off of the individual nozzles.

Another experiment was conducted in the metal shop at DAL AC to calculate response time (i.e., lag time between camera detection and spray discharge time) for the VRC. Camera image acquisition time combined with image processing time was determined using a milli-timer function built into the custom software. A light emitting diode (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 with 149 frames per second. The video was recorded displaying when the VRC received feedback information from the computer (LED was ON) until the controller opens the valve to discharge the liquid through the nozzle orifice. The experiment was repeated 10 times and video images were analyzed with V1 HOME 2.0 software (Interactive Frontiers, Inc., Plymouth, Mich.), allowing for a frame by frame analysis of response time between VRC and spray discharge. The total response was calculated as follows:

$$T_{rt} = T_{ic} + T_{ip} + T_{vd} \qquad (1)$$

where T_{rt} = *total response time*, T_{ic} = *time taken by camera for image acquisition*, T_{ip} = *image processing time for plant, weed or bare spot detection and time from computer (sending signal) to VRC*, T_{vd} = *time from VRC to spray discharge*.

2.2.2.2 Field Testing Smart Sprayer

Two wild blueberry fields were selected in central Nova Scotia in fall of 2010 to test the performance accuracy of the VR sprayer for spot-application of agrochemicals. The selected fields were the Debert site (45.4418°N, 63.4496°W, 1.6 ha) and the Frank Webb site (45.4047°N, 63.6727°W, 2.5 ha). Both fields were in crop year of the biennial crop production cycle in 2010 during the experiment and sprout year in 2009. 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 the wild blueberry crop were red sorrel and moss in the Debert field, while the red sorrel was dominate in the Frank Webb field.

2.2.2.2.1 Smart Sprayer Field Experiment 1

The tracks were constructed using a measuring tape and boundaries, bare spots and weed patches of selected tracks were mapped with a real-time kinematics (RTK) GPS (On GRADE Inc., Dartmouth, NS, Canada). Twelve WSPs were fastened at randomly selected weed patches (targets) and plant/bare spot areas (non-targets), six in each (Fig. 2-8). The papers were orientated parallel to the ground and selected targets were marked with RTK-GPS. The field was sprayed using flumioxazin herbicide at a rate of 0.31 kg ha^{-1} active ingredient in 187 L ha^{-1} water on 15 November 2010. Flumioxazin was applied using TeeJet TP8004 flat fan nozzles, calibrated to deliver the appropriate water volume at a pressure of 275 kPa. WSPs were collected after travelled over by the VR sprayer. The WSPs were scanned and processed to calculate PAC of the sprayed (weeds) and non-sprayed (plants and bare spots) targets using WinRHIZO image analysis system (Regent

Instruments Inc., Quebec City, QC, Canada) for comparison. A student T-test was performed to examine whether the PAC of the sprayed targets were different than the PAC of the non-targets.

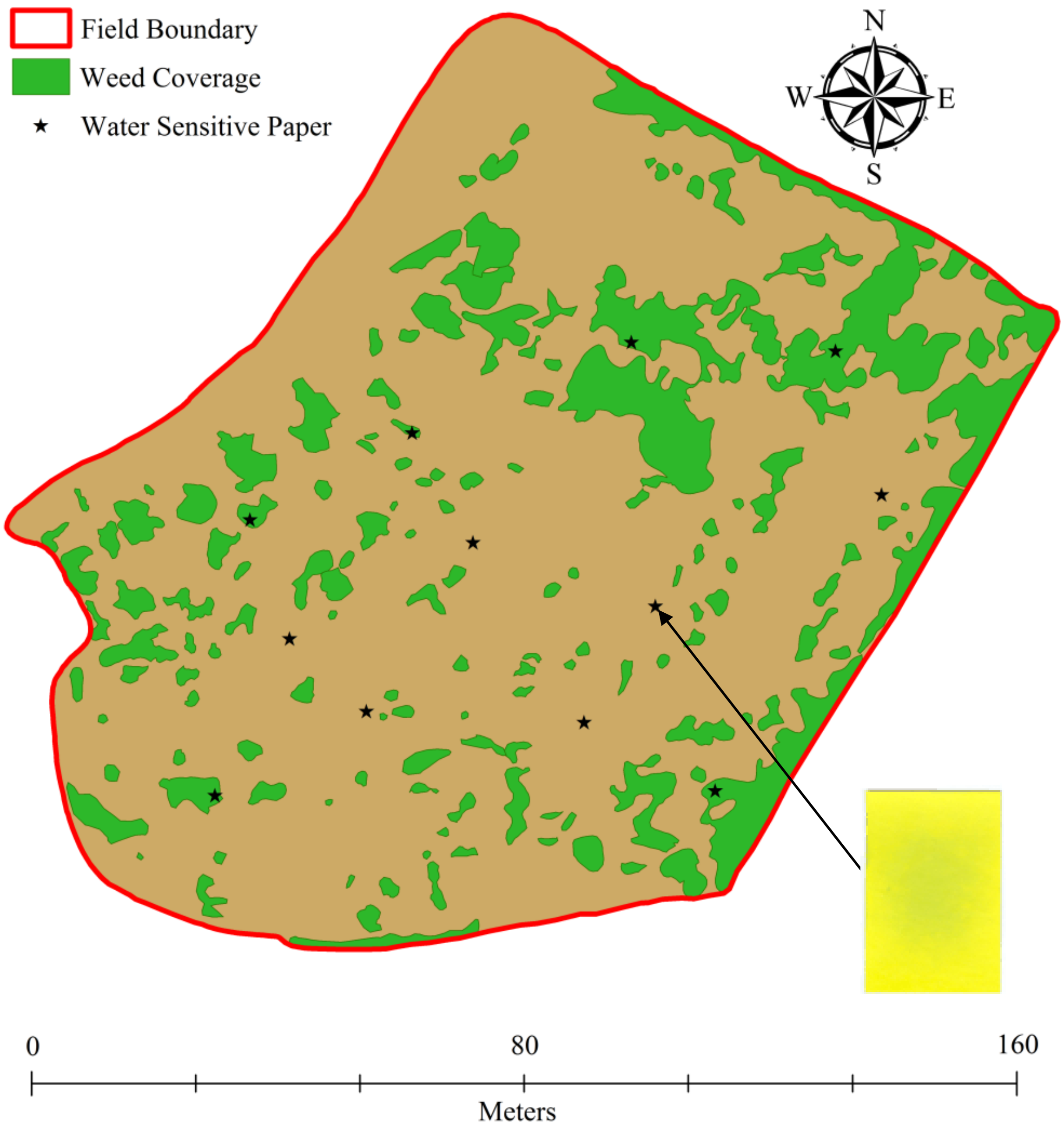


Figure 2-8: Experimental field map showing weed coverage and water sensitive paper locations used for VR spray application with prototype VR sprayer in the Debert wild blueberry field after mowing.

2.2.2.2.2 Smart Sprayer Field Experiment 2

The target locations were marked with an RTK-GPS in the Frank Webb field before and after spray application of propyzamide. The targets (before and after spray) were mapped in ArcMap 10 software (ESRI, Redlands, Calif.) and placed side by side for visual comparison. Propyzamide was applied on 30 November 2010 with an application rate of 2.23 kg ha^{-1} ai in 187 L ha^{-1} water on red sorrel in the Frank Webb field after mowing in fall (Fig. 2-9). The nozzle pressure was maintained at 275 kPa while the ground speed during the field operations was 6 ± 0.2 km h^{-1}. The buffer, before and after the target was adjusted at 25 cm for precise overlapping of propyzamide application on targets.

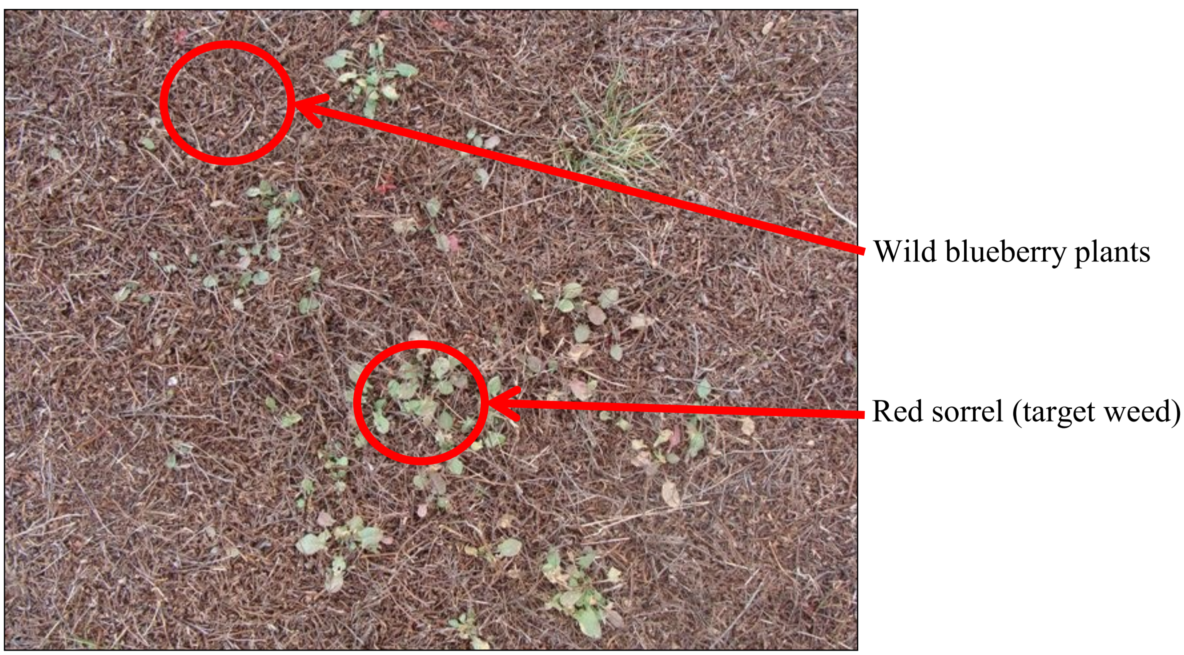


Figure 2-9: Original color image showing the Frank Webb field condition with red sorrel and blueberry plants after mowing in fall of 2010.

2.3 RESULTS AND DISCUSSION

Results indicated that the MLC performed dependably and promptly to regulate the flow rate in each nozzle. Variation of the flow measurements versus the readout on the

MLC decreased when more nozzles were activated over a 1 min time interval (Table 2-1). A possible reason for this large difference was the limitations of the flow meter being able to properly read very low flow rates (~1.4 L min^{-1}). The sprayer operates most effectively when there are between 8 and 16 nozzles open at one time (Table 2-1). Currently, the flow meter was required to handle a wide range of flow rates based on a variation of ground speed and nozzle output. A recommendation for improvement of the flow system would be to add additional flow valves and flow meters which can be all controlled by a single MLC. Each servo valve and flow meter would only be required to control four nozzles thus allowing for less fluctuation in flow rate per boom section with the on/ off actions of the VR sprayer. The benefit might be less spray output fluctuation and therefore better application coverage.

Table 2-1. MLC discharge measurement with measured discharge from the nozzles in different sections of sprayer boom.

Spray Nozzle(s) Open	Measured Flow Rate (L min^{-1})	MLC Flow Rate (L min^{-1})	Difference between Measured Flow and MLC Flow (%)
3	1.44	1.01	29.4
7	1.47	1.08	26.7
10	1.42	1.02	27.9
12	1.46	1.04	28.7
16	1.42	1.05	26.3
1	0.780	0.500	35.9
2	0.588		15.0
4	1.17	0.833	28.6
13	1.16		28.6
1	0.835	0.667	20.2
3	0.743		10.3
14	0.800		16.7
16	0.815		18.2
2	1.07	0.944	11.7
6	1.03		8.60
8	1.05		9.99
10	1.02		7.10
12	1.02		7.71
16	1.03		8.60

1	0.892	0.833	6.54
3	0.898		7.24
5	0.883		5.66
7	0.883		5.66
9	0.888		6.19
11	0.893		6.72
13	0.890		6.37
15	0.887		6.01
1	0.892	0.875	1.94
2	0.885		1.13
3	0.910		3.85
4	0.890		1.68
5	0.887		1.39
6	0.878		0.380
7	0.890		1.68
8	0.900		2.78
9	1.06	1.00	5.36
10	1.07		6.83
11	1.02		1.90
12	1.01		1.32
13	1.01		1.32
14	0.970		-3.09
15	1.01		0.990
16	1.00		0.332
1	0.898	0.917	-2.12
2	0.890		-2.99
3	0.930		1.43
4	0.902		-1.66
5	0.896		-2.31
6	0.880		-4.17
7	0.917		0.000
8	0.897		-2.23
9	0.912		-0.548
10	0.880		-4.17
11	0.906		-1.18
12	0.895		-2.42
13	0.893		-2.61
14	0.853		-7.42
15	0.890		-2.99
16	0.892		-2.80

The VRC was accurate and fast enough to spray application on selected targets during the experiments in the selected fields with a response time of 0.131 ± 0.003 s. The

VRC automatically compensated changes in response time caused by variation in ground speed during operation for accurate applications. The VRC was operated easily from the PPC using wireless Bluetooth® with Windows Mobile® compatible software. Results of this study also implied that automated identification of weeds in real-time and spot-application of herbicide using μEye digital cameras and fast controllers would help in controlling their growth in wild blueberry fields.

The T-test for target versus non-targets PAC indicated that there was significant bias (P-value = 0.00) in the weed detection (Table 2-2). Visual observation also revealed that the VR sprayer performed reliably during the field experiments, permitting real-time target (weed) sensing, and spot-application at correct targets in the specific section of the sprayer boom where the weeds had been detected. A VR sprayer using μEye digital cameras and VRC could be used for spot-application of agrochemicals within wild blueberry fields to increase farm profitability.

Table 2-2. Summary statistics of percent area coverage of the water sensitive papers for determining the precision of spot-application on weeds at select points in the field using the prototype VR sprayer (95% level of significance).

Water Sensitive Paper Location (n)	Min. (%)	Max. (%)	Mean (%)	S.D. (%)	P - value
Non-targets (6)	0.00	2.76	1.81	1.13	0.00
Targets (6)	51.8	85.5	70.1	11.0	

There was negligible PAC on the non-targets (Fig. 2-10). It was observed that some WSPs changed to a slightly blue color before spray on the targets. Slight blue coloring of the non-targets could have been due to drift because of wind speed and direction and or humidity. The significance of the T-test for weeds versus plant targets PAC indicated that there was significant bias (P-value = 0.00) in the weed detection with spot-application and the application of spray on weeds using spot-application was accurate (Table 2-2). The principle components of the prototype VR sprayer detected targets and sprayed reliably and accurately at proper targets in wild blueberry fields. Therefore, the equipment (VRC, MLC, cameras, solenoid valve, and nozzles) could be used to develop a VR sprayer to detect targets (weeds) and deliver a spot-application of agrochemicals at proper targets to reduce the cost of production and protect the environment.

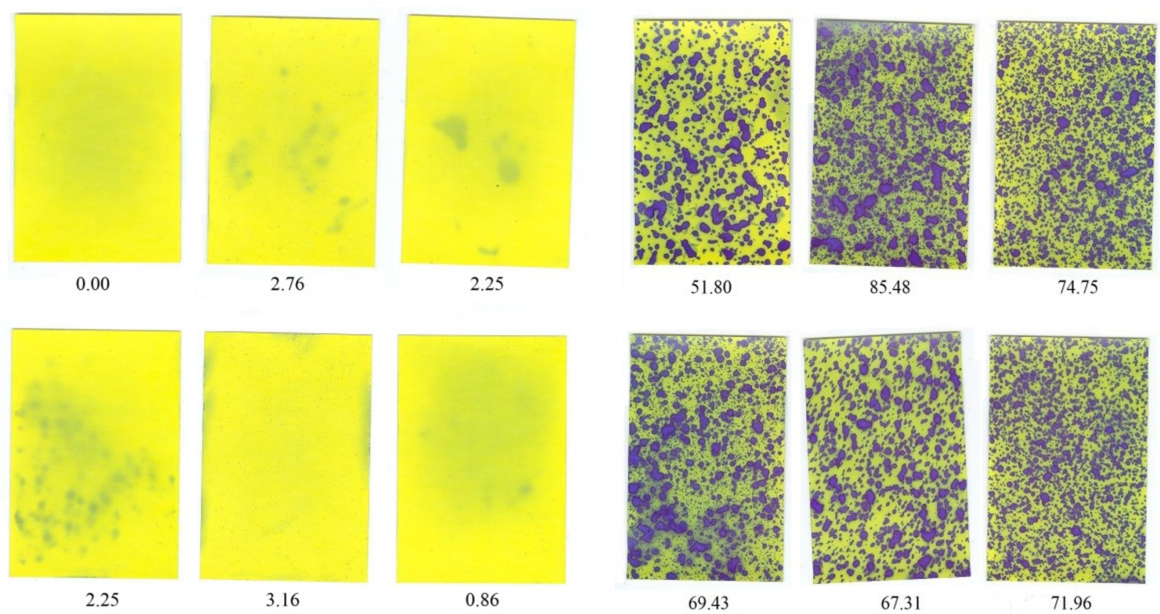


Figure 2-10: Resulting percentage area coverage of water sensitive papers placed in non-target blueberry patches (left) and target red sorrel patches (right) using spot-application technique.

Ninety-seven weed patches were measured and mapped in a 2.5 ha field (Fig. 2-11). The chemical saved with spot-application was 69% with 28% weed cover and 25 cm buffer before and after the weed targets in the selected field. Weed maps before and after spray showed that the automated VR sprayer performed well for spot-application of agrochemicals and applied propyzamide accurately and efficiently on weeds (Fig. 2-11).

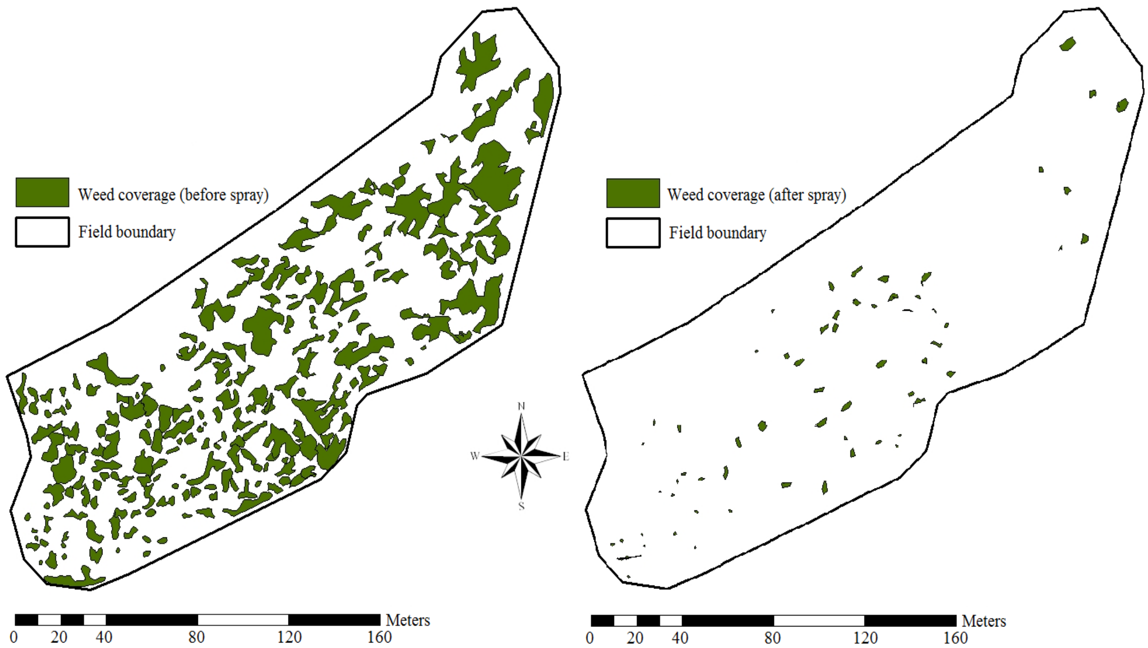


Figure 2-11: Field map showing red sorrel coverage before spray (left) and after spray (right) in field 2.

The weed map after propyzamide spray application showed that red sorrel was suppressed at most places (3% of the total weed cover as compared to 28% before spray) (Fig. 2-11). The reason for very few weeds in spring might be due to the biology of red sorrel which is a creeping perennial with underground roots from which buds are capable of generating new shoots at random intervals along its length (Sampson et al., 1990). Repeated control attempts are needed to exhaust the bud and stored reserves (Ross and Lembi, 1999) for effective suppressing of the red sorrel. Results of this study suggested that the VR sprayer could be used for spot-application of agrochemicals in wild blueberry cropping systems to significantly reduce the amount of agrochemical usage and environmental pollution.

2.4 CONCLUSIONS

The sensing and control system of the prototype commercial VR sprayer proved to be very efficient at detecting weeds and spraying correctly at target areas with an actual lag time of 0.131 ± 0.003 s. The T-test suggested that the PAC of WSPs in target and non-target areas after the flumioxazin application was significant indicating spot-application technique using VR sprayer accurately applied the flumioxazin on targets. Propyzamide savings was 69% with 28% weed coverage and 25 cm buffer before and after weed targets in the selected wild blueberry field with spot-application using VR sprayer. Based on the results of this study, the prototype commercial VR sprayer performed well for targeting moss and red sorrel in wild blueberry fields.

The successful target applications of the developed VR sprayer resulted in an increased interest within wild blueberry farmer's community, as they could see the benefits of this technology. However, one of their concerns about the developed sprayer was that it can only work during day time but the wind speed is typically lower early morning and late evening to minimize drift effects. In order to address this industrial need and make this VR sprayer an effective option for wild blueberry growers, an artificial light source system was required to be developed and implemented into the VR sprayer to perform agrochemical application in early morning and late evening. The details about an artificial light source system are discussed in Chapter 3.

CHAPTER 3 SUPPLEMENTARY LIGHT SOURCE DEVELOPMENT FOR CAMERA-BASED SPRAYING IN LOW LIGHT CONDITIONS

High wind constraints during day time agrochemical spraying has pushed the wild blueberry producers to apply agrochemicals during the early morning, evening or after dark, to avoid drift problems due to low wind conditions. The objective was to develop an artificial light source system combined with a smart sprayer comprising of a digital camera based sensing system to allow cameras to detect target areas (weed, plant or bare soil) in real-time for accurate application of agrochemicals in low light conditions. After testing and evaluation of different light sources, a rugged light source system equipped with polystyrene diffuser sheets was constructed to provide an even distribution of light across the entire 12.2 m machine vision sensor boom. Distribution of artificial light underneath the sensing boom at zero ambient light was examined by recording the light intensity at 0.15 m spacing on the ground under the camera boom using a lux meter. Results of light distribution revealed that the Magnafire® 70 W high intensity discharge (HID) lights provided wide angle of even light illumination, high intensity and rugged construction.

A wild blueberry field was selected in central Nova Scotia, Canada, and a test track was made to evaluate the performance of the artificial light source system to apply agrochemicals on a spot-specific basis under low natural light conditions. A real-time RTK-GPS was used to map the boundary of the test track, selected bare soil areas, weed areas and wild blueberry plant areas in the field. WSPs were placed at randomly selected locations, the smart sprayer was operated under low light conditions, and the PAC was calculated. The mean PAC from WSPs located in bare soil, weeds and blueberry spots in the track was 5.19%, 27.53% and 1.74%, respectively. PAC of the WSPs placed in bare soil and blueberry patches were 22.34% and 25.79% lower than in weed patches, respectively. Results reported that the custom developed artificial light source system was accurate enough to detect targets in low light conditions. Additionally, spot-spraying only in weed areas resulted in 65% chemical saving.

3.1 INTRODUCTION

Nova Scotia, Canada consumed 441,609 kg of pesticide active ingredients in 2003. The majority (67.7%) of the pesticide was herbicide, while 13.4% was fungicide, 8.6% was insecticide, and 10.3% was not identified (Brimble et al., 2005). Pesticide use has been steadily increasing with approximately 6 billion kg of pesticides being produced worldwide in 2005 (Carvalho, 2006). Herbicides constitutes the significant portion of the total applied pesticides, and are needed for adequate weed control to increase yields. Typically, herbicides are applied covering the entire field uniformly, with inadequate attention being given to the substantial spatial variability of weeds that are present in most agricultural fields. The blanket application of herbicides poses a serious problem for producers in terms of increased cost of production and environmental risks associated with air and ground water (Pimentel and Lehman, 1993). The portions of the cropland with no weed species receive the same amount of herbicide as the portions that have a severe weed infestation with conventional uniform-application (UA). Spot-application (SA) of herbicides only in weed areas using VR applicators can address this problem.

Wild blueberries are native to Northeastern North America and grow naturally from cleared wood lots or abandoned farm lands (Eaton, 1988). Wild blueberry fields have significant (up to 50%) bare spot areas in newly developing fields (Zaman et al., 2008). Weeds have always been considered as a major yield-limiting factor and are a challenging problem in wild blueberry production (Jensen and Yarborough, 2004; Agriculture and Agri-Food Canada, 2011). Malay (2000) reported that the excessive soil loss as a result of poor blueberry cover and excessive use of herbicides threatens the sustainability of the wild blueberry industry. The unique features such as bare spots and weed species present in wild blueberry fields suggest the importance of site-specific management and the need to develop an affordable and reliable site-specific smart sprayer for a more sustainable spot-application of herbicide in the wild blueberry cropping system. Some researchers have attempted to develop technologies for site-specific management of wild blueberries (Chang et al., 2012b; Chang et al., 2014; Esau et al., 2013; Esau et al., 2014a; Michaud et al., 2008; Percival et al., 2014; Zaman et al., 2011; Zhang et al., 2010) to date.

Generally, wild blueberry producers apply herbicides early in the morning, late evening or at night because of lower wind speeds or time limitations (Food and Agriculture Organization of the United Nations, 2008). During these low-light hours, a machine vision system with controlled lighting is required to detect and spray weed patches within the field. Some researchers have developed machine vision systems with evenly distributed controlled light sources for other cropping systems (Arima et al., 2003; Benson et al., 2003; Kane and Lee, 2007). Hemming and Rath (2001) developed computer-vision-based weed identification under field conditions using controlled lighting for use in vegetable crops (cabbage and carrots). Depending on growth stage and weed density between 51 and 95% of the plants were classified correctly. Slaughter et al., (2008) used controlled illumination to create a stable lighting condition independent of variations in natural illumination for use with hyperspectral images for weed discrimination. Baron et al. (2002) used natural sunlight as an illumination source for an imaging system. The researchers used the natural light to reliably determine the portion of each image occupied by green growing plants and measured the stability of the green cover measurement in response to naturally occurring changes in sunlight intensity and sun angle throughout the day. Several researchers have developed image processing techniques to overcome illumination changes that are present in most field conditions (Nejati et al., 2008; Kurtulmus et al., 2011; Hijazi et al., 2012b). Kurtulmus et al. (2011) concluded that RGB color images are feasible for citrus yield monitoring and algorithm advances could improve processing time and accommodate for more varied outdoor conditions.

Outdoor images require a camera with a wide dynamic range due to the potential for brightness variations (Nayar and Mitsunaga, 2000). The human eye has an exceptional dynamic range enabling a clear view under a wide variety of illumination conditions (Blackwell, 1946). However, a conventional digital camera provides only 8 bits (256 levels) of illumination at each pixel (Nayar and Mitsunaga, 2000). If the illumination is above the threshold of the camera's dynamic range, it causes saturation leading to incorrect results of the imbedded image processing technique (Debevec and Malik, 1997). Obtaining a truly high dynamic range requires multiple image detectors and precision optics for the alignment of all images as well as additional hardware for image acquisition and processing (Nayar and Mitsunaga, 2000). Debevec and Malik (1997) developed a method of recovering high dynamic range radiance maps by fusing multiple photographs into a single high quality image, however this requires additional cameras and light exposure settings that increases processing time.

Different light source options are readily available in the market. Davies (2009) reviewed numerous papers relating to machine vision in agriculture and concluded that fluorescent tube lights have greater machine vision classification accuracy as compared to incandescent and fluorescent ring lights. Hemming and Rath (2001) used commercially available 400 W metal halogen lamps to illuminate the recording area of the developed machine vision system for weed detection. Slaughter et al (2008) used tungsten-halogen bulbs for illumination of the cameras field of view for weed targeting. Dowling et al. (2003) developed an LED powered illumination system specifically for use with machine vision systems that require consistent light color and intensity. Hecht (2005) developed an efficient LED illumination system with reflectors for area-based scanning equipment such as video cameras. Hecht (2005) found typical incandescent or HID light sources are not ideal because they are inefficient and consume more energy and generate large amounts of heat as compared to LED illumination systems. Thrailkill (1998) developed a highly efficient diffuser with LED's which producers a relatively uniform light field which illuminates the object for machine vision recognition. Mahaney (1998) invented a system for controlling light intensity in a machine vision system to lie within a predetermined narrow range of light intensity. Slaughter et al. (1999) designed a passive mechanical shade for a row crop machine vision system to provide a uniform diffuse illumination of the seed line at all times independent of tractor orientation. Cucchiara et al. (2001) improved errors in digital images that were caused by shadows in moving objects during image acquisition by adjusting the hue, saturation and value (HSV) color information from the RGB images. Stauder et al. (1999) and Horprasert et al. (1999) incorporated a shadow detection and correction technique into an algorithm for improved image processing results after dark using an artificial light source. Steward and Tian (1998) stated that most of the machine vision weed sensing research has been done with controlled lighting rather than variable natural lighting associated with outdoor field conditions. Image acquisition with sunlight as an illumination source poses a greater challenge than those captured under controlled illumination.

A limited number of commercial machine vision spraying systems are available for various cropping systems that require herbicide on target weeds with bare soil background. (Hanks and Beck, 1998; McCarthy et al., 2010). In season wild blueberry herbicide applications require custom image processing to target weed species growing within the blueberry plant foliage (Chang et al, 2012b). McCarthy et al. (2010) reviewed three commercial machine vision based weed spot spraying technologies. They reported that the available systems were able to detect weeds on a soil background only. They also suggested that a machine vision technology equipped with controlled lighting that uses leaf color, shape, and texture to differentiate between crops and weed species is needed for accurate target detection and spot-spraying. Hanks and Beck (1998) determined that the ambient light was unsatisfactory with the Detectspray system (Concord Manufacturing, Fargo, N.D.), since varying sunlight adversely affected its operation. Variations in sunlight may be unnoticeable to the human eye, however, it can be readily detected with the use of sensors. Shadows created by the spray frame that were projected into the sensor's field of view adversely effecting the stability of the sensing system. Variable light conditions and cloud cover demands for constant sensor adjustments to minimize the false triggering where weeds were not present or to avoid weed patches that should be sprayed (Hanks and Beck, 1998). To reduce these lighting issues, Hanks and Beck, (2008) recommend to use the WeedSeeker® (Model PhD 1620, NTech Industries, Inc., Ukiah, Cal.) with built in LED light source to compensate the fluctuating lighting conditions or spraying after dark. This system performed well with a reduction of spray volume ranging from 50 to 82%. This WeedSeeker® was unable to differentiate between weed species or green foliage during most herbicide application timings, which was considered as a major drawback of this system (Sui et al., 2008). Evans et al. (1994) used three linear fluorescent ultraviolet black lights arranged in a triangle for a light intensified machine vision system to measure chemical spray deposit on cotton leaves. Evans et al. (1994) was able to achieve very consistent high quality images however, an enclosure was required to cover the spray target from stray ambient light. O'Neall and Sandford (1993) invented a herbicide spraying system using optical sensors comprised of an infrared transmitter and receiver; however, it was limited to row crops with weed infestations that grow taller than the plants. Runtz (1991) developed a weed discrimination algorithm for use with natural sunlight with machine vision systems. They reported that a wide range of lighting composition, intensity, and reflectance patterns negatively affect the image acquisition and accuracy of machine vision systems for spraying applications.

Esau et al. (2013) developed a small prototype sprayer for spot-application of fungicide in wild blueberry using digital color cameras and custom image processing software, capable of discriminating blueberry plants from bare soil patches. The modified 6.1 m wide boom sprayer propelled by an ATV was able to travel at 6 km h^{-1} while controlling eight individual nozzles with fungicide savings ranging from 10 to 50%. However, this sprayer was limited to applications during the day, when light illumination was above 500 lux. Esau et al. (2014a) developed a prototype smart sprayer with 12.2 m spray boom mounted on a farm tractor and saved 69% herbicide while targeting only select weeds in wild blueberry fields using a camera based machine vision system on the front boom and custom software. The smart spraying system worked efficiently and reliably to detect weeds and spot-spraying on an as-needed basis. The sprayer reduced the weed infestation by 89.3% however, the camera vision was limited to use during the day time. The grower's preference to spray early morning, late evening and after dark to avoid drift problems, demands for the development of an artificial light source system for effective operation of the machine vision system for target detection and spot-spraying. Therefore, the objective of this study was to develop and test a robust light source system, incorporate it into a smart sprayer, allowing the machine vision system to operate effectively during low light conditions for spot-applications of agrochemicals in wild blueberry fields. The goal is to maintain a consistent light distribution of between 500 lux and 2500 lux for the entire 12.2 m boom width to sustain quality image acquisition after dark.

3.2 MATERIALS AND METHODS

3.2.1 Light Source Selection

Five different 12 V lights were selected and tested in the precision agriculture (PA) research lab at the Dalhousie Agricultural Campus for their effectiveness to illuminate the 12.2 m wide machine vision field of view (Table 3-1). Lights 1, 2 and 3 were featured as LEDs. Lights 4 and 5 were both Magnafire 3000® series lights (Havis, Warminster, Pa.) featuring a metal halide HID ballast, however, light 5 was equipped with a 2 mm thick polystyrene diffuser (Plaskolite, Inc., Columbus, Ohio) on the light surface. This type of diffuser material is used commercial building lighting ballasts, allowing for even light distribution within rooms or halls.

Table 3-1. Light source specifications and cost for use with smart sprayer machine vision system.

	Light 1	**Light 2**	**Light 3**	**Light 4**	**Light 5**
Illustration					
Part number	PAR36	37634B	AR111	KR-31	KR-31
Manufacturer	LED Light Company, Reseda, Cal.	United Pacific, Long Beach, Cal.	Dongguan Jingliang Lighting Factory, Dongshan, China	Havas, Warminster, Pa.	Havas, Warminster, Pa.
Power Consumption (W)	6	36	12	70	70
Amperage (A) @ 12 V	0.4	2.4	0.8	7	7
Voltage (V)	10-30	12-24	12	12	12
Type	126 LEDs	12 LEDs	6 LEDs	1 Metal Halide HID	1 Metal Halide HID
Dimensions: L/W/H (m/m/m)	0.11/0.11/ 0.06	0.17/0.07/ 0.06	0.11/0.11/0. 06	0.34/0.14/0. 12	0.34/0.14/0.1 2
Weight (kg)	0.19	0.73	0.18	3.63	3.63
Lumen rating	500	900	853	6,000	6,000
Beam angle (degree)	30	15	25	80	80
Life expectancy (h)	25,000	35,000	30,000	15,000	15,000
Cost (CAD $)	30	150	80	500	510

The light source comparison was conducted in the PA lab with natural light blocked from entering and effecting the analysis. Each of the five lights were fixed to a surveying tripod and positioned straight down at a height of 1.2 m off the ground. The tripod and lights were positioned in the center of the lab with a clear floor surface where illumination readings were taken at the ground level. All lights were connected to a constant 12 V power supply during tests. A lux meter (LX1010BS, V&A Instrument CO., LTD., Shanghai, China) was positioned at ground level directly under the center of the light beam and the illumination was recorded (Fig. 3-1).

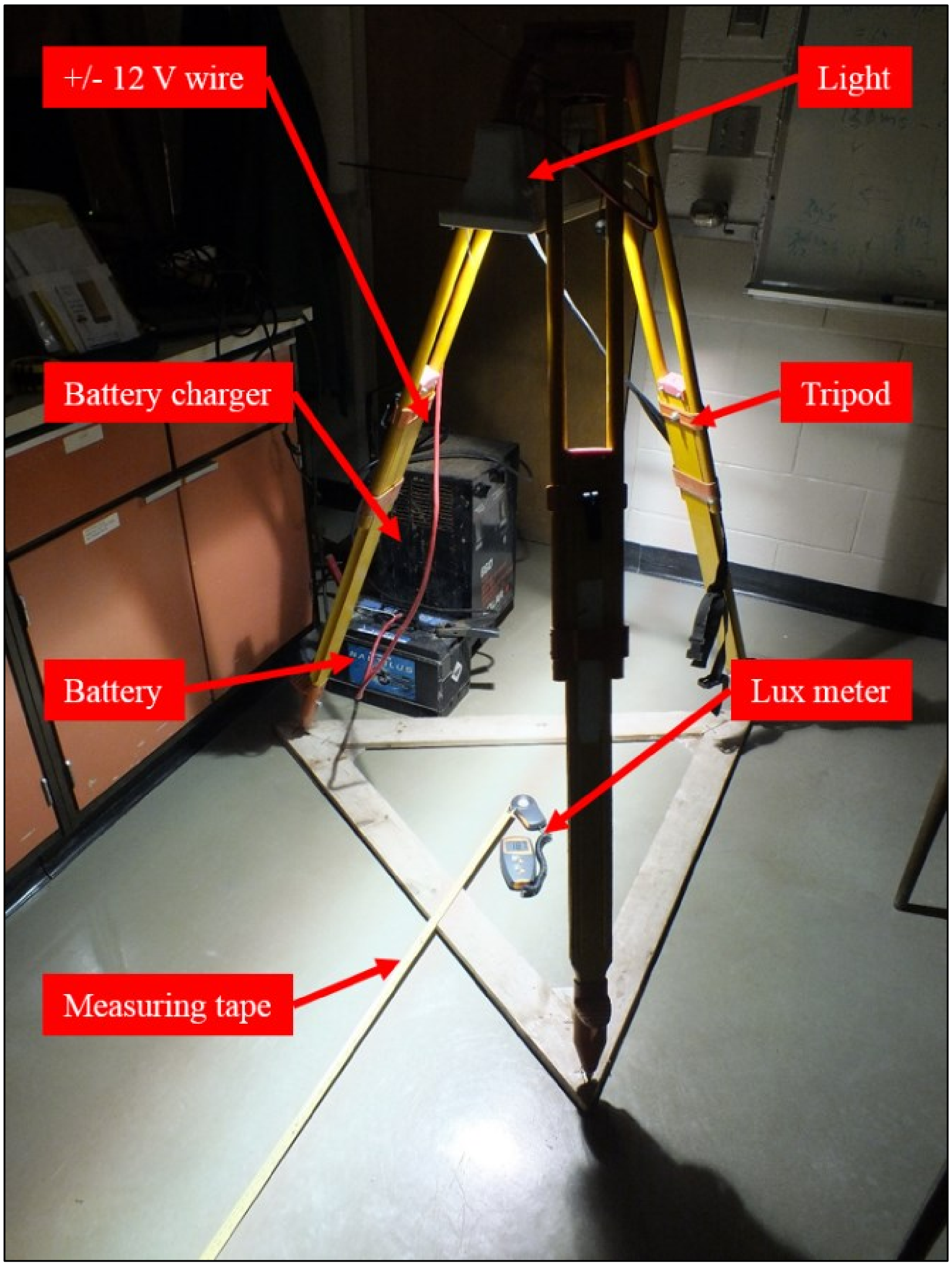


Figure 3-1: Light source testing platform used during experimental setup in the precision agriculture laboratory.

An area of 1 m by 0.75 m was used as the area of interest based on the reasonable goal of one light source per meter width required to be installed on the sensor boom. The lux readings along the center and 15 cm on either side of the centerline were recorded and averaged (Fig. 3-2). Following the same protocol, the lux readings were taken at 15 cm intervals along the centerline up to a total distance of 450 cm (Fig. 3-2). This procedure was repeated three times for each of the five light source devices. Split-plot design with three replications was used to quantify the illumination at different positions on the ground from each light source. This design was modeled with light source as the main plot and location on ground where illumination was measured as the sub plot and lux as the response variable. Split-plot designs are typically used when the multifactor factorial experiment is not practical to completely randomize the order of runs (Montgomery, 2009).

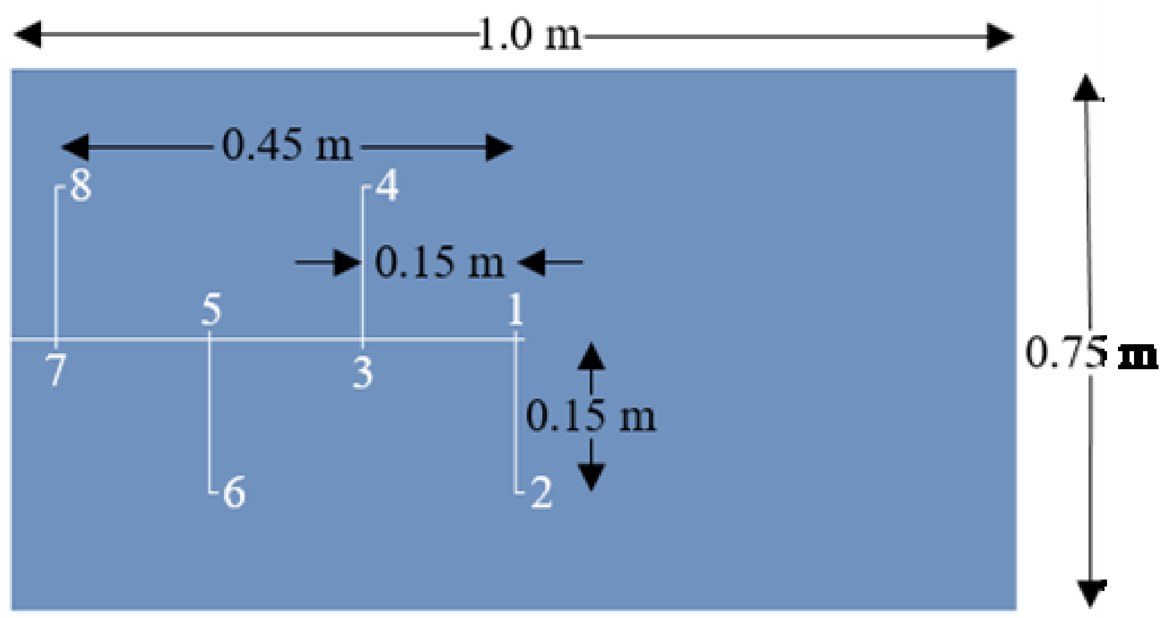


Figure 3-2: Experimental setup showing the position and distance spacing for each of the lux measurements recorded.

Light illumination measurements from each light were analyzed using SAS® (SAS Institute Inc., Cary, N.C.). Data was checked for normality and constant variance. The mixed-model procedure at 1% level of significance was used to test the significance of the treatments. Least square (LS) means comparison was used to determine if the illumination varied across the width of the light beam when projected from a height of 1.2 m off the ground surface. The multiple means comparison provided an evidence to effectively use a light source for smart spraying after dark. Multiple means comparison also provided a statistical ruling to determine the number of lights, and the spacing between lights for selected light source to be mounted on the machine vision boom. The selected light source was plotted using a line graph in Excel (Microsoft, Redmond, WA) to fine tune the spacing between lights for even distribution of light on the ground surface. The goal was to create a consistent light illumination with lux values ranging from 500 (low) to 2500 (high). The final results of spacing were incorporated into the smart sprayer and tested in a wild blueberry field for spot-applications during low light conditions.

For image acquisition purposes a 1 m x 0.75 m rectangular navy blue cloth was placed on the floor to reduce noise caused by light reflection from shiny waxed floor. A µEye digital color camera was positioned at a height of 1.2 m off the ground to capture images. The height of 1.2 m was chosen to mimic the actual sensor boom camera and height position. The µEye camera was connected via USB cable to a laptop computer. Imaging Development System (IDS) camera suite software allowed acquisition of images from the µEye camera to be recorded from each of the five lights. Dark areas of low illumination were not desirable because the image processing software is not able to properly count the RGB pixels for analysis or use the texture of the image. However, if the light produced too much illumination, it caused white outs “hot-spots” that would also cause error in the image analysis process. To achieve suitable image processing results the selected light should give an even light distribution covering a rectangular area (12.2 m length by 0.30 m width) under the sensor boom.

3.2.2 Incorporation of Light Source on Developed Smart Sprayer

A prototype smart sprayer used for this study was developed for spot-application of herbicides on weeds/grasses and fungicides on plant foliage for the wild blueberry cropping system (Esau et al., 2014a). Eight, digital color cameras were incorporated on a boom in front of the tractor at a height of 1.2 m (Fig. 3-3). Each camera covered two sections of the boom (0.762 m each section). Cameras were attached using active link USB cables to a PC featuring a solid state hard drive located in the tractor cabin. The image processing software bundle installed in the PC was capable of processing images to differentiate between bare soil, blueberry plants and weeds in real-time and send on/ off commands to control the solenoid valves opening or closing the spray nozzles (Chang et al., 2014). Six of the selected lights were rigidly mounted on the front boom of the smart sprayer at a height of 1.2 m off the ground with proper spacing to allow even light distribution. The operator can control the lights using an on/ off toggle switch from the driver’s seat of the tractor.

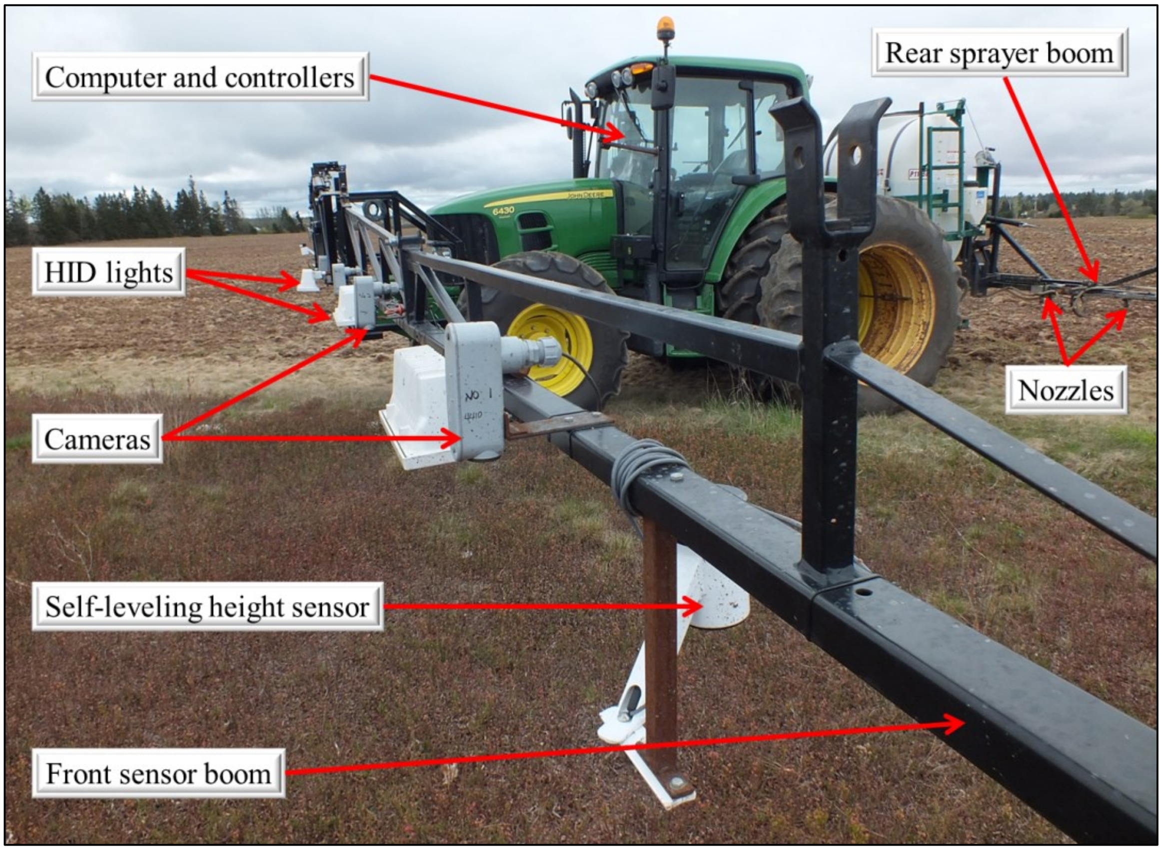


Figure 3-3: Diagram highlighting the main components of prototype smart sprayer in conjunction with artificial light source system for real-time spot-application of agrochemical.

3.2.3 Real-Time Field Test Using Machine Vision System with Added Light Source

A wild blueberry field was selected in Debert, Nova Scotia, Canada (45.441425°N, 63.45068°W, 0.68 ha) to test the performance accuracy of the smart sprayer for spot-application on weed targets after dark. Water was used for the applications to ensure no crop damage with repeated tests within the same tracks in selected field. The field was in its sprout vegetative year of the biennial crop production cycle in 2012 at time of application, and crop year in 2011. The main weed species, in competition with the wild blueberries were *Agrostis capillaris* L. (grass) and red sorrel. The average blueberry plant height was only 0.03 m, which is very typical after mowing. The grass and red sorrel height ranged from 0.01 m to 0.05 m.

On May 03, 2012, a test track (80 m × 12.2 m) was selected to test the accuracy of the smart sprayer for detecting weeds and spraying at the right targets during low light conditions using the selected light source system. The boundary of the selected track was mapped with a RTK-GPS. Six WSPs with dimensions of 0.052 m × 0.076 m were positioned on the ground at randomly selected weed spots, bare soil spots and wild blueberry plant spots. The bare soil spots were not equally distributed in the fields. There were no bare soil spots in the center of the test track however, there was large bare soil spots concentrated on both North and South ends of the track closer to the edge of the field boundary. The WSP targets were placed on the ground for detection and spot-spraying. The WSPs were orientated parallel to the ground and selected targets were marked with the RTK-GPS for mapping in ArcMap 10 GIS software. The water was sprayed on spot-application mode with different camera and light source settings and WSPs were collected after drying. The wind recorded during the time of the experiment was 10 km h^{-1} directed to the South (National Climate Data and Information Archive, 2012). The WSPs were stapled on the ground again after each consecutive test run for comparison. The application maps were also recorded for each test using the coverage maps built into the MLC. The WSPs were scanned and processed using a custom developed software package to calculate PAC of the sprayed targets (Fig. 5-7). The analysis of variance (ANOVA) with LS method was performed to examine the PAC of the sprayed targets at different locations (bare soil, weeds and blueberry plants) within the test track. The minimum, maximum, mean and standard deviation of the PAC targets for all applications were determined using Minitab® 16 statistical software (Minitab® Inc., State College, Pa.).

The ground speed during the field operations was 6 ± 0.2 km h^{-1}. The buffer was adjusted at 0.25 m before and after the target, for precise overlapping of spray at weed targets. The application rate was setup at 187.0 L ha^{-1} in the MLC. An application savings analysis was performed to compare spot-application technique with UA. Sprayed areas were recorded with the MLC and imported into ArcMap 10 computer software, to evaluate the performance of the smart sprayer. The chemical savings were calculated from the sprayed area and the track size using the following formula:

$$Application\ Savings\ (\%) = 100 - \frac{Sprayed\ Area}{Total\ Area}\ 100 \qquad (2)$$

3.3 RESULTS AND DISCUSSION

Figure 3-4 shows the 1 m x 0.75 m images taken using the µEye digital color camera for each of the five light source combinations. Figure 3-4 indicated significant variations in light intensity throughout the cameras field of view for lights 1, 2 and 3. Figure 3-4b illustrated that light 2 created a spot-style illumination pattern showing pure white in the center of the image instead of the true navy blue color. Similarly light 4 has a narrow horizontal beam of intense illumination causing a similar hot-spot distorting the actual color of the surface (Fig. 3-4d). Visually, light 5 seems to have an even light distribution with the addition of the diffuser sheet.

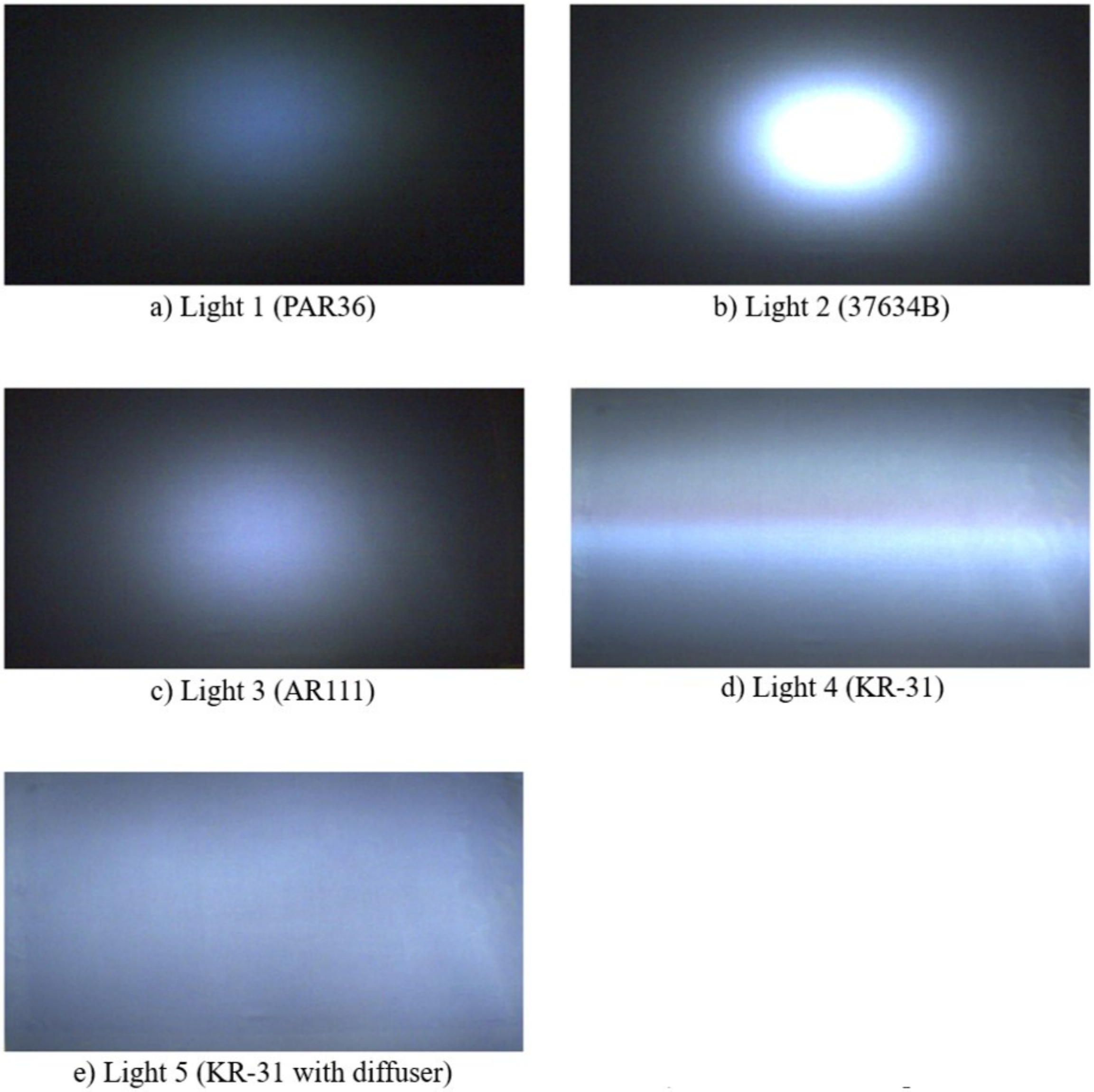


Figure 3-4: Lab test showing light illumination for selected five lights.

Light 2 had the highest illuminance value of 11,617 lx at position 1 at the center of the cameras field of view (Table 3-2). The lowest illuminance (972 lx) from position 1 at the center of the cameras field of view was observed from light 1 (Table 3-2). The light that created the greatest variation in illumination (11,464 lx) throughout the field of view was light 2. Results revealed that lights 1, 2 and 3 have large variation in illumination throughout the camera's field of view. A major disadvantage of choosing one of these lights is that it requires a large number of lights to cover the entire width of the cameras field of view over the 12.2 m wide sensor boom creating a time consuming and costly install. Both lights 2 and 4 created illumination values that were higher than required (500 < lux < 2500) for image acquisition after dark. Multiple means comparison of the illumination from lights 1 through 4 showed a significant difference in the lux readings from the positions measured. However, light 5 showed very even distribution with no significant difference with any of the lux readings at the eight positions measured. Lights 4 and 5 both had the highest standard deviation ranging from 134 to 489 lx. The possible reason for the higher standard deviation might be the flood beam style ballast and higher illumination. Results indicated that the addition of a 2 mm thick polystyrene diffuser greatly improved an even light diffusion over the camera’s field of view allowing the camera to easily focus without any hot-spots or areas that were too dark. Based on the lux comparison, light 5 was selected for further evaluation because of the wide angle, and an even light illumination with high intensity.

Table 3-2. Comparison of mean lux readings at different ground positions for each light source.

Pos	Light 1 (lx)	S.D. (lx)	Light 2 (lx)	S.D. (lx)	Light 3 (lx)	S.D. (lx)	Light 4 (lx)	S.D. (lx)	Light 5 (lx)	S.D. (lx)
1	972[a]	11	11617[a]	282	1952[a]	20	2790[a]	410	1976[a]	489
2	571[b]	44	1577[c]	57	1050[b]	37	1809[bc]	307	1836[a]	337
3	540[b]	26	2280[b]	286	1066[b]	28	2760[a]	372	1950[a]	465
4	333[c]	59	879[d]	19	615[c]	27	1711[bc]	260	1698[a]	431
5	174[d]	8	495[e]	50	377[d]	24	2627[a]	284	1709[a]	283
6	108[e]	13	336[f]	24	272[e]	19	1499[c]	134	1447[a]	291
7	57[f]	1	203[g]	6	141[f]	15	2360[ab]	108	1428[a]	222
8	44[f]	2	153[g]	2	108[f]	13	1374[c]	241	1185[a]	218
	Treatment Factor: Mixed ANOVA									
Pos	***		***		***		***		NS	

Means from columns followed by different letters are significantly different at p= 0.01
**** Significant at the 0.001 probability level*
NS = Non-significant

The light source spacing graph suggested that the addition of the diffuser sheet on light 5 helped to ensure even light distribution (Fig. 3-5). Results revealed that light 4 has a significantly higher illumination along the center line of the light beam as compared to the edge of the light beam (Fig. 3-5). Light 5 has a less intense spread of illumination values allowing the cameras to potentially focus without causing undesirable hot-spots. Spacing of light 5 across the boom to maintain proper illuminance (500 < lux < 2500) encompasses six lights positioned at 1.05 m, 3.15 m, 5.25 m, 7.05 m, 9.15 m, 11.25 m and 12.3 m from one end of the sensor boom (Fig. 3-5).

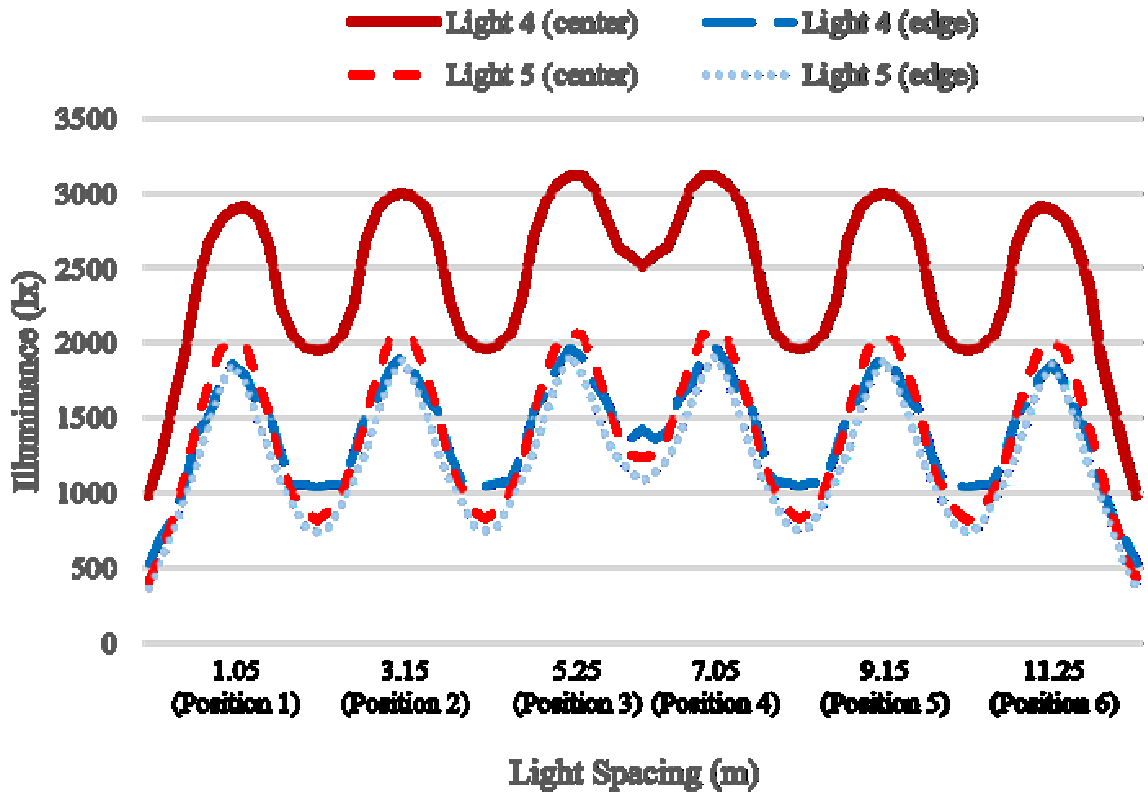


Figure 3-5: Comparison between lights 4 and 5 showing light source spacing required to maintain adequate illuminance across the 12.2 m boom width.

Field tests concluded that a consistent light illumination over the entire boom width was required for proper image acquisition and image processing. Even light distribution also ensured the camera's focus using the same aperture settings. It was found during testing that areas of high illumination "hot-spots" caused pixel noise when processing the images through the custom software due to the limitation of the cameras dynamic range (60 dB). The best image processing results were found with an evenly distributed light illumination under the entire boom width. Figure 3-6 shows comparison of the light illumination with and without the addition of 2 mm thick polystyrene diffuser sheet. The addition of the diffuser sheet reduced the hot-spots concentrated along the center of the light beam and distributed it more evenly allowing for the cameras to take images and process without creation of pixel noise from areas of high illumination (Fig. 3-6).

Figure 3-6: Light source 4 (left) and light source 5 with added light diffuser sheet (right).

Visual observation from field testing indicated that the smart sprayer performed reasonably well with the addition of the developed light source system for use after dark. The application showed spray coverage on most weed patches in the selected track (Fig. 3-7). Some sprayed patches within the blueberry plant or bare soil spots could have been the result of cameras detecting small newly developing green weeds that were not mapped with the RTK-GPS. Also, it was observed that pixel noise was greater when using lights due to the light reflecting off water/frost particles that were more common at night time. The PAC of the sprayed targets ranged from 0.05% to 16.08% in bare soil locations and from 3.48% to 38.06% in weeds and 0.00% to 4.91% in blueberry plants, respectively (Fig. 3-7). The reason of variation in PAC might be due to the height of the sprayer boom off the ground when travelling over the rough blueberry terrain. When nozzles are closer to the ground the area directly under the nozzles gets a higher application rate as compared to areas directly between adjacent nozzles. A boom leveling system would be helpful to address this issue, however, the variation in coverage is hard to fully overcome, due to the natural rough topography present in most wild blueberry fields in Nova Scotia. The wind speed of 10 km h^{-1} directed to the South could also have had an impact on resulting spray patterns, causing fluctuations during the experiment.

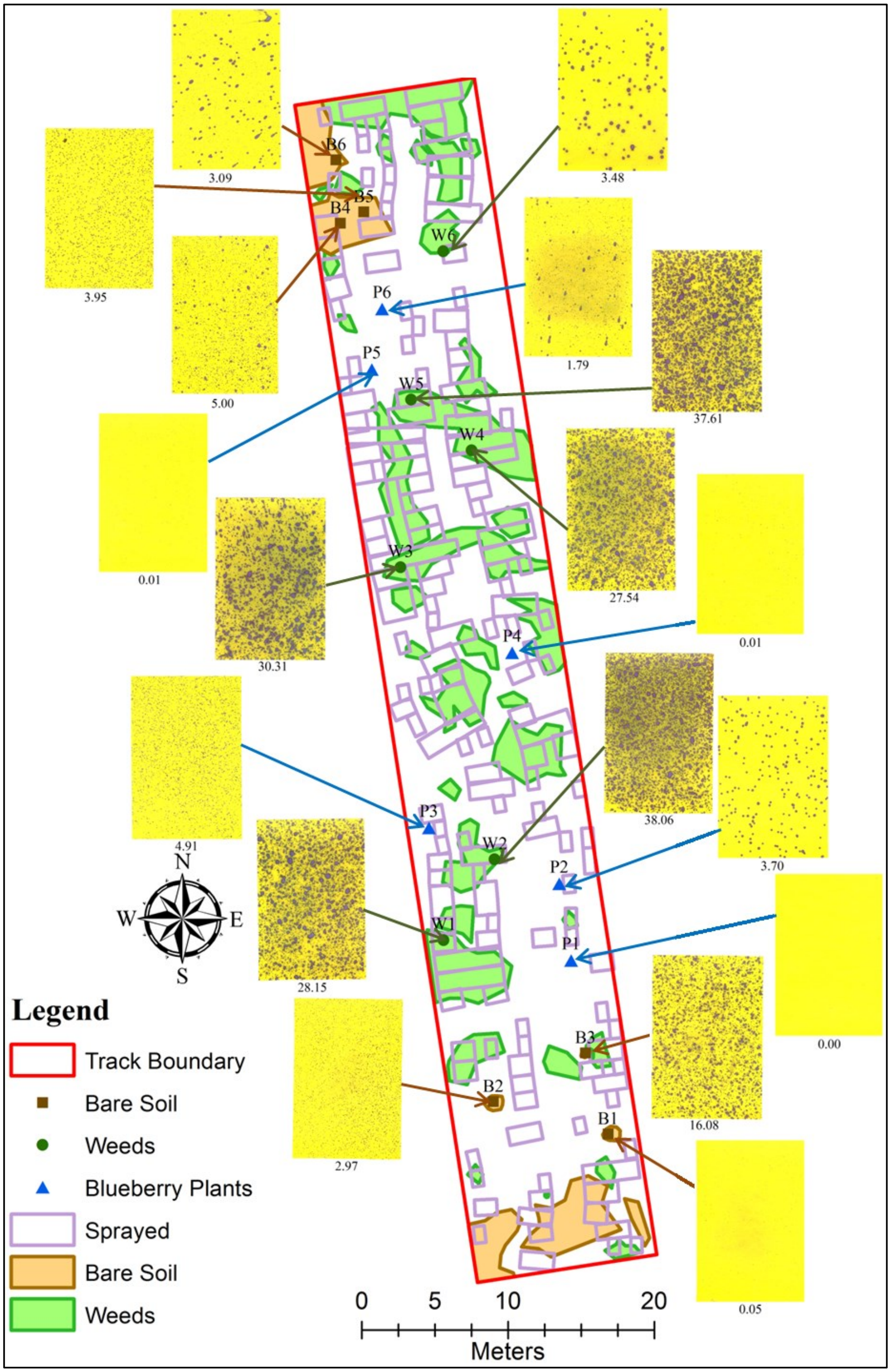


Figure 3-7: Field application map indicating percent area coverage of targeted water sensitive paper.

The mean PAC from WSPs located in bare soil, weeds and blueberry plants in the track was 5.19%, 27.53% and 1.74%, respectively (Table 3-3). The PAC of WSPs from bare soil and blueberry plants was significantly lower than that of WSPs in weed patches (22.34% point and 25.79% point, respectively). The WSPs in the blueberry plants were not significantly different from the PAC of the WSPs placed in bare soil. The WSPs placed in weed patches had the highest standard deviation (12.64) most likely due to the uneven ground causing varying boom height. The average PAC from the weed WSPs (27.53%) was sufficient for eradication using a contact herbicide. The lowest PAC (3.48%) from the WSPs in the weed areas would preferably be higher for insuring proper weed eradication. Spraying on a wind free day or incorporating a correction factor from side winds into the programming to allow adjacent nozzles to turn for complete coverage, could be a possible solution. During a head or tail wind the nozzles could be programmed to turn on earlier or stay on later to compensate. The high PAC (16.08%) from the bare soil WSPs was most likely caused from small weed seedlings starting to emerge or frost on the soil surface causing pixel noise from reflected light. A significant difference (P-value < 0.01) was observed between WSPs PAC from the three target locations. These results were in accordance with results from Zaman et al. (2011).

Table 3-3. Summary statistics of percent area coverage of the sprayed targets for determining the precision of spot-application technique for targeting using machine vision system with the light source at night.

Location (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
Bare Soil (6)	0.050	16.08	5.19[b]	5.58	<0.01
Weeds (6)	3.48	38.06	27.53[a]	12.64	
Blueberries (6)	0.00	4.91	1.74[b]	2.14	

Means followed by different letters are significantly different at a significance level of 0.05.

The smart sprayer application savings using spot-application was 65% based on the weed coverage in the selected test track (Table 3-4). The spot-application of agrochemicals using smart sprayer in conjunction with an artificial light source system can lower the cost of production and mitigate environmental risks associated with the chemical applications. Another added benefit of the spot-application is fewer trips back to the water truck to refill the sprayer tank, which saves time, labor and fuel.

Table 3-4. Prototype commercial smart sprayer saving with spot-application technique.

Plot #	Total (m^2)	Bare Soil (m^2)	Weeds (m^2)	Plants (m^2)	Sprayed (m^2)	Chemical Savings (%)
1	1012	62	208	742	354	65

3.4 CONCLUSIONS

Results suggested that the developed artificial light source system using the Magnafire 3000® series lights with added 2 mm thick polystyrene diffuser, was efficient enough to provide an even distribution of light, allowing the cameras to detect targets and spot-spraying under low ambient light conditions. The construction of the light source and incorporation on the front boom of the smart sprayer provided an even light distribution under an entire 12.2 m machine vision sensor boom. Results of this study provided strong evidence enabling the smart sprayer to work in low light conditions. Addition of diffuser sheets eliminated the hot-spots created by the lights, and enhanced the performance of the sprayer after dark. Results showed significant savings in bare spot areas with PAC in bare soil and blueberry plant areas being 22.34% and 25.79% lower than in weed patches, respectively. Total spray savings using the light source system was 65%. Further testing can be done to the image processing software to reduce the noise from light reflection from frost and moisture during the night. This would most likely increase the accuracy and performance of the spot-application smart sprayer for better weed targeting during low natural light conditions.

The front mounted custom developed smart sprayer equipped with an artificial light source system performed accurately and reliably in detecting targets and spot-spraying on an as needed basis. However, the presence of the front boom added complexity during field operations as wild blueberry fields have gentle to severe topography. The cost of building and incorporating the front boom also increased the cost of modifications in the existing sprayers to convert into a smart sprayer. Handling of both the front and rear boom also added complexity for the operator during field operation. These conditions demanded for a robust and compact sprayer with sensing system and spray nozzles on the rear boom for the ease of operation allowing for a more commercial unit, which can be easily adopted by the wild blueberry industry. With the availability of fast computing capabilities, in the next phase of this study a rear mounted sprayer equipped with machine vision and spray nozzles on the same boom was developed, tested and evaluated to meet the industrial requirements. Details about the rear mounted compact sprayer are discussed in Chapter 4.

CHAPTER 4 REAR MOUNTED MACHINE VISION SMART SPRAYER FOR SPOT-APPLICATION OF AGROCHEMICALS

The development of a smart sprayer for the wild blueberry industry is essential to minimize input costs, improve crop yield while reducing environmental pollution. The developed smart sprayer system was installed on a 13.7 m wide boom three-point hitch mounted sprayer attached to a farm tractor. The modified sprayer featured an 1135 L storage capacity and 27 spray nozzles. Solenoid valves were connected directly to the sprayer nozzle bodies for rapid response and low drip lag. Each nozzle covered a 0.51 m wide section of the sprayer boom. The machine vision system incorporated nine digital color cameras installed ahead of the sprayer nozzles on the boom. The cameras were connected via USB cables to a ruggedized computer where custom image processing software analyzed each image. Triggering signals were sent in real-time to the individual solenoids to open the specific nozzle where the target was detected. Wild blueberry fields were selected in central Nova Scotia to evaluate the smart sprayer system. Water sensitive papers were used to quantify targeting performance at select points in the field. The smart sprayer was setup to apply a spot-application of herbicide to weed targets within the field and fungicide application to only wild blueberry plant areas within the field. The sprayer had the ability to save substantial amounts of herbicides and fungicides in commercial fields with variable weed pressures and bare spot areas.

4.1 INTRODUCTION

Pesticides are important for agricultural crops to control weeds, disease and pests within the field. Pesticides are heavily applied to Canadian farmland each year with approximately 6 billion kilograms being applied worldwide in 2006 (Carvalho, 2006).

Typically farmers apply these pesticides uniformly without considering the substantial field crop/weed variation that exist on many farms. The overuse of pesticides increases the cost of production and pollutes the environment (Pimentel and Lehman, 1993). Spot-application of pesticides to target areas in the field that need the application is a valuable method to reduce pesticide use while maintaining weed, disease and pest control within agricultural fields. Wild blueberry producers can benefit from spot-application technology because of the substantial soil, blueberry plant and weed variability within the fields.

Wild blueberries are a naturally occurring crop developed from deforested wood land and are native to northeastern regions of North America (Eaton, 1988). Bare spots within the wild blueberry fields require different pesticide treatments as compared to the blueberry plant areas. Newly developing wild blueberry fields can have significant (up to 50%) bare spot coverage (Zaman et al., 2008). Weeds and grass species exist in most of all commercial wild blueberry fields. These weeds and grasses should be treated on a spot-specific basis to ensure pesticides are not being wasted in non-target areas that exist within the fields. A smart sprayer that is able to target weed, grass or diseased areas within the field and turn on/ off the nozzles would be a very important asset for the future success of the wild blueberry industry. A smart sprayer using an automated machine vision system would allow farmers to apply the pesticides to target areas in the field while saving in areas that do not require treatment. The end result could save time, money and cause less pollution to the environment.

Many machine vision systems have been developed and tested for agricultural crops (Baron et al., 2002; Benson et al., 2003; Evans et al., 1994; Hijazi et al., 2012b; Nejati et al., 2008; Runtz, 1991; Slaughter et al., 1999; Steward and Tian, 1998). Arima et al. (2003)

developed a robot to reduce the amount of chemicals applied to strawberry plants by using two direct lights for illumination of 5 CCD cameras for detection and spot-spraying of diseased plants. The robot's vision system was also used for strawberry fruit quality grading, traceability and harvesting. O'Neall and Sandford (1993) invented a herbicide spraying system using optical sensors; however, it was limited to row crops with weed infestations that grow taller than the non-target plants. McCarthy et al. (2010) reviewed the three main commercial machine vision-based weed spot-spraying technologies available and found they are restricted to detecting weeds on a soil background only and will not work to detect weeds amongst a growing crop. McCarthy et al. (2010) suggest machine vision technology is needed that enables leaf color, shape and texture to differentiate between crop and weed species. McCarthy et al. (2010) concludes that weed detection algorithms require consideration of shape, spectral and/or texture properties of vegetation in controlled lighting to achieve robust species discrimination in a scene containing adjacent weeds and crop. Moller (2010) concluded that applying computer vision technology to agricultural operations lowers operator stress levels.

This study was designed to test the performance difference between a machine vision system mounted on a separate boom at front of the sprayer as compared to that mounted near the rear sprayer boom just ahead of the nozzles for spot-applications of herbicide and fungicide in wild blueberry fields.

4.2 MATERIAL AND METHODS

4.2.1 Development of Rear Mounted Machine Vision System on Smart Sprayer

A smart sprayer integrated with rear mounted machine vision technology, image processing software and control system, was achieved for agrochemical application in wild blueberry fields. The smart sprayer system consisted of nine digital color cameras connected to a ruggedized computer via active link USB cables (Fig. 4-1). Image processing software specifically designed for applications in wild blueberry fields process each image and send triggering information to a 12 V relay switch box that powers the appropriate solenoid valve opening the spray nozzles in the specific section that the target was initially identified. An on-board flow regulating system allows the line pressure to stay constant while turning on/ off different combinations of nozzles.

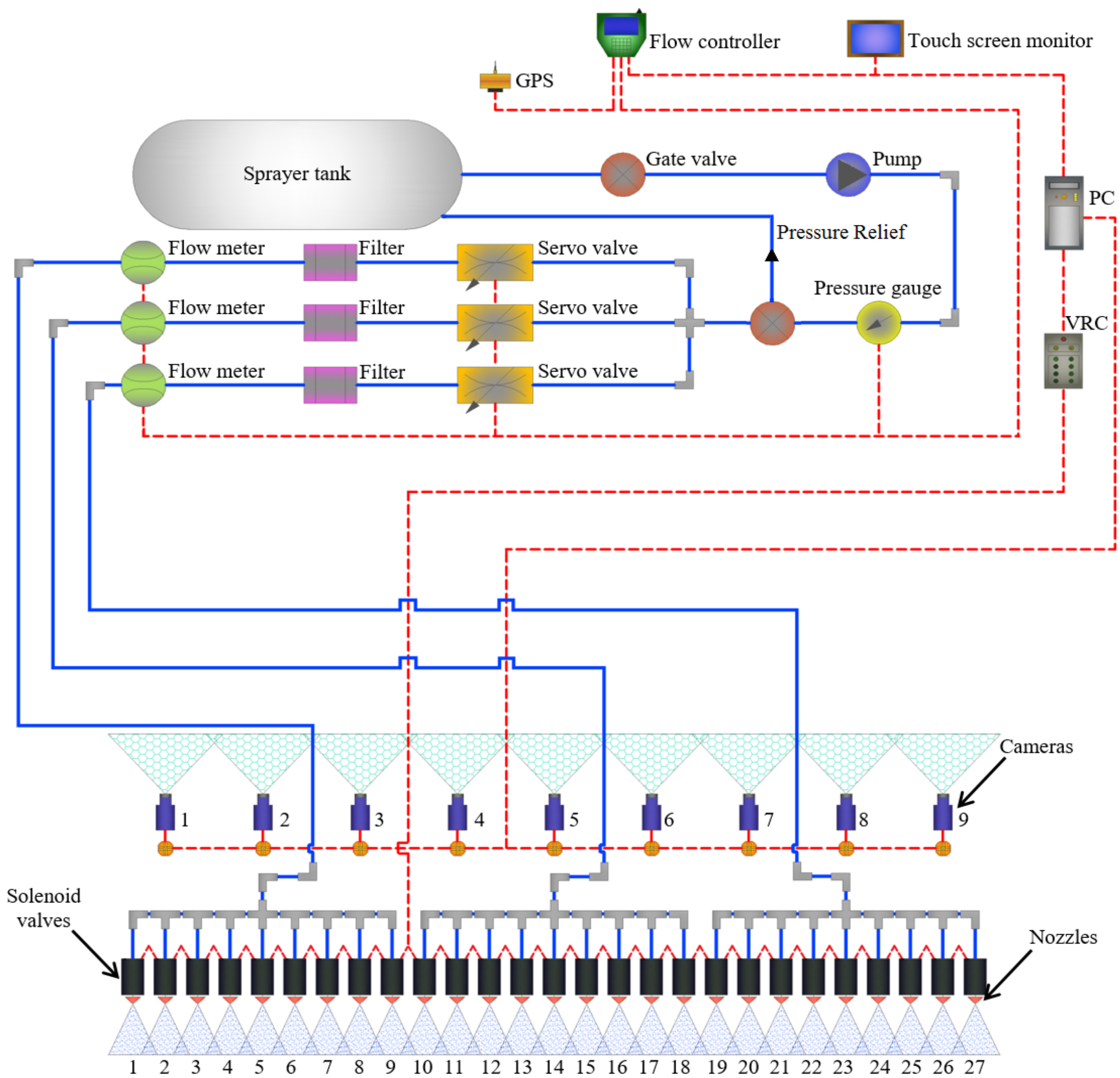


Figure 4-1: Smart sprayer diagram showing main components required for spot-specific application of agrochemicals.

4.2.1.1 Imaging Processing

Image processing algorithms were developed and tested primarily for use with a specific agrochemical application suited for the wild blueberry industry. During spring and fall herbicide applications weeds can typically be targeted using the color contrast between the green target weeds and the reddish brown background wild blueberry plants and soil surface. Further details of the sensing system using digital photography technique can be found in Chang et al. (2014). During in season herbicide and fungicide applications texture analysis is required to help differentiate between the wild blueberry plants and weed species that are typically similar in color. The touch screen interface mounted in the tractor cabin allows users the ability to shut all nozzles off with the press of a single button (Fig. 4-2). A second set of buttons allows the user to further adjust the sprayer boom with three sections of control (nine spray nozzles per section for a total of 27 spray nozzles). The control settings are either off (nozzles are not spraying), on (nozzles are on and spraying uniformly) or auto (nozzles are controlled individually based on feedback from the machine vision system). The touchscreen interface uses two buttons to control the foam marker on/ off and left/ right used to assist the operator with guidance while spraying. The user has the ability to change the image processing algorithm and settings based on the specific application being applied. The interface also shows in real-time the images that are being processed (Fig. 4-2).

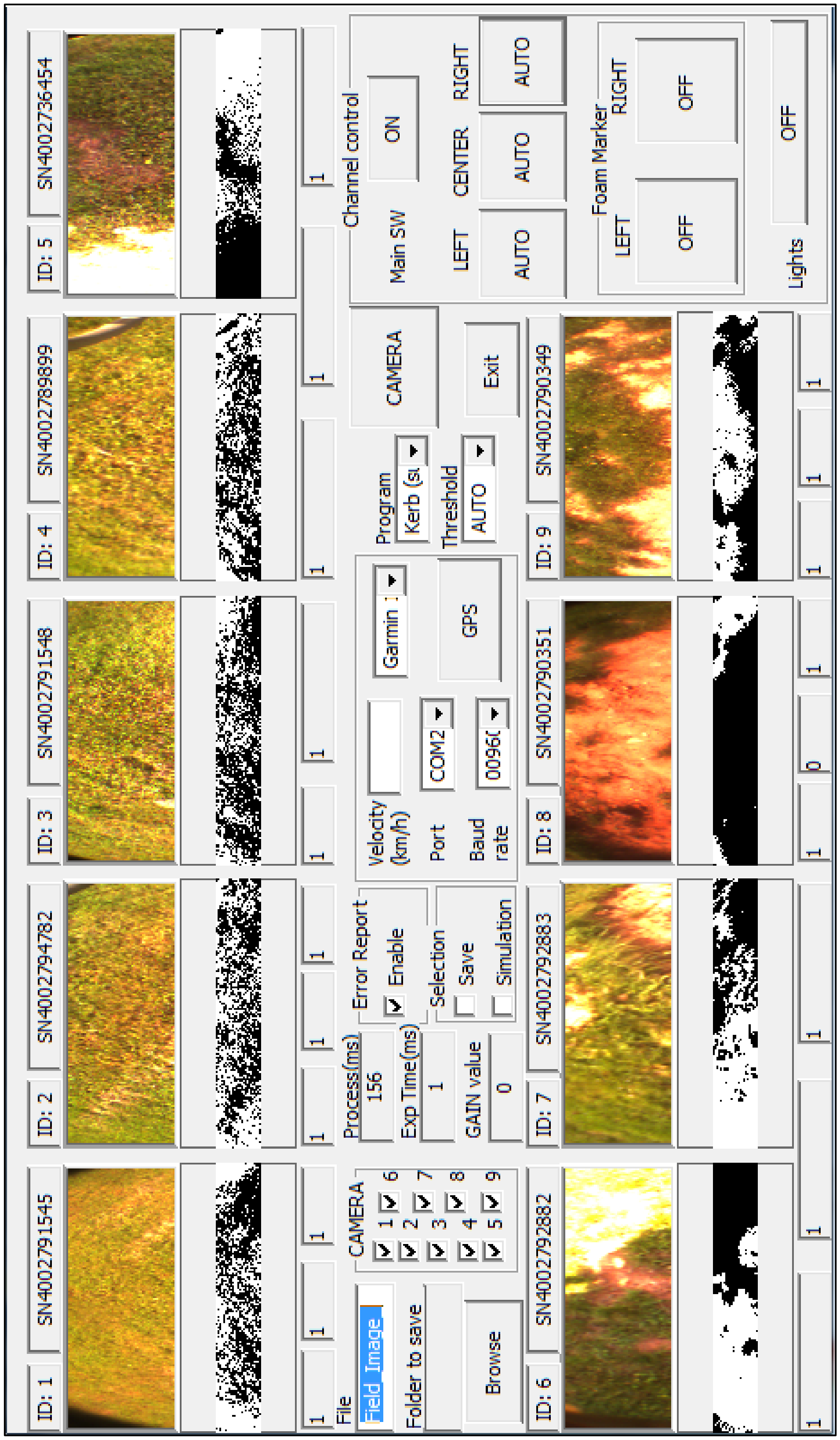


Figure 4-2: Smart sprayer touch screen user-interface showing camera field of view and controls for spot-application of agrochemical.

Nine μEye cameras were equally spaced at 1.52 m apart and each cover the area for control of three spray nozzles (Fig. 4-3). The cameras were positioned on the sprayer boom to maintain a height of 1.2 m off the ground surface to enable the images from each camera to cover the complete boom width without over or under lapping (Fig. 4-3).

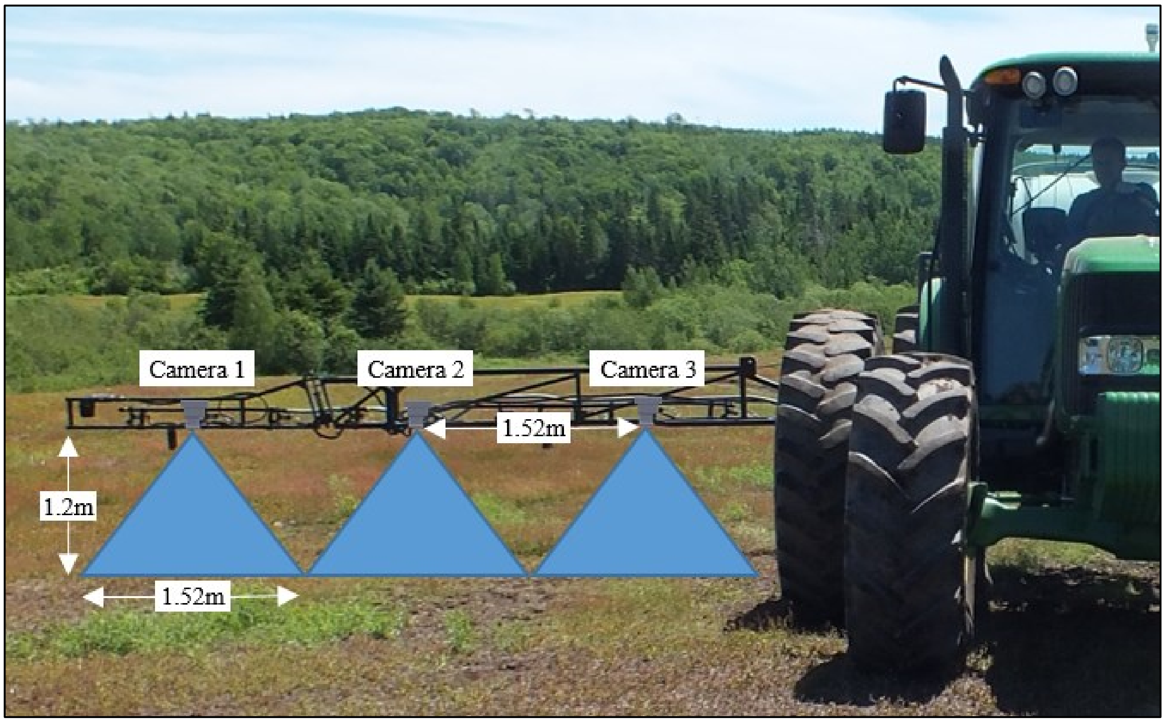


Figure 4-3: Smart sprayer camera field of view for proper image acquisition.

The camera lenses had 3.5 mm focal length with a fixed aperture (f/4.0) with infinity focus). Exposure time and digital gain were automatically controlled by auto exposure shutter/ auto gain control to adjust for variable outdoor lighting conditions. The maximum auto exposure shutter was set to 2 ms to prevent picture blurring while travelling over rough field terrain. The cameras were positioned 0.18 m in front of the spray nozzles (Fig. 4-4). Each image represents an area on the ground surface equal to 1.52 m wide by 0.914 m tall. For rapid image processing only the front portion (1.52 m by 0.28 m) of the image is used and the remainder is disregarded (Fig. 4-4).

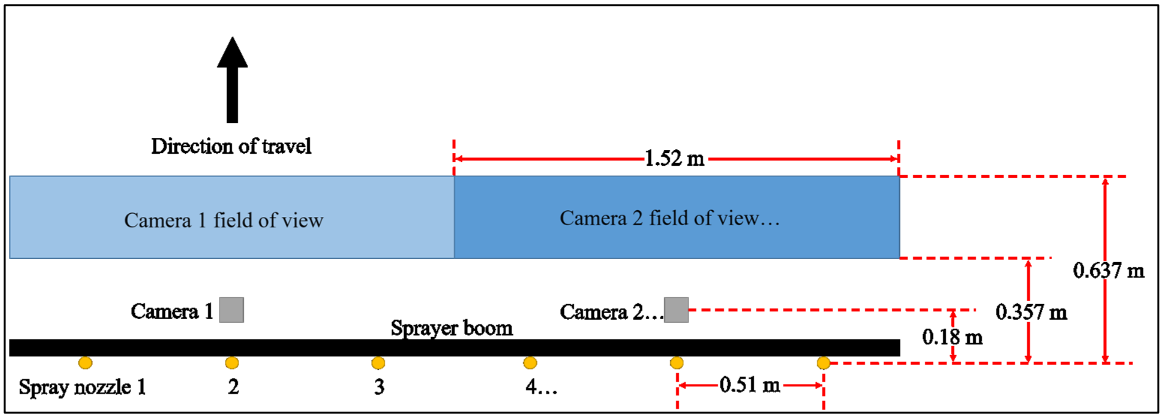


Figure 4-4: Schematic diagram showing camera field of view with relation to sprayer boom and nozzle position.

The image acquisition time was found to be 0.015 s (Table 4-1). The processing time required for the PC to analyze the nine images simultaneously was 0.135 s (Table 4-1). An additional 0.052 s time delay was required for the PC to send a triggering signal to turn on the solenoid valve and spraying (Table 4-1). The determination of the maximum travel speed while spraying is 1.77 m s^{-1} and was found using the following formula:

$$Smart\ sprayer\ maximum\ speed = \frac{spray\ nozzle\ to\ camera\ field\ of\ view\ (m)}{camera\ \&\ spray\ delay\ time\ (s)} \quad (3)$$

$$= \frac{0.357\ m}{0.202\ s}$$

$$= 1.77\ m\ s^{-1}$$

Table 4-1. Camera and spray delay parameters.

Machine vision & spray delay time	Time (s)
Image acquisition	0.015
Image processing	0.135
Mechanical delay	0.052
Total	0.202

4.2.2 Comparison between Front Boom Machine Vision and Rear Boom Mounted Machine Vision

A commercially available farm tractor (John Deere 6430) and sprayer (MS 1135E) was modified using a combination of hardware and software to operate on a spot-specific basis using the developed machine vision system (Fig. 4-5). The main components added was µEye digital color cameras, computerized 20-channel VRC, a MLC, a servo valve, a flow meter, individual nozzle solenoid valves and a self-leveling front sensor boom. The front cameras were at a distance of 6.6 m ahead of the sprayer nozzles while the rear cameras were mounted on the rear sprayer boom 0.18 m ahead of the spray nozzles. The cameras were connected to a PC inside of the tractor cabin by active link USB cables because of the extended 10 m length. Custom image processing software capable of discriminating the difference between blueberry plants, weed patches and bare soil was installed on the PC. As the sprayer moves in the field the image processing software analyzes each image and sends triggering information to the corresponding solenoid valve opening and closing the individual spray nozzles on a spot-specific basis. The PC also continuously sends triggering information to the MLC which regulates the flow rate based on the number of nozzles open at that time and the vehicle travelling speed. The rear sprayer boom was positioned approximately 1.2 m off the ground and each of the sprayer nozzles covered a 0.51 m section on the ground surface. The nozzles were Hypro lo-drift™ (LU-DB02F120, Hypro, New Brighton, MN, 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 was operated with 12 V. The feed line from the pump went through a flow valve and flow meter then separated into three lines, each line feeding nine nozzles of the boom. The 3 piston diaphragm pump was operated by the tractors power take off (PTO).

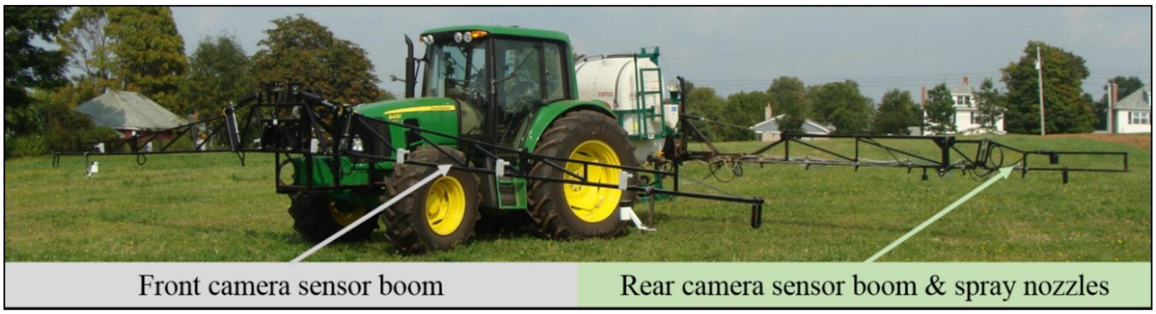


Figure 4-5: Smart sprayer showing front machine vision boom and rear machine vision boom and spray nozzles.

4.2.3 Front Machine Vision Boom and Rear Machine Vision Boom Comparison Test for Targeting Wild Blueberry Plants within the Field

A wild blueberry field was selected in central Nova Scotia in summer of 2013 to test the performance accuracy of the smart sprayer operating with a front machine vision boom versus a rear machine vision boom for targeting wild blueberry plant areas within the field. The selected field was the Frank Webb site located in Highland Village (45.405501°N, 63.669183°W, 4.6 hectare). The field was in sprout year of the biennial crop production cycle in 2013 during the experiment and crop year in 2012. The field had been under commercial management over the past decade and received biennial pruning by mowing as well as conventional fertilizer, weed, and disease management practices. During mid-July Bravo® fungicide is typically applied to commercial sprout fields to protect against disease pressures. For the comparison test water was used as the application to ensure that repeated coverage to the test track would not damage the crop or pollute the environment.

The test track was constructed using a measuring tape and marked with colored boundary flags. A RTK-GPS was used to map the track boundary as well as any bare soil present within the test track (12.2 m x 126 m). The bare soil patches were not equally distributed in the field. There were large bare zones in the center portion of the test track where smaller bare zones were concentrated on both the North and South ends of the track.

On July 15, 2014 water was applied on a spot-specific basis to wild blueberry plants to compare the application targeting performance while using the front machine vision boom versus the rear machine vision boom (Fig. 4-6).

Figure 4-6: Left image shows smart sprayer operating in the selected track. Right image shows field conditions during experiment and placement of water sensitive paper in a non-target bare soil patch within the test track.

Prior to spray application twelve WSPs were positioned on the ground at randomly selected bare spots in the track and twelve WSPs were placed in blueberry plant zones (Fig. 4-6). The WSPs were orientated parallel to the ground and selected targets were marked with the RTK-GPS for mapping in ArcMap 10 GIS software. The water was initially sprayed on spot-specific mode while using the front cameras as sensors for targeting the blueberry plant zones. The sprayer was driven from the South to North direction length way along the test track and WSPs were collected after drying and placed in a sealed zip lock bag. New WSPs were again fastened to the same positions on the ground surface at each of the 24 positions. Next, the sprayer was operated in the same direction using cameras mounted on the rear sprayer boom for sensing and control of the individual nozzles for wild blueberry plant detection and spraying. The application maps were also recorded for each test using the coverage maps built into the MLC. The WSPs were scanned and processed using a custom software package to calculate PAC of the sprayed targets. ANOVA was performed to examine whether the mean PAC of the sprayed targets deferred at the different locations (bare soil and blueberry plants) within the test track using the two different camera positions. Classical statistical analysis was performed to calculate minimum, maximum, mean and standard deviation of PAC targets for all applications using Minitab® 16 statistical software.

The ground speed during the field operations was 6 ± 0.2 km h^{-1}. The application rate was setup at 187.0 L ha^{-1} in the MLC. An application savings analysis was performed to compare spot-application technique with uniform application. Sprayed areas were recorded with the MLC and imported into ArcMap 10 computer software, to evaluate the performance of the smart sprayer. The chemical saving potential was calculated from the sprayed area and the track size using the following formula:

$$Application\ Savings\ (\%) = 100 - \frac{Sprayed\ Area}{Total\ Area} * 100 \qquad (2)$$

4.2.4 Field Testing Refined Rear Boom Machine Vision Smart Sprayer System

The smart sprayer was tested for agrochemical application in two selected fields in Debert, Nova Scotia, Canada. During the time of selection both fields were in the vegetative sprout year of the biennial crop production cycle. The wild blueberry fields were both well-developed and had been commercially managed using traditional growing practices over the past decade. Conventional rates of fungicide for disease control, herbicide for weed management and insecticide for pest control were applied.

Hypro low drift 120° flat fan nozzles with 0.757 L min^{-1} flow at 276 kPa were used during the time of application. The nozzle is specially designed to produce large air-filled droplets, which cut drift dramatically compared to a standard flat fan nozzle. 27 Viton No.2201 1-amp solenoid valves were mounted directly to the nozzle body and allowed rapid control of each nozzle. The 27 spray nozzles with 0.51 m spacing were divided into three sections (nine nozzles per section). A PTO driven three piston diaphragm pump was used to propel the agrochemical from the 1135 L storage tank to each of the three boom sections (Fig. 4-7). Each boom section used its own electronically controlled flow valve which allowed for flow regulation based on the current number of nozzles that were spraying as well as the tractors ground speed that was recorded using a Garmin GPS. The flow valves each received flow rate feedback from in-line flow meters. The operator can monitor the application output from each section from the visual display on the dashboard of the MLC mounted in the cabin of the tractor. The controller also allows the operator to visually monitor the swath patterns easily showing the areas in the field that were already applied with agrochemical.

Figure 4-7: Smart sprayer with rear mounted cameras and 27 spray nozzles.

4.2.4.1 Field Experiment 1

The East Mines Field (45.426956, -63.482069) was selected to apply an application of Chateau® herbicide to reduce the infestation of hair cap moss that was present in the field. A RTK-GPS HiPer® lite+ (Topcon Positioning Systems Inc., Livermore, CA, USA) was used to manually map the field boundary and moss infected areas in the field (Fig. 4-8). The total field size was 3.68 ha and twelve tracks each 120 m long were marked with flags (Fig. 4-8). The twelve test tracks were broken into four replications of three different application techniques (control (CN) – 0.0 g/ha Chateau®, uniform application (UA) – 0.6 kg ha^{-1} Chateau®, SA – 0.6 kg ha^{-1} Chateau® applied only to target moss areas). Figure 4-8 shows both an aerial photograph of the East Mines Field with twelve test tracks and a GIS map representing the moss infected areas.

Figure 4-8: East Mines Field aerial photograph (top) showing experimental track setup and GIS map showing moss infected areas (bottom).

On November 8, 2013 the smart sprayer was used to apply the treatment application to each test track. The temperature during the time of application was 2.9 °C with a relative humidity of 57%. The average wind speed was 11 km h^{-1} directed to the East (Environmental Canada Weather Archive). Prior to application six 5.2 x 7.6 cm WSPs were placed horizontally at ground level in moss infected areas of track three while six WSPs were placed in wild blueberry areas within the same test track (Fig. 4-9). For comparison, six WSPs were also placed in UA track two.

(a)

(b)

Figure 4-9: WSP placed in blueberry plant zone (a), and moss infected zone (b).

The WSPs were collected after the smart sprayer completed the pass across the test tracks and they were placed in a sealed zip lock bag and brought back to the Dalhousie University Agricultural Campus (DAL-AC) lab. The WSPs were each scanned and converted into a .bmp image. Each of the .bmp image files were imported into custom software that was able to determine the PAC of spray (Fig. 4-10). The software was used to enhance and count the mostly blue pixels on each WSP, and expressing the result as a percentage of total blue pixels (Fig. 4-10). ANOVA with LS means was performed to examine the PAC of the sprayed targets at different locations (blueberry plant zone, moss infected zone) within the test tracks. The minimum, maximum, mean and S.D. of the PAC targets for all applications were determined using Minitab® 16 statistical software.

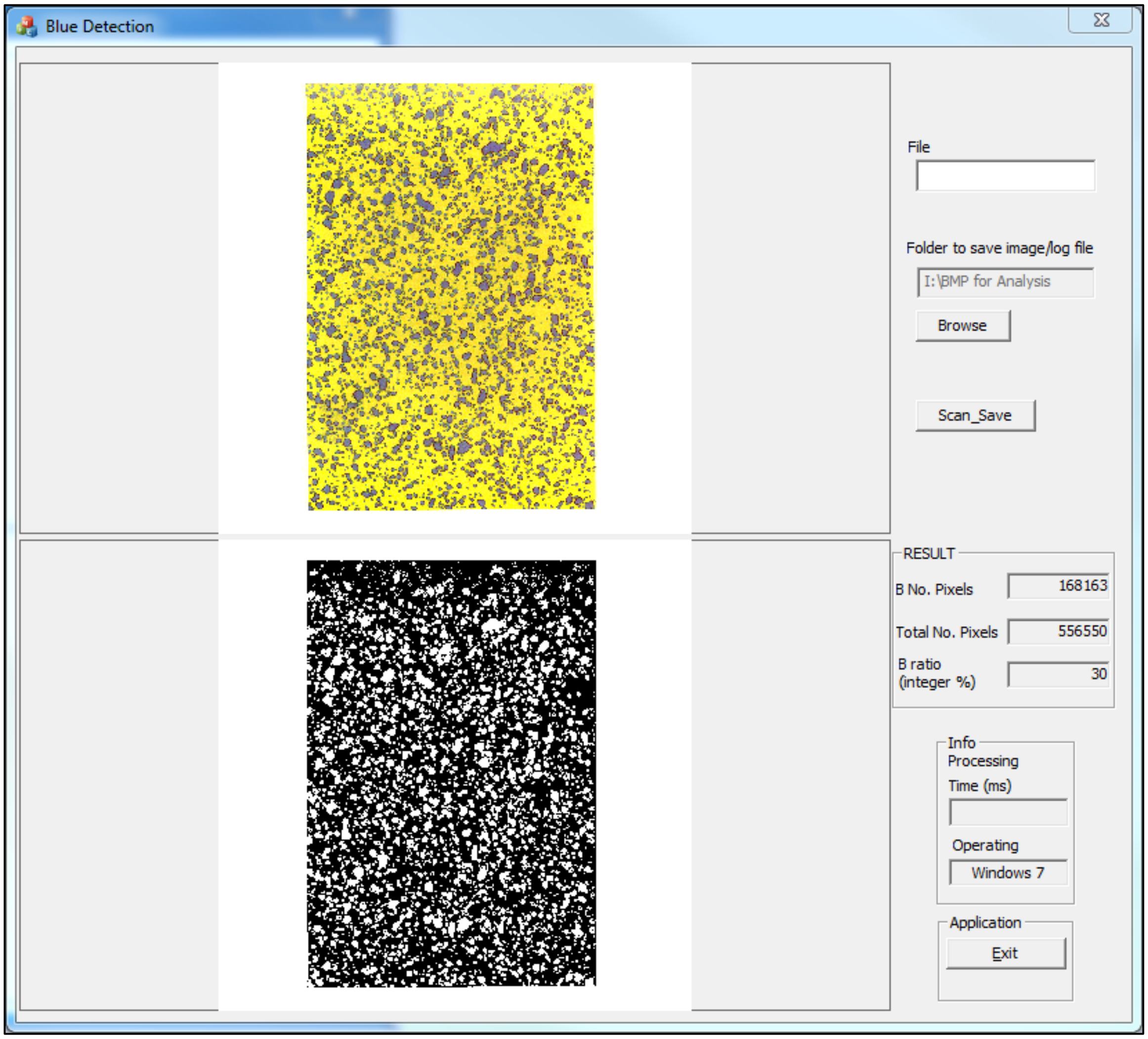


Figure 4-10: Custom software for determining percent area coverage of each WSP.

The ground speed during the field application was 6 ± 0.2 km h^{-1}. The herbicide application rate was setup at 0.6 kg ha^{-1} Chateau® with a total flow volume of 187.1 L ha^{-1}. The total amount of agrochemical was recorded from the display screen on the MLC after completion of each track. The agrochemical application amounts were used in combination with the percent moss coverage to determine the amount of agrochemical savings that was achieved from each test track.

The wild blueberry yield was manually collected on August 20, 2015 using a 36 tooth hand rake from ten randomly selected sampling plots in each track (SA, UA and CN) to assess the effect of Chateau® on harvestable yield. A steel quadrant measuring 0.5 m x 0.5 m was used to mark out the area for the yield collection from each plot. The collected yield samples were packaged in a sealed plastic bag and weighed in at the DAL-AC lab. ANOVA was used to examine the difference between the mean yield weight from each test track (SA, UA and CN).

Percent moss coverage was recorded from a 0.5 x 0.5 m steel frame quadrant at ten randomly selected points in each test track. Each location was marked with a plastic marker stake so the procedure could be repeated at the same location at different times throughout the year. A 16-megapixel Fijifilm finePix HS30EXR (Fujifilm, Mississauga, ON, Canada) digital color camera was pointed downward at a height of 1.0 m above the ground to record a digital image of each plot for comparison. The data was collected on November 15, 2013, January 15, 2014, May 8, 2014, July 2, 2014 and May 25, 2015 (Fig. 4-11). Percent moss coverage from each plot was analyzed using SAS®. The data was checked for normality and constant variance. The minimum, maximum, mean and S.D. of the percent moss coverage for all applications were determined using Minitab®. The mixed-model procedure at 5% level of significance was used to test the significance of the treatments. LS means comparison was used to determine if the percent moss coverage varied with the treatment methods or over time.

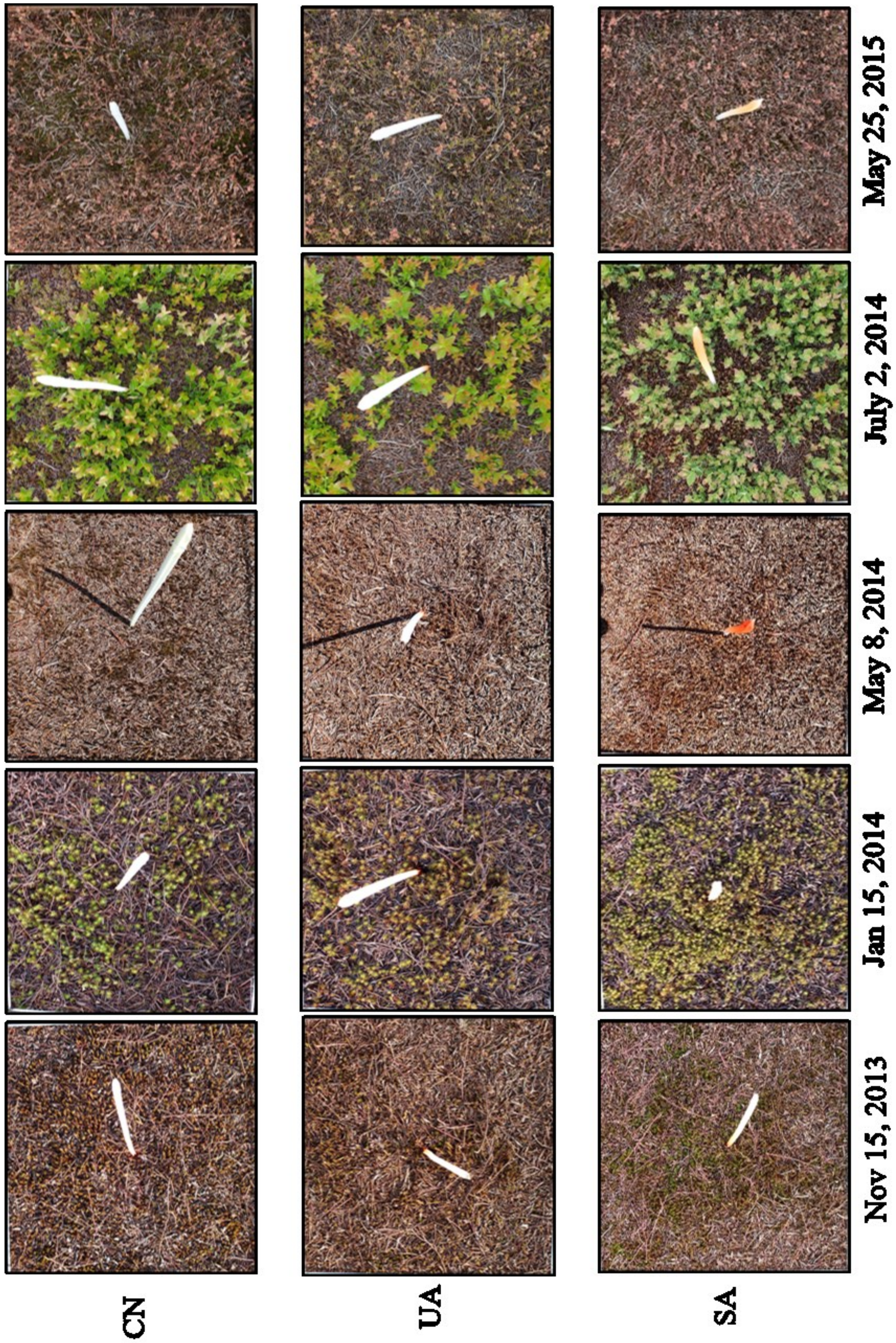


Figure 4-11: Sample images showing moss percent area coverage at different collection intervals for each of the three application techniques.

4.2.4.2 Field Experiment 2

The Middle Road Field (45.425706, -63.497650) was selected to apply an application of Bravo® and Proline® fungicide to protect the plants from disease that may reduce yield in the field. TruPhos Magnesium (29% phosphoric acid, 5% soluble potash and 4% magnesium) and ZincMax (10.2% zinc and 0.5% boron) foliar fertilizers were also tank mixed with Bravo® and Proline® fungicides to increase the plants nutrient supply with the hopes to increase yield. An RTK-GPS was used to manually map the field boundary and bare soil areas in the field. The total field size was 5.26 ha and nine tracks each 75 m long were marked with flags. The nine test tracks were broken into three replications of three different application techniques (CN – 0.0 L/ha Bravo®/ Proline®/ TruPhos Magnesium / ZincMax, UA – 4.94 L ha^{-1} Bravo®, 0.35 L ha^{-1} Proline®, 3.71 L ha^{-1} TruPhos Magnesium, 1.24 L ha^{-1} ZincMax, SA – 4.94 L ha^{-1} Bravo®, 0.35 L ha^{-1} Proline®, 3.71 L ha^{-1} TruPhos Magnesium, 1.24 L ha^{-1} ZincMax applied only to foliage areas). Figure 4-12 shows an aerial photograph of the East Mines Field including the nine test tracks. Figure 4-13 shows the bare soil areas (non-target zone) in the field that did not receive fungicide or fertilizer application when applied using the smart sprayer on spot-application mode.

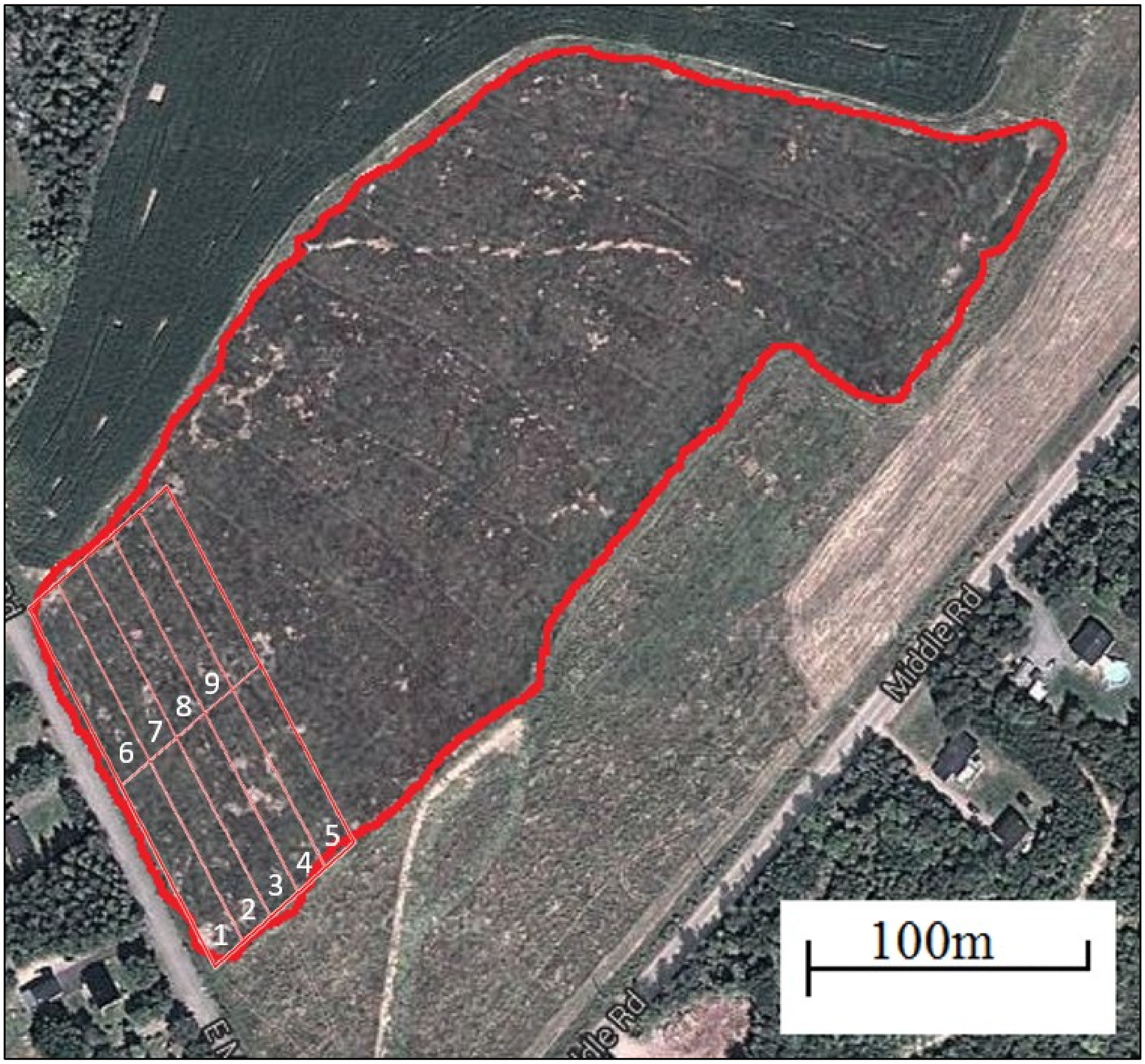


Figure 4-12: Arial photograph of the Middle Road Field showing nine test tracks and the bare soil variability through the field.

Figure 4-13: Image showing non-target bare soil areas in the Middle Road Field.

On July 21, 2014 the smart sprayer was used to apply the treatment application to each test track. The temperature during the time of application was 25.5 °C with a relative humidity of 47%. The average wind speed was 10 km h^{-1} directed to the North (Environmental Canada Weather Archive). A mixing station was used to properly mix the two fungicide and two liquid foliar fertilizer blends together (Fig. 4-14).

Figure 4-14: Agrochemical mixing station used for pumping the fungicide and foliar fertilizer mix into the sprayer storage tank.

The ground speed during the field application was 6 $\pm$ 0.2 km h^{-1}. The fungicide application rate was set to 4.94 L ha^{-1} Bravo®, 0.35 L ha^{-1} Proline®, 3.71 L ha^{-1} TruPhos Magnesium and 1.24 L ha^{-1} ZincMax with a total flow volume of 187.1 L ha^{-1}. The total amount of agrochemical was recorded from the display screen on the MLC after completion of each track. The agrochemical application amounts were used in combination with the percent bare soil coverage to determine the amount of agrochemical savings that was achieved from each test track. Ten randomly selected locations within each track were marked using a field stake and recorded position using RTK-GPS for use for plant parameter data collection.

On October 9, 2014 a 16-megapixel Fujifilm finePix HS30EXR digital color camera was used to visually record the effect of Bravo® and Proline® fungicide and foliar fertilizers on plant growth and leaf retention. The camera was pointed downward at a height of 1.0 m above the ground to capture a digital image from each of the ten plots within each track. A steel frame measuring 0.5 × 0.5 m was placed on the ground beforehand to identify the area where image was to be taken. The 90 images were randomly numbered and saved on a memory stick. Five different classes were developed based on plant health (0 –

complete leaf defoliation, 1 – partial leaf defoliation, 2 – no leaf defoliation (mostly red plants, 3 – no leaf defoliation (red/green plants), 4 – no leaf defoliation (mostly green plants) (Fig. 4-15). The images were given to five different people who separated each of the images into one of the five classes based on their visual observation of the plant health. The results were averaged and converted to a percentage of healthy plants per image. Plant health data from each plot was analyzed using SAS®. The data was checked for normality and constant variance. The minimum, maximum, mean and S.D. of the percent of healthy plants for all applications were determined using Minitab®. The mixed-model procedure at 5% level of significance was used to test the significance of the treatments. LS means comparison was used to determine if the visual plant health varied with the treatment methods (SA, UA and CN).

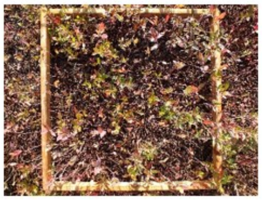
	0 – Complete leaf defoliation
	1 – Partial leaf defoliation
	2 – No leaf defoliation (mostly red plants)
	3 – No leaf defoliation (red/green plants)
	4 – No leaf defoliation (mostly green plants)

Figure 4-15: Wild blueberry plant visual health classification chart used to rank the digital images taken of the plots from each track.

On December 22, 2014 plant growth parameters were measured from the ten plots within each of the nine tracks to assess the effect of Bravo®, Proline® and foliar fertilizer. A steel quadrat measuring 0.15 × 0.15 m was used to mark out the area for stem density measurements. Six blueberry stems from each 0.15 × 0.15 m sample area were randomly cut using a knife to measure the stem height, stem diameter, number of branches and number of floral buds. The six recordings taken from each quadrat were averaged to show the number per stem. Classical statistics was used to calculate minimum, maximum, mean and S.D. using Minitab®. ANOVA and post hoc LS means with 95 % confidence interval was performed using SAS® to examine and compare the effect of Bravo®, Proline® and foliar fertilizer on the plant parameters with SA, UA and CN.

The wild blueberry yield was manually harvested on August 20, 2015 using a 36 tooth hand rake from within a 0.5 x 0.5 m steel quadrate at each of the ten plots in each track to assess the effect of the fungicide and fertilizer tank mix on harvestable yield. The blueberries were collected 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 at the DAL-AC lab. Classical statistics was used to calculate minimum, maximum, mean and S.D. using Minitab®. ANOVA and LS means with 95 % confidence interval was performed using SAS® to examine and compare the effect of Bravo®, Proline® and foliar fertilizer on harvestable yield with SA, UA and CN.

4.3 RESULTS AND DISCUSSION

4.3.1 Front Versus Rear Mounted Machine Vision System

The results indicated that the smart sprayer performed very similar when using either front mounted cameras or rear mounted cameras when travelling over a straight application track. The application maps show good spray coverage on most blueberry patches in the selected track (Fig 4-16). Some sprayed patches within bare soil zones could have been the result of cameras detecting small amounts of newly developing foliage that were not mapped with the RTK-GPS. Also, it was observed that wind caused spray drift that resulted in some WSP non-targets being sprayed and vice versa.

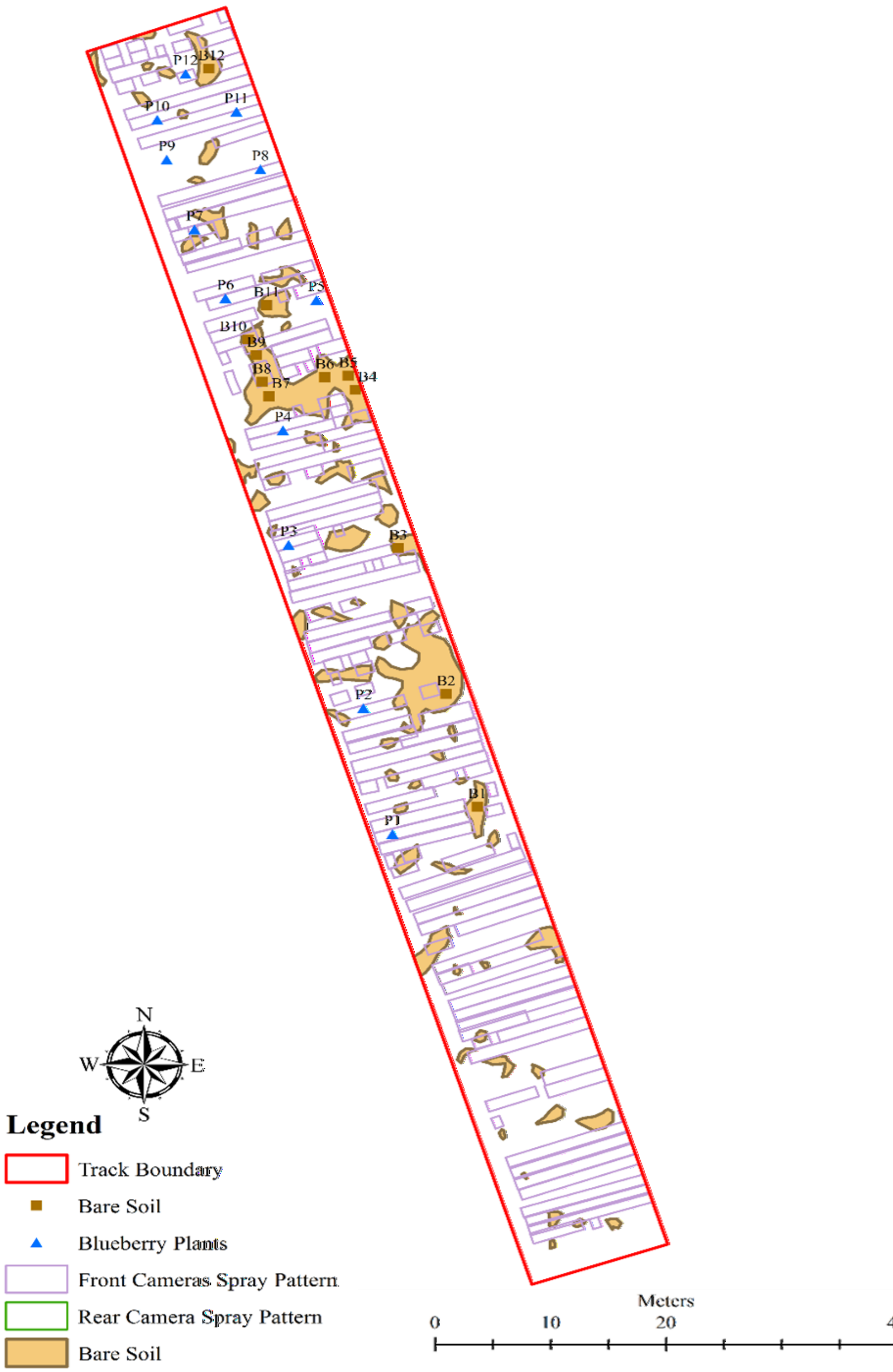


Figure 4-16: Test track application map showing boom targeting and positions of water sensitive paper in both blueberry plant and bare soil patches.

The PAC of the sprayed targets while using front cameras ranged from 0.01% to 31.84% in bare soil locations and from 0.11% to 94.93% in blueberry plant locations within the track (Fig. 4-17). The PAC of the sprayed targets while using rear mounted cameras ranged from 0.19% to 8.73% in bare soil locations and from 2.85% to 95.20% in blueberry plant locations within the track (Fig. 4-17). The reason of variation in PAC might be due to the height of the sprayer boom off the ground when travelling over the rough terrain. When nozzles are closer to the ground the area directly under the nozzles gets a higher application rate as compared to areas directly between adjacent nozzles. A boom leveling system would help this issue but due to the natural rough topography present in most wild blueberry fields in Nova Scotia, Canada this variation in coverage is hard to fully overcome. Wind also has an effect on spray patterns and on July 15 of 2013, the wind speed ranged between 10 km h^{-1} and 20 km h^{-1} directed to the North East (National Climate Data and Information Archive, 2013).

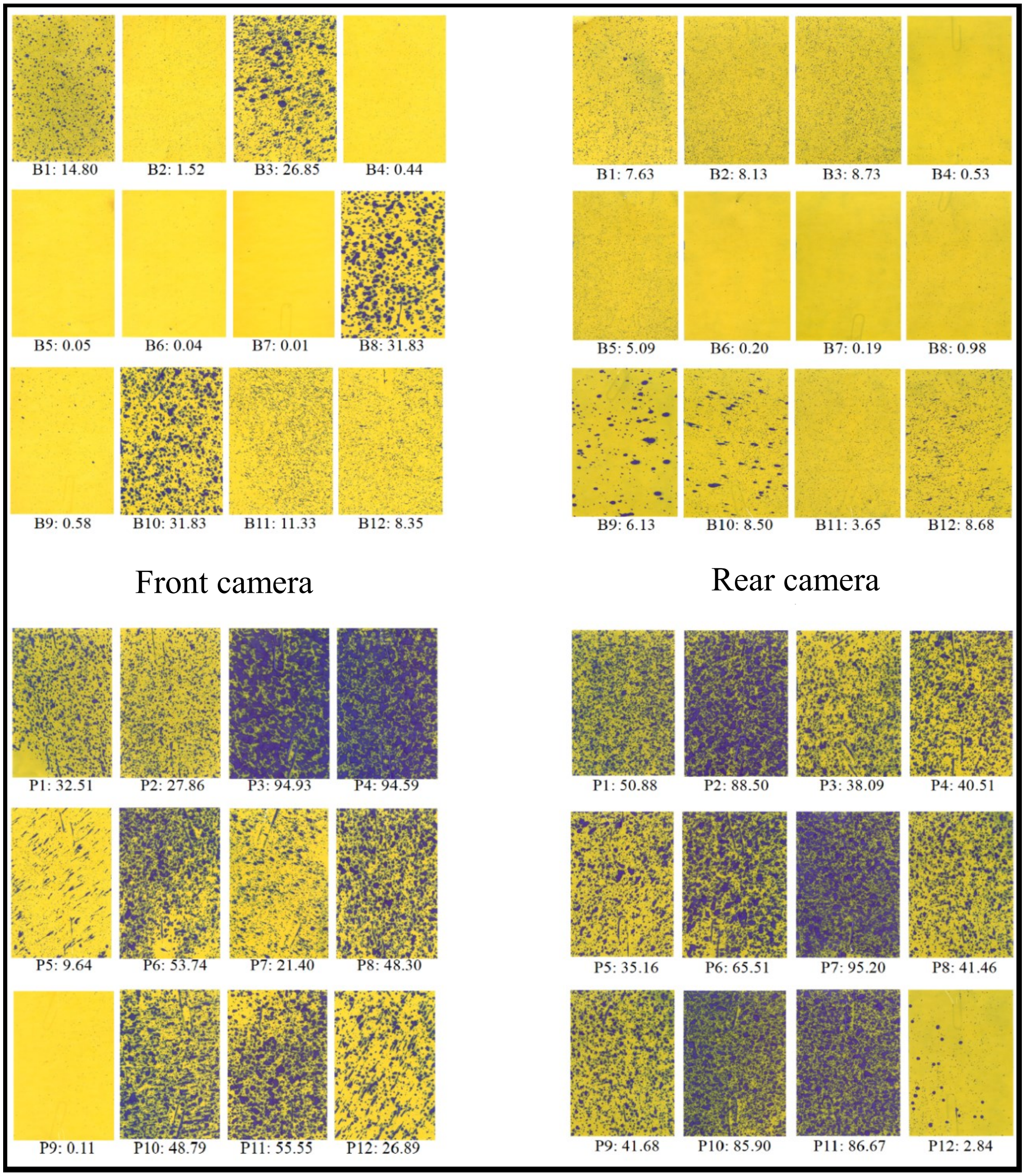


Figure 4-17: Water sensitive paper from wild blueberry plant areas and non-target bare soil points within the test track. Water sensitive papers used during front machine vision test (left) and rear machine vision test (right) were placed in non-target locations (top) and target locations (bottom). Percent area coverage of the water sensitive papers are displayed numerically below each.

There was a significant difference between the mean PAC from WSPs located in bare soil (10.58%) and blueberry spots (42.86%) in the track when using the front machine vision (Table 4-2). Similarly there was a significant difference between the mean PAC from WSPs located in bare soil (4.87%) and blueberry spots (56.03%) in the track when using rear machine vision (Table 4-2). The PAC of WSPs from bare soil locations was significantly lower than that of WSPs in blueberry plant locations in the track for both front mounted and rear mounted camera positions. The WSPs in the bare soil areas in the test track was not significantly different when comparing the two camera positions. Similarly, the WSPs in blueberry plant areas in the test track had mean PAC that was not significantly different when comparing the two camera positions. The WSPs placed in blueberry plant areas had the highest standard deviation for both the front and back camera positions (29.71 and 28.25%, respectively). The reason for this large variation was most likely due to the uneven ground causing varying boom height.

Table 4-2. Summary statistics of percent area coverage of the sprayed targets for determining the precision of spot-application technique for targeting using machine vision system mounted on front/back boom of the tractor.

Location (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
Front Cameras Bare Soil (12)	0.01	31.84	10.58a	12.74	<0.001
Front Cameras Plants (12)	0.11	94.93	42.86b	29.71	
Back Cameras Bare Soil (12)	0.19	8.73	4.87a	3.59	
Back Cameras Plants (12)	2.84	95.20	56.03b	28.25	

The track size was 1537.20 m^2 and if sprayed uniformly would require 28.76 L of water following an application rate of 87.7 L ha^{-1}. However, the smart sprayer application savings using spot-application with front cameras and rear cameras was 7.20% and 14.33% based on the application map and the amount of water applied to the test track (Table 4-3). The application savings directly lowers the cost of production as well as having lower environmental impact. Another added benefit is fewer trips back to the water truck to refill the sprayer tank saving time, labor and fuel.

Table 4-3. Smart sprayer saving with spot-application technique.

Application	Track Area (m^2)	Bare Soil (m^2)	Plants (m^2)	Coverage (m^2)	Sprayed (L)	Savings (%)
Uniform application	1537.20	206.69	1330.51	1537.20	28.76	0
Spot-application (front cameras)	1537.20	206.69	1330.51	1426.52	26.69	7.20
Spot-application (rear cameras)	1537.20	206.69	1330.51	1317.25	24.64	14.33

4.3.2 Rear Mounted Machine Vision Field Experiment 1

The maximum PAC from the SA tracks in the wild blueberry plant zones was 0.03% (Fig. 4-18). The minimum from the moss zones from SA and UA tracks were 30.22% and 18.23%, respectively (Fig. 4-19 and Fig. 4-20). The mean PAC from WSPs located in wild blueberry plant and moss areas from the SA track was 0.01% and 37.59%, respectively (Table 4-4). The PAC of WSPs from the UA track was 37.01%. The PAC from WSP located in blueberry plant areas using SA was significantly lower than that of WSPs in moss patches for both SA and UA (37.58% point and 37.00% point, respectively). The WSPs in the moss areas in the SA test track was not significantly different from the UA

WSPs. The WSPs placed in the UA track had the highest S.D. (10.45) most likely due to the uneven ground causing varying boom height and slight spray drift from wind gusts. The average PAC from the SA on moss WSPs (37.59%) was sufficient for eradication using a contact herbicide as it coincided with the UA amounts. The P-value was <0.00 when comparing the WSPs PAC from the target locations. These results were in accordance with results from Zaman et al. (2011).

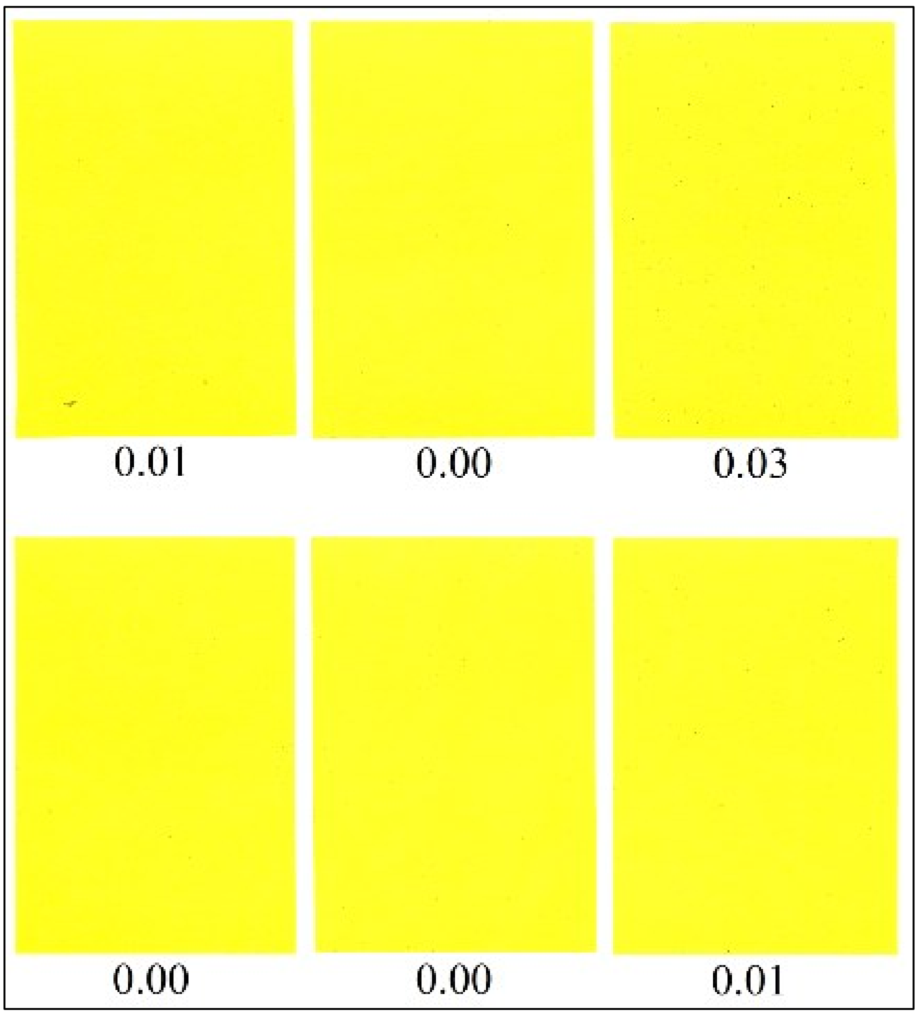


Figure 4-18: WSP from non-target blueberry plant locations in selected spot-application test track.

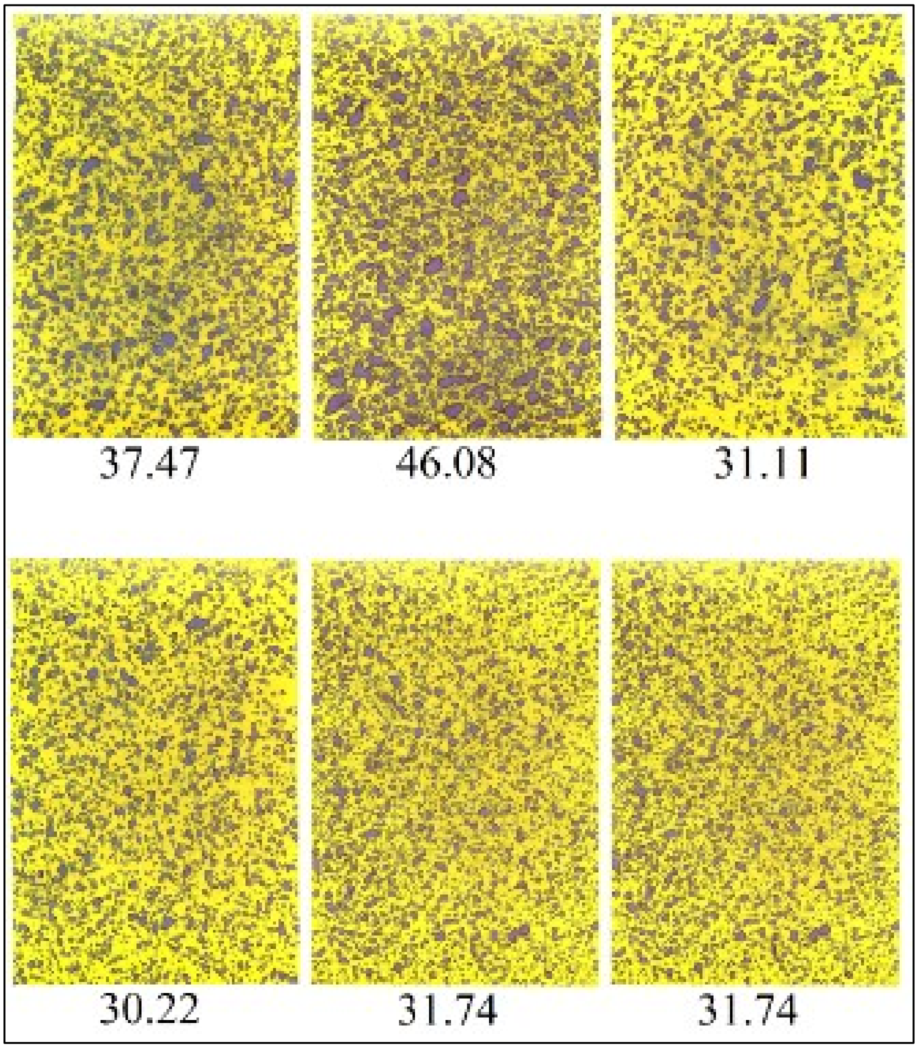


Figure 4-19: WSP from target moss locations in selected spot-application test track.

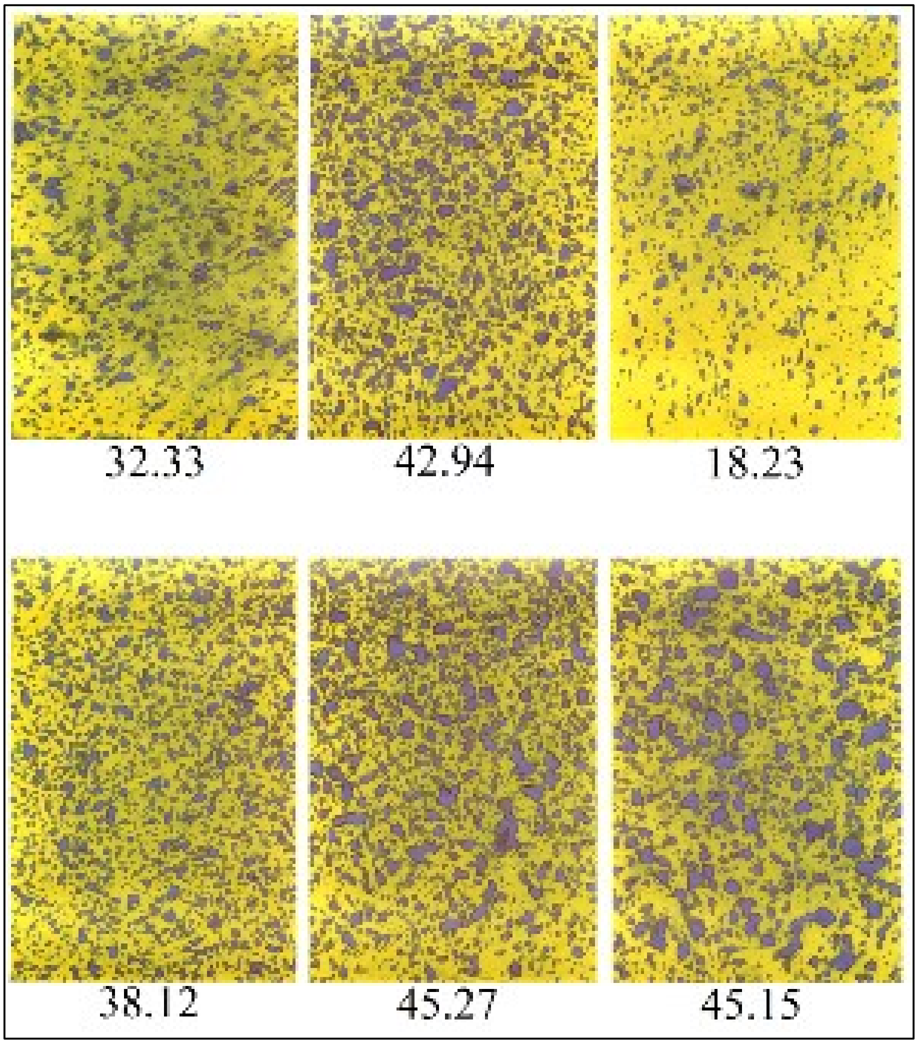


Figure 4-20: WSP from blueberry plant and moss infected zones of UA test track.

Table 4-4. Summary statistics of percent area coverage of the sprayed targets for determining the precision of spot-application technique relative to UA with smart sprayer for targeting moss infected zones in the field.

Location (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
SA Plants (6)	0.00	0.03	0.01[a]	0.01	<0.00
SA Moss (6)	30.22	48.91	37.59[b]	8.13	
UA (6)	18.23	45.27	37.01[b]	10.45	

Means followed by different letters are significantly different at a significance level of 0.05.

The CN test tracks obtained 100% agrochemical savings because they did not receive any Chateau® herbicide application. SA tracks 3, 5, 9 and 11 had 275.4 m^2, 179.9 m^2, 272.8 m^2, and 250.6 m^2 moss coverage, respectively (Table 4-5). UA tracks 2, 6, 8, and 12 had similar moss coverage; 221.5 m^2, 147.2 m^2, 141.3 m^2, and 244.1 m^2, respectively (Table 4-5). The average moss coverage for SA, UA, CN was 16.7%, 12.9% and 9.2%, respectively. UA had the highest amounts (26.9 L, 31.1 L, 23.1 L and 28.4 L) of total application applied to the test tracks because it was applied at the grower's uniform rate (Table 4-5). The reason for variation in application amounts could have been the result of turning the nozzles on slightly too early or too late causing discrepancy in application amounts. SA lowered the total amount applied to 6.2 L, 5.4 L, 6.1 L and 5.0 L of agrochemical applied to each of the four test tracks (Table 4-5). The agrochemical savings using SA technique was 77.4%, 80.3%, 77.7% and 81.8% from the four test tracks (Table 4-5). The average amount of agrochemical saved using SA, UA and CN was 79.3%, 0% and 100%, respectively. The agrochemical savings from SA have a direct impact on the farmers input cost.

Table 4-5. Summary results showing test track area, moss infected area, agrochemical sprayed amount and agrochemical savings from each test track using the smart sprayer.

Plot #	Total (m^2)	Moss (m^2)	Plants (m^2)	Sprayed (L)	Agrochemical Savings (%)
1 (CN)	1464	251.9	1212.1	0.0	+100
2 (UA)	1464	221.5	1242.5	26.9	+1.8
3 (SA)	1464	275.4	1188.6	6.2	+77.4
4 (CN)	1464	139.7	1324.3	0.0	+100
5 (SA)	1464	179.9	1284.1	5.4	+80.3
6 (UA)	1464	147.2	1316.8	31.1	-13.5
7 (CN)	1464	50.8	1413.2	0.0	+100
8 (UA)	1464	141.3	1322.7	23.1	+15.7
9 (SA)	1464	272.8	1191.2	6.1	+77.7
10 (CN)	1464	95.8	1368.2	0.0	+100
11 (SA)	1464	250.6	1213.4	5.0	+81.8
12 (UA)	1464	244.1	1219.9	28.4	-3.7

The percent moss coverage varied from a minimum of 9.5% to a maximum of 75%. ANOVA (P-value < 0.05) showed no significant difference between percent moss coverage in the CN tracks at any of the five collection intervals (36.3, 36.3, 36.3, 23.6, 30.5%) (Table 4-6). However, after July 2, 2014 both UA (15.3%) and SA (16.6%) tracks had a significantly lower moss coverage than initial readings (40.9 and 52.9%, respectively) (Fig. 4-21). There was no significant difference (P-value = 0.211) in the percent moss coverage from the three treatments at the collection times on November 15, 2013, January 15, 2014 and May 8, 2014. Similarly, there was no significant difference (P-value = 0.166 and 0.736) in the percent moss coverage from the three treatments at the collection times on July 2, 2014 and May 25, 2015, respectively. Standard deviation (S.D.) was relatively high most likely due to non-controllable factors such as soil type, winter kill, disease, insect damage or herbicide resistance.

Table 4-6. Summary statistics and ANOVA comparison of percent moss coverage for determining the effectiveness of SA and UA of Chateau® relative to CN for control of moss.

Application (n)	Date	Min	Max	Mean	S.D.	P-value
CN (4)	Nov 15, 2013	27.0	45.5	36.3[abc]	7.31	0.211
UA (4)		26.5	49.5	40.9[ab]	10.0	
SA (4)		37.5	75.0	52.4[a]	17.1	
CN (4)	Jan 15, 2014	27.0	45.5	36.3[abc]	7.31	0.211
UA (4)		26.5	49.5	40.9[ab]	10.0	
SA (4)		37.5	75.0	52.4[a]	17.1	
CN (4)	May 8, 2014	27.0	44.5	36.3[abc]	7.31	0.211
UA (4)		26.5	49.5	40.9[ab]	10.0	
SA (4)		37.5	75.0	52.4[a]	17.1	
CN (4)	July 2, 2014	14.5	31.5	23.6[cd]	8.41	0.166
UA (4)		10.5	17.5	15.3[d]	3.23	
SA (4)		9.5	21.0	16.6[d]	5.36	
CN (4)	May 25, 2015	13.5	48.5	30.5[bcd]	14.3	0.736
UA (4)		16.0	29.0	23.5[cd]	5.49	
SA (4)		16.0	54	29.2[bcd]	17.1	

Means followed by different letters are significantly different

Results from plotted moss coverage versus collection interval reveal that the largest drop in moss coverage was in spring most likely due to winter kill (Fig. 4-21). The results show that the herbicide was not an effective method in reducing the amount of moss coverage in the selected plots. Possible reasons could have been due to the reasonably high wind speeds during the time of application (11 km h^{-1}). Another possible factor that could have contributed to the ineffectiveness of the herbicide is unfavorable weather conditions after application causing the herbicide to leach into the soil or being evaporated into the air rather than staying on the surface to be used to eradicate the moss species. The results suggest that there is an utmost importance to insuring that the proper herbicide is being applied at the proper rate at the proper time and also with favorable weather conditions. If these measures are not met the result can be a waste in terms of time and money causing higher input costs to the farmer with no measurable reward.

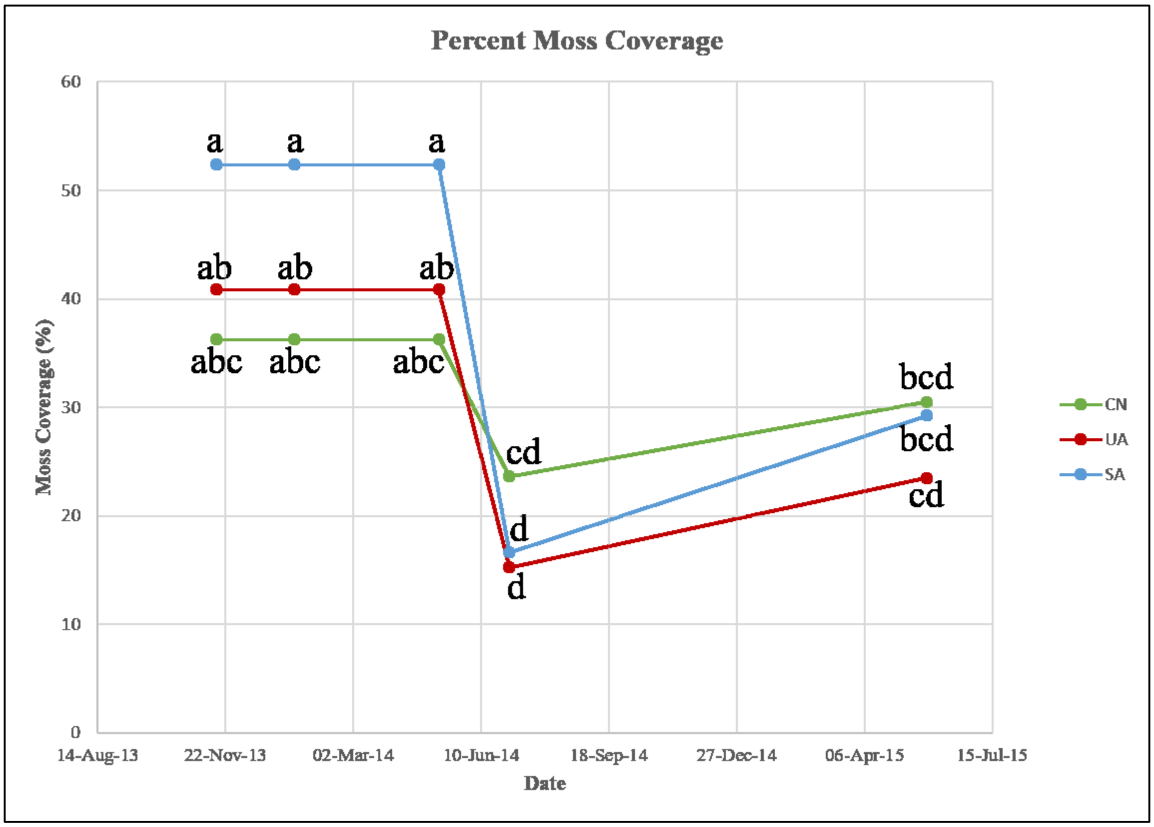


Figure 4-21: Line graph showing the collected moss percent coverage at selected plots at each collection interval.

Results from the harvest of the 120 plots showed the mean blueberry fruit yield was 1.02, 1.14, 1.19 kg m^{-2} in CN, UA and SA tracks, respectively (Table 4-7). ANOVA (P-value > 0.05) indicated that the harvestable yield was not significantly different between the three treatments. The results are as expected because the data showed no significant difference in moss coverage at the last collection interval before harvest. The variance in blueberry fruit yield parameters could be from external factors such as soil properties, disease and insect damage, pollination, winter kill and seasonal variations other than the Chateau® application. From the data gathered it was not favorable to apply the Chateau® herbicide for control of the moss species.

Table 4-7. Summary statistics and ANOVA comparison of blueberry yield (YD) for determining the precision of SA technique relative to the UA with the prototype smart sprayer applying Chateau®. Reference was made to CN tracks.

Application (n)	Plant yield parameter	Min	Max	Mean	S.D.	P-value
CN (40)	YD (kg m^{-2})	0.514	1.85	1.02a	0.264	
UA (40)	YD (kg m^{-2})	0.522	1.69	1.14a	0.291	0.085
SA (40)	YD (kg m^{-2})	0.318	1.98	1.19a	0.369	

Means followed by different letters are significantly different

4.3.3 Rear Mounted Machine Vision Field Experiment 2

Visual observation from the field testing indicated that the smart sprayer performed well for spot-application of agrochemical on foliage and shutting the nozzles off in bare soil zones in the test tracks. The agrochemical applied map recorded using the MLC shows solid rectangular polygons of same width (13.7 m) in each of the UA tracks (Fig. 4-22). However, the polygons shown in the SA tracks show rectangular shapes of different widths showing where nozzles were turning on/ off while travelling across the test tracks (Fig. 4-22). Areas that show spray on bare soil could have been caused by the machine vision cameras picking up small foliage areas growing within bare soil patches causing the nozzles to be triggered on. The image processing software could be modified to be less sensitive to detecting small foliage areas however, it is best to have the smart sprayer target all areas of foliage so nothing is missed to ensure that the blueberry plants are well protected from disease. The CN tracks did not have agrochemical applied so no polygons were recorded during travel.

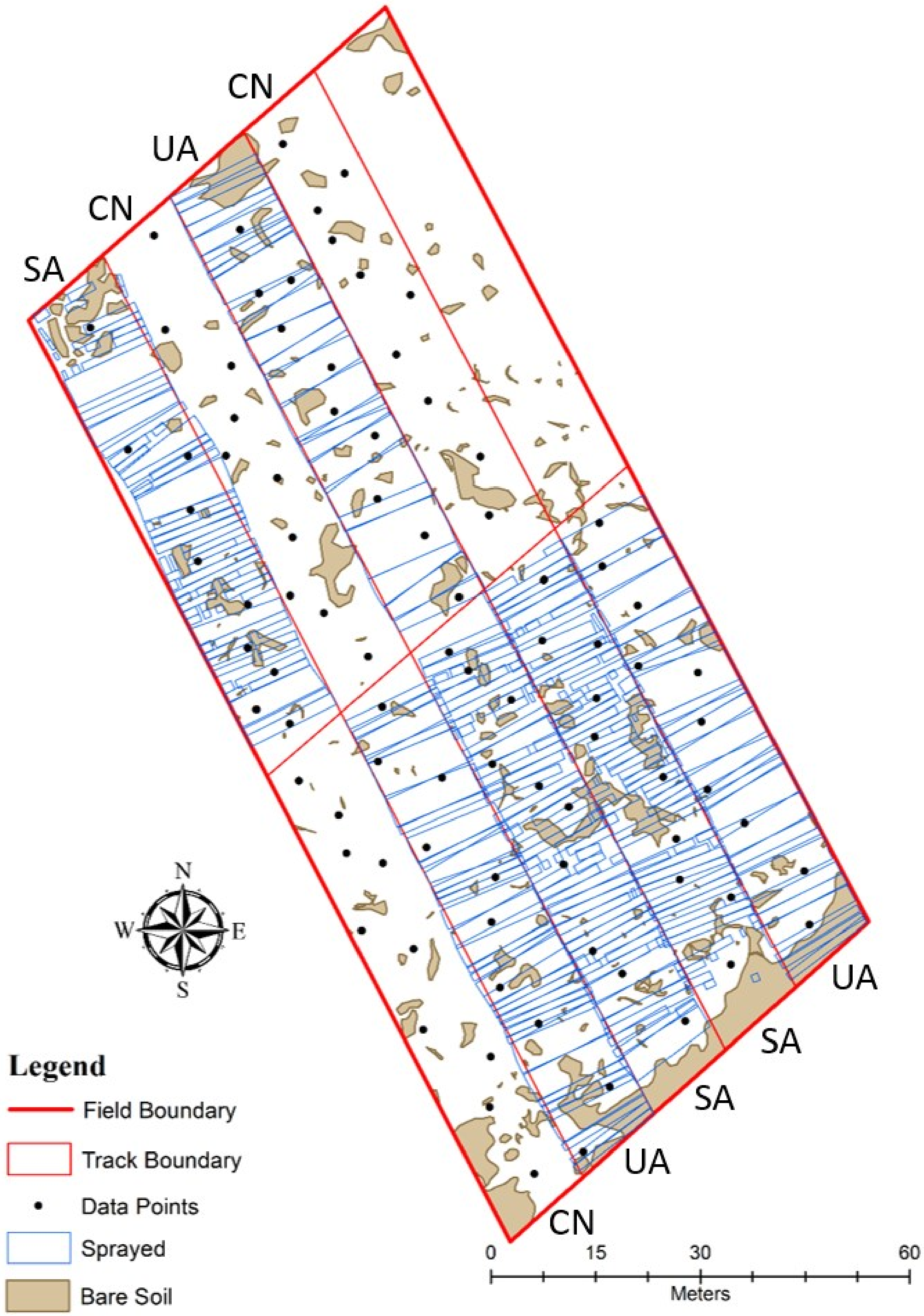


Figure 4-22: Middle Road Field map showing bare soil areas, flow controller applied areas and selected data points where plant parameter data and harvested yield was collected.

Each test track had a total area of 1027.5 m^2. SA tracks 3, 4, and 6 had 116.0 m^2, 177.5 m^2, and 97.4 m^2, bare soil coverage, respectively (Table 4-8). UA tracks 2, 5, and 8 had similar bare soil coverage; 101.2 m^2, 110.7 m^2, and 120 m^2, respectively (Table 4-8). SA had the lowest application amounts of 16.9 L, 16.8 L, and 17. 3 L from the three test tracks (Table 4-8). MLC data showed the SA of Bravo®, Proline® and foliar fertilizer savings ranged from 10.0 to 12.6%. The SA savings were dependent upon the percentage of bare soil that was present in each track (9.5 to 17.3%). The agrochemical savings from SA have a direct impact on the farmers input cost. The average amount of agrochemical saved was 100%, 0% and 11.6% with CN, UA and SA, respectively. The average bare spot coverage was 7.7%, 10.8% and 12.7% with CN, UA and SA, respectively. The UA has the highest amounts (20.6 L, 19.3 L and 17.8 L) of total application applied to the test tracks because it was applied to both foliage areas and bare soil areas in each test track. Variation in the UA most likely was caused by starting the nozzles too early without the tractor in motion causing a slight spike in application at the start of the track or stopping the nozzles too early or late causing under or over application at the end of the test track. The control tracks show 100% agrochemical savings because no application was applied. The results would be expected to show higher agrochemical savings using SA from a developing field that had a higher proportion of bare soil.

Table 4-8. Summary results showing test track area, bare soil area, agrochemical sprayed amount and agrochemical savings from each test track using the smart sprayer.

Plot #	Application	Total (m^2)	Bare Soil (m^2)	Plants (m^2)	Sprayed (L)	Chemical Savings (%)
1	CN	1027.5	116.1	911.4	0	+100
2	UA	1027.5	101.2	926.3	20.6	-7.1
3	SA	1027.5	116.0	917.3	16.9	+12.1
4	SA	1027.5	177.5	850.0	16.8	+12.6
5	UA	1027.5	110.7	916.8	19.3	-0.4
6	SA	1027.5	97.4	932.6	17.3	+10.0
7	CN	1027.5	57.6	969.9	0	+100
8	UA	1027.5	120.0	907.5	17.8	+7.4
9	CN	1027.5	63.2	964.3	0	+100

The digital image results suggested that the application of Bravo®, Proline® and foliar fertilizer significantly improved the wild blueberry leaf retention and visual plant healthiness (Fig. 4-23). The percentage of healthy plants varied from 0 to 70% in the CN tracks, 30 to 100% in the UA tracks and 45% to 100% in the SA tracks in the field (Table 4-9). The UA and SA showed the application of Bravo®, Proline® and foliar fertilizer increased the percentage of healthy plants by 41.0 and 57.8% points, respectively. ANOVA comparison (P-value < 0.000) showed UA and SA of Bravo®, Proline® and foliar fertilizer had a significantly higher percentage of healthy plants as compared to the CN tracks. Bravo® has been suggested to reduce foliage disease keeping the blueberry plants green and healthy improving carbohydrate production for the developing floral buds (Percival and Dawson 2009). SA tracks showed the highest percentage of healthy plants most likely due to the significant plant variability that exists in wild blueberry fields. Large variation in percentage of healthy plants with CN (S.D. = 21.12) could have been due to the natural variation of blueberry rust and *Septoria* leaf spot damage. Each wild blueberry field has several different clones of wild blueberry and some of them may be more resistant against blueberry rust and *Septoria* leaf spot than others.

Figure 4-23: Digital image showing wild blueberry plant leaf retention from UA plot 2 (left) and CN plot 1 (right) on October 9th, 2014.

Table 4-9. Summary statistics and ANOVA comparison of percentage of healthy green plants from CN, UA and SA tracks.

Track (n)	Min (%)	Max (%)	Mean (%)	S.D. (%)	P-value
CN (30)	0.00	70.00	23.00a	21.12	
UA (30)	30.00	100.00	64.00b	19.36	<0.000
SA (30)	45.00	100.00	80.83c	19.66	

Means followed by different letters are significantly different

ANOVA test (P-value = 0.416) showed no significant difference between blueberry plant density 585, 628 and 586 stems m^{-2} in CN, UA and SA tracks, respectively (Table 4-

10). This most likely was because new blueberry stems are already formed in early spring of the sprout year (McIsaac, 1997). There was a significant difference (P-value < 0.00) between mean stem heights 0.151a, 0.172b and 0.191c m in CN, UA and SA tracks, respectively. Reasons why the UA and SA tracks had higher stem heights were most likely due to the ability of the foliar fertilizer to increase the nutrient supply causing increased growth. Similarly, there was a significant difference (P-value = 0.005) with number of branches per stem 1.98a, 2,57ab, 2.83b in CN, UA and SA, respectively. There was also a significant difference (P-value < 0.00) between stem diameters 0.0017a, 0.0020b and 0.0021b m between CN, UA and SA tracks, respectively. The reasons for UA and SA tracks having larger stem diameters would also likely be due to the ability of the foliar fertilizer to increase the plants nutrient intake causing amplified plant growth compared to the CN tracks.

Table 4-10. Summary statistics and ANOVA comparison of plant density (PD), stem height (SH), number of branches (NB), and stem diameter (SD) for determining the precision of SA technique relative to the UA with the smart sprayer applying Bravo® and Proline®. Reference was made to CN tracks.

Application (n)	Plant growth parameter	Min	Max	Mean	S.D.	P-value
CN (30)	PD (stems m^{-2})	311	978	585	146	
UA (30)	PD (stems m^{-2})	356	978	628	154	0.416
SA (30)	PD (stems m^{-2})	400	800	586	124	
CN (30)	SH (m)	0.102	0.202	0.151a	0.026	
UA (30)	SH (m)	0.123	0.210	0.172b	0.023	0.000
SA (30)	SH (m)	0.142	0.275	0.191c	0.033	
CN (30)	NB (# branches $stem^{-1}$)	1.00	3.33	1.98a	0.627	
UA (30)	NB (# branches $stem^{-1}$)	1.17	4.83	2.57ab	1.04	0.005
SA (30)	NB (# branches $stem^{-1}$)	1.00	7.00	2.83b	1.22	
CN (30)	SD (m)	0.0012	0.0021	0.0017a	0.0002	
UA (30)	SD (m)	0.0015	0.0024	0.0020b	0.0002	0.000
SA (30)	SD (m)	0.0017	0.0025	0.0021b	0.0002	

Means followed by different letters are significantly different

Results suggested that the application of Bravo®, Proline® and foliar fertilizer significantly increase the floral bud count as compared to CN tracks. The mean values of floral buds per stem were 2.74a, 5.31b, and 7.60c in CN, UA and SA, respectively (Table 4-11). The UA and SA of Bravo®, Proline® and foliar fertilizer increased floral bud formation by 93.8 and 177.4%, respectively over the CN tracks (Table 4-11). Results were similar to that found by Percival and Dawson (2009). Results from the harvested yield collection showed the mean wild blueberry fruit yield was 0.222a, 0.412b and 0.528b kg m^{-2} in CN, UA and SA tracks, respectively (Table 4-11). ANOVA (P-value < 0.00) indicated that the harvested yield was significantly higher in the UA and SA tracks as compared to the CN tracks. The Bravo®, Proline® and foliar fertilizer increased the harvestable yield by 85.6 and 137.8%, respectively over the CN tracks. These results are in accordance with Percival and Dawson (2009) who found that Bravo® fungicide significantly increased harvestable yields. The variance in blueberry fruit yield parameters could have been caused from external factors such as soil properties, insect damage, pollination, winter kill and seasonal or clonal variations other than the Bravo®, Proline® and foliar fertilizer application. The results from this experiment suggest that Bravo®, Proline® and foliar fertilizer is beneficial for increased plant healthiness, stem height, stem diameter, number of branches and floral bud count resulting in an increased harvestable yield.

Table 4-11. 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 smart sprayer applying Bravo®, Proline® and foliar fertilizer. Reference was made to CN tracks.

Application (n)	Plant yield parameter	Min	Max	Mean	S.D.	P-value
CN (30)	FB (# buds stem^{-1})	0.67	6.33	2.74a	1.39	
UA (30)	FB (# buds stem^{-1})	1.67	16.00	5.31b	3.12	0.000
SA (30)	FB (# buds stem^{-1})	2.33	17.33	7.60c	3.71	
CN (30)	YD (kg m^{-2})	0.046	0.59	0.222a	0.134	
UA (30)	YD (kg m^{-2})	0.100	0.96	0.412b	0.199	0.000
SA (30)	YD (kg m^{-2})	0.086	1.37	0.528b	0.313	

Means followed by different letters are significantly different

4.4 CONCLUSIONS

The developed smart sprayer with comparison of front versus rear mounted cameras showed non-significant differences in spot-applications. The travel speed of 6 km h^{-1} gave the PC enough time to grab the image from the camera and allow the software to process the images sending triggering signals fast enough to open the nozzles and spray at the proper location required. The cameras mounted 0.18 m ahead of the nozzles performed accurately in detecting and spot spraying at the targets. The rear mounted sprayer eliminated the front boom and other hardware accessories, and made the smart sprayer robust, cost-effective, compact and user friendly. Additionally, the rear cameras allowed for better precision when spraying curvy fields due to shorter sensor to discharge distance. Spray savings using the front and rear mounted camera vision system for spot-application to blueberry plant foliage was 7.2% and 14.33%, respectively. These result could allow wild blueberry production to be more profitable as well as environmentally sustainable.

Chateau® savings with SA ranged from 77.4 to 80.3% based on moss coverage within the field. Chateau® did not show any significant difference on harvestable yield among the three applications. Results suggested that there is an utmost importance in insuring that the er herbicide is being applied at the proper rate at the proper timing and also with favorable weather conditions.

The Bravo®, Proline® and foliar fertilizer savings with SA ranged from 10.0 to 12.6% based on bare spot coverage within field. Bravo®, Proline® and the foliar fertilizer did not show any significant difference on plant density however, stem height, stem diameter and number of stem branches all were significantly higher with the application applied. The percentage of healthy plants was higher by 41.0 and 57.8% points for UA and SA, respectively over the CN. There was a significant increase in floral buds with both UA (93.8%) and SA (177.4%) of Bravo®, Proline® and foliar fertilizer as compared to CN. There was also a significant increase in harvestable yield by 85.6 and 137.8% for UA and SA, respectively over the CN.

The SA savings while using the smart sprayer have a direct impact on farmers input costs associated with the agrochemical application. The smart sprayer equipped with rear mounted sensing system has a great potential to reduce the farmers input costs and increase farm profitability of the wild blueberry growers.

Results of extensive evaluations, comparison of smart sprayer equipped with front and rear sensing boom and chemical savings via spot-applications showed great potential for adoption of this technology by wild blueberry growers. However, the growers were keen to know the potential savings in comparison with the existing sprayer systems to set a base line for cost reduction to grow wild blueberries. In order to address this challenge, three sprayer systems *i.e.,* smart sprayer, basic and swath control, were compared for chemical saving to give farmers an idea of cost reduction in relative sense, for the ease of understanding the technology benefits for the evolving agriculture sector. Details on the comparison of different spraying systems are discussed in Chapter 5.

CHAPTER 5 ECONOMIC ANALYSIS FOR SMART SPRAYER APPLICATION IN WILD BLUEBERRY FIELDS

The wild blueberry industry is spending over $80 million CAD per year on agrochemicals for 93,000 ha under production in North America. A pressing need to reduce agrochemical usage and production cost has resulted in the development of a smart sprayer for spot-application of agrochemicals in wild blueberry fields. This study encompasses the economic analysis to determine the potential savings for spot-applications of agrochemicals using a smart sprayer. The economic analysis compared the smart sprayer with two other commercially available sprayers (basic and swath control).

The swath control sprayer and smart sprayer both featured GPS auto-steer and boom section control to reduce over-spray in already applied areas based on GPS position. The basic sprayer used a foam marker for guidance with no swath control management. The smart sprayer featured a machine vision system that automatically detected target areas in the field further reducing agrochemical input buy shutting individual nozzles off in non-target areas in the field. The cost analysis was performed to compare the different features of the sprayer technologies, i.e., base sprayer, additional technology, training, usage, repair and maintenance. The additional components installed on the smart sprayer were justified in terms of agrochemicals/water savings via spot-applications, tractor fuel and operator's time.

The application total cost was $2052 ha^{-1} using the basic sprayer, $1799 ha^{-1} using the swath control sprayer, and $1138 ha^{-1} using the smart sprayer over a two year production cycle of the selected fields that were used in this study. The payback period ranged from 2.0 years (60 ha field size) to 9.8 years (20 ha field size) using the swath control sprayer. The payback period ranged from 11 months (60 ha field size) to 3.5 years (20 ha field size) when using the smart sprayer. Results revealed that the smart sprayer had significant advantage from both an environmental and economic perspective over the other two sprayers.

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5.1 INTRODUCTION

Wild blueberry (*Vaccinium angustifolium* Ait.) fields use agrochemicals to sustain high yielding crops (Yarborough, 2004). These agrochemicals are applied uniformly using commercially available sprayers, hence ignoring the substantial variations in field and crop characteristics. The wild blueberry industry has set a goal to reduce agrochemical usage by 20% to 40% (Zaman 2011). Wild blueberries are typically managed on a two year production cycle with the majority of herbicides being applied during the first year (vegetative growth stage) and insecticides during the second year (fruit production stage). Fungicides are applied during both years of production (Anonymous 2015). Kerb™ herbicide is sometimes applied in late fall after harvest or in early spring of the vegetative year when the blueberry plants are dormant (Burgess et al. 2014). Propyzamide is used for advanced control of mainly fescue grass and broadleaf weeds including red sorrel (Burgess 2015). In central Nova Scotia, a tank mix of hexazinone (Velpar®) and terbicil (Sinbar®) herbicide is commonly used for pre-emergence weed and grass control (Burgess 2015). Metzger and Ismail (1977) reported that a newly developing field can have 20 to 40% wild blueberry cover. Zaman et al. (2008) estimated 30 to 50% wild blueberry cover in developing fields. Wild blueberries spread slowly by rhizomes underneath the soil surface and prefer grass or weed shaded ground as compared to barren soil for effective growth (Kender and Eggert 1965). Producers apply herbicides uniformly on both blueberry plants and bare soil areas of the field, which not only increase the production cost but also contaminate the environment via leaching, runoff and erosion (Zaman et al. 2010). Spot-application of pre-emergence herbicide to wild blueberry plants allows the crop to flourish weed-free. Not targeting bare soil can encourage native species of grasses or weeds to occupy the bare ground limiting soil erosion, keeping the organic matter and promote the spread of the wild blueberry rhizomes (Morrison et al. 2000). Mesotrione (Callisto®) and fluazifop-P-butyl (Venture®) selective contact herbicides are commonly tank mixed in June for post-emergence suppression of weed and grass species (Boyd and White 2010; Boyd et al. 2014). Spot-application of mesotrione and fluazifop-P-butyl herbicide solely in the target areas has potential to significantly reduce herbicide with effective weed and grass control. Tank mix fungicide applications of Bravo® and prothioconazole (Proline®) in July of the vegetative year for control of *Septoria* (leaf spot) and *Thekopsora minima* (blueberry rust) can be reduced by applying spot-specifically only to the blueberry plants (Esau et al. 2013; Percival and Dawson 2009). In the crop year, propiconazole (Topas®) fungicide is applied in late May and/or early June for control of *Monilinia vaccinia-corymbosi* (*Monilinia* blight) (Percival and Dawson 2009). Chlorothalonil may also be applied a second time in June of the crop year depending on the disease potential within the field (Cote et al, 2015). Pristine™ is typically a last fungicide applied in June of the crop year to control *Septoria* spp. (valdensinea leaf spot) and blueberry rust (Annis and Stubbs 2004). Blueberry maggot will contaminate blueberry fruit, so fly traps are set in

July to estimate the infestation levels and spray acetamiprid (Assail®) insecticide if required (Renkema et al. 2014).

Sprayers used in the wild blueberry industry range from hand wand backpack models up to large 36.6 m wide self-propelled models. Studies have shown that the foam marker guidance systems can have error factors of up to 10% of the sprayer boom width (Ehsani et al. 2004). Wild blueberry fields are naturally developed and typically situated on rough terrain with gentle to severe topography (Zaman et al. 2010). Keeping the sprayer nozzles close to the blueberry canopy without coming in contact with the uneven terrain and maneuvering over/around rocks, hills, trees or other obstacles in the field can be very challenging. A combination of the latest precision agriculture technologies and farmer's knowledge of proper spraying procedures can improve the effectiveness of agrochemical applications (Doruchowski and Holownicki 2000). Smart sprayer machine vision technology and tractors equipped with auto-steer GPS guidance systems could be an ideal way for wild blueberry farmers to precisely travel the rough land without overlapping each spray boom pass. Early versions of auto-steer GPS systems have been difficult to use on wild blueberry ground, because travelling on a side slope, the GPS position was offset resulting in either over- or under-spraying. Many advanced GPS guided auto-steer systems now have a built in gyroscope to allow for proper GPS co-ordinate correction compensation based on the tilt angle of the tractor (Gomez-Gil et al. 2011). A gyroscope for tilt sensing may not be as important on flat agricultural ground but essential for the rough wild blueberry fields (Zaman et al. 2010). One of the most affordable types of GPS guidance is a light bar which involves a small display with arrows and embedded lights that visually guide the operator down each spray swath (Griffin et al. 2005). The light bar system is an affordable option, however, it does involve human error and requires more skill by the operator to drive effectively with accuracy as high as +/- 0.1 m (Griffin et al. 2005). Typically drivers are required to look behind, to ensure the boom is at proper height off the ground and to avoid collisions with obstacles, which can result in operator error. The human errors in a GPS auto-steering system can be reduced by automating the tractor steering system. Several tractor manufacturers now offer auto-steering as a factory option or farmers can choose from a variety of other companies that are now selling bolt-on kits. Auto-steering only offers command/control while the tractor is travelling along the sprayer swath paths, which is considered as one of the limitation to these systems. The operator is required to manually steer the tractor around corners and the auto-steer will start up and continue to steer along the next adjacent swath path. Research has been conducted to fully automate the tractor, however, further testing is required for spraying in rough wild blueberry fields (Pérez-Ruiz et al. 2015).

Advanced flow rate controllers are an important technology for precision spraying (Giles and Comino 1990). Original sprayers were designed to operate at a constant pressure given the number of nozzles and a set travel speed (Paice et al. 1995). Calibration consisted of determining the volume of spray being applied over a set period of time (Hoeg 2015). The operator is required to travel at a consistent speed when applying agrochemical to the field. Lower tractor speed due to maneuvering around corners and obstacles causes error which results in excess product application. Spray controllers have been designed to keep the application flow rate consistent with respect to ground speed (Giles and Comino 1992). The control systems are linked either to a wheel speed sensor or a GPS to compensate flow rate with the changing ground speed. Another advanced feature of newer flow rate controllers is the ability to automatically turn off boom sections to avoid overlap of application. Minimum overlap is achieved using an onboard GPS (Batte and Ehsani 2006). This technology has proved to be an effective option for famers to reduce production cost, minimize crop damage due to over-application, and mitigate environmental risks (Batte and Ehsani 2006; Burgess 2015).

In addition to advanced flow rate controllers and GPS guidance systems, some companies offer sensors that provide automatic green foliage detection and spray selectively (Michielsen et al. 2010). Gerhards and Oebel (2006) concluded that site-specific weed control offers farmers huge potential for herbicide reduction. Esau et al. (2014b) tested a prototype smart sprayer for spot-application of agrochemical in wild blueberry fields. However, the economic analysis of this smart sprayer has never been performed. The objective of this study was to conduct an economic comparison of a basic sprayer versus a swath control and a smart sprayer.

5.2 MATERIALS AND METHODS

5.2.1 Parameter Comparison between a Basic Sprayer, Swath Control Sprayer and a Smart Sprayer.

Two electronically advanced precision sprayers were compared to a standard non-precision (basic) sprayer in this study (Table 5-1). Each three point hitch mount sprayer featured a 13.7 m wide self leveling x-fold hydraulic boom, with a 1135 L capacity polyethylene tank and standard pump and hose configuration mounted to a 75 kW farm tractor with enclosed cab (Fig. 5-1). The basic sprayer used a factory installed foam marker drop kit for guidance, while the swath control and smart precision sprayers were equipped with an RTK-GPS controlled autosteer guidance system. The foam marker guidance system were assumed to have an overlap error of 9% of the boom width with each pass across the field (Ehsani et al. 2004). The operators using an RTK-GPS controlled autosteer system were able to concentrate their efforts in keeping the boom at a safe distance off the ground as the tractor accurately manoeuvers across the field with negligible overlap error. The RTK-GPS controlled autosteer system installed on the precision sprayers was also assumed to have a tilt sensor correction to compensate for travel over steep sloped areas in the field. The basic sprayer used in this study operated at a constant line pressure with no nozzle or separate boom section control. The calibration of the basic sprayer required the operator to measure the output flow volume over a set distance and travel speed. After calibrations, the tractor operator was required to travel at a constant ground speed in the field to maintain a consistent output flow rate. Maintaining a constant ground speed is a difficult task in traditional wild blueberry fields because of the rough and unpredictable nature of the field layout resulting in over or under-application of agrochemical. A MLC was used on both the swath control and smart sprayers which allowed the user to calibrate the flow rate more easily and without the requirement to travel at a constant velocity across the field (Esau et al. 2014b).

Figure 5-1: Precision sprayer mounted on farm tractor.

Each sprayer consisted of 27 nozzles on a sprayer boom, spaced at a standard 0.5 m apart. The non-precision basic sprayer consisted of a manually controlled on/ off boom switch that controls the entire boom as a whole. The swath control sprayer uses features built into the flow rate controller that is able to shut off three sections of the boom individually with an inline solenoid valve. Each section of the boom (4.57 m) controlled nine spray nozzles. Using the GPS attached to the flow rate controller, the swath manager has the ability to shut off each boom section individually once the boom is positioned in an already sprayed area in the field. They turn back on automatically once a non-sprayed zone is entered. This feature allows the operator to drive around obstacles with lower stress and avoids overlap/overspray into other spray tracks. Similarly the smart sprayer using an accurate GPS guidance system has control of boom sections. The solenoid valve positioned directly on each sprayer nozzle body allows for individual nozzle control with negligible overlap and drip. Another advantage of the smart sprayer is the ability to detect target areas within the field for spot-applications of agrochemicals.

Wild blueberry fields are highly variable consisting of randomly distributed weed, grass and bare soil patches. The built in real-time machine vision system was programmed to detect the target areas and rapidly send triggering information to the corresponding solenoid valve, opening the nozzle in the precise location where a target has been detected. If the sprayer passes over a non-target area in the field, the corresponding nozzles will automatically shut off and agrochemical will not be wasted. For this study, the sprayer operating speed was 6 km h^{-1} with an application flow rate setpoint of 187.1 L ha^{-1} (Table 5-1). For adequate wild blueberry field management, each sprayer type required nine separate agrochemical applications to each field. Three of the applications were herbicide (propyzamide, hexazinone/terbicil tank mix, mesotrione/fluazifop-P-butyl tank mix), five were fungicide (chlorothalonil, chlorothalonil/prothioconazole, propiconazole, propiconazole, boscalid/pyraclostrobin) and one was insecticide (acetamiprid).

Table 5-1. Parameter comparison between a basic sprayer, swath control sprayer and a smart sprayer.

	Basic sprayer	**Swath control sprayer**	**Smart sprayer**
Boom width (m)	13.7	13.7	13.7
Guidance	Foam marker	Auto steer (RTK-GPS)	Auto steer (RTK-GPS)
Swath overlap	9% of boom width (1.23 m)	Negligible	Negligible
Swath control	Constant pressure system with manual on/off switch control for combined 27 nozzles spaced at 0.5 m	Automatic overlap control of three equal width boom sections each with nine nozzles spaced at 0.5 m	Automatic overlap control of each of the 27 nozzle's spaced at 0.5 m. Machine vision to control spot-application on target only locations in the field using custom controller
Flow rate controller	Manual throttling valve for pressure adjustment	GPS controlled flow valve and flow meter for feedback control	GPS controlled flow valve and flow meter for feedback control
Application speed (km h^{-1})	6	6	6
Application flow rate (L ha^{-1})	187.1	187.1	187.1

5.2.2 Cost Comparison between a Basic Sprayer, Swath Sprayer and Smart Sprayer.

The initial purchase price of the basic sprayer (not including farm tractor) used in this comparison was $15,000 CAD, which included the price of the foam marker kit. Adding the additional RTK-GPS auto steer control and swath manager is estimated to double the initial cost to $30,000. The addition of the machine vision system on the smart sprayer increased the price an additional \$10,000 for an initial purchase price of \$40,000 (Table 5-2). The basic sprayer using foam marker for guidance required an addition of a 23.8 L poly tank for holding the foam marker concentrate. Thirty minutes were required for refilling and mixing pesticide in the sprayer tank. The additional cost for operating the basic sprayer is approximately \$150 for foam marker concentrate depending on the amount of land covered and the travel speed. Extra expenses each year for operating the swath control and smart sprayer include an RTK-GPS correction subscription, solenoid valve and various other electrical component servicing. For the swath controlled sprayer, the additional cost was estimated to be approximately \$1500 per year, whereas the smart sprayer with the added machine vision costs approximately \$2000 per year due to the added solenoid valves and electronic components. The additional costs, not included in Table 5-2, could comprise of licensing software fee that may be required for the image processing. The diesel cost of \$1.35 L^{-1} was used with an average consumption rate of 15 $L\ h^{-1}$ for this study. The operator of the sprayer was assumed to have an hourly wage of \$16.

Table 5-2. Cost comparison of different components of basic, swath control and smart sprayer systems used in this study.

Parameter	Basic sprayer	Swath control sprayer	Smart sprayer
Initial cost ($) • 1135 L tank • Diaphragm pump • 13.7 m wide hydraulic self-leveling boom • 27 nozzles	15,000 • Constant speed/ constant pressure • Foam marker	30,000 • Variable speed management • Auto steer using RTK-GPS • Three solenoid valve controlled boom sections • Flow rate controller	40,000 • Variable speed management • Auto steer using RTK-GPS • 27 solenoid valve individual controlled nozzles • Flow rate controller • Machine vision
Additional supplies/ maintenance/ subscriptions required per year ($)	150 • Foam marker concentrate	1500 • RTK-GPS subscription • Swath control solenoid valve servicing/replacement	2000 • RTK-GPS subscription • Nozzle control solenoid valve servicing/replacement • Electronics' servicing/replacement
Diesel fuel price ($ L^{-1})	1.35	1.35	1.35
Diesel fuel consumption (L h^{-1})	15	15	15
Diesel fuel consumption (L ha^{-1})	16.47	16.47	16.47
Operator wage ($ h^{-1})	16	16	16
Tank refill/mix time required (h)	0.5	0.5	0.5
Total machine operating costs ($ ha^{-1})	59	56	44

5.2.3 Simulated Field Comparison between Applications made with a Basic Sprayer, Swath Control Sprayer and a Smart Sprayer.

Two simulated fields each 20 ha in size were created in ArcMap 10 for demonstrating the spraying pattern followed by the three different types of boom sprayers. Field A is a rectangle measuring 973.2 m long and 205.5 m wide (Fig. 5-2a). The operator would typically start spraying the field by completing the perimeter then proceeding to create vertical swath paths within the boundary of the outside initial pass. Field B is a triangle with a base dimension of 583.9 m and a height of 685.0 m (Fig. 5-2b). Similarly the operator would first spray the perimeter of the triangle then continue to spray straight line swathes in the vertical direction until finished. The variability in bare soil and weed patches is illustrated in Figure 5-2. A typical sprayer applies a uniform blanket application across the entire field without taking into consideration this variability. The spot-applications using a smart sprayer based on accurate target detection can save significant amount of agrochemicals, which can lower the production cost and mitigate the environmental risks.

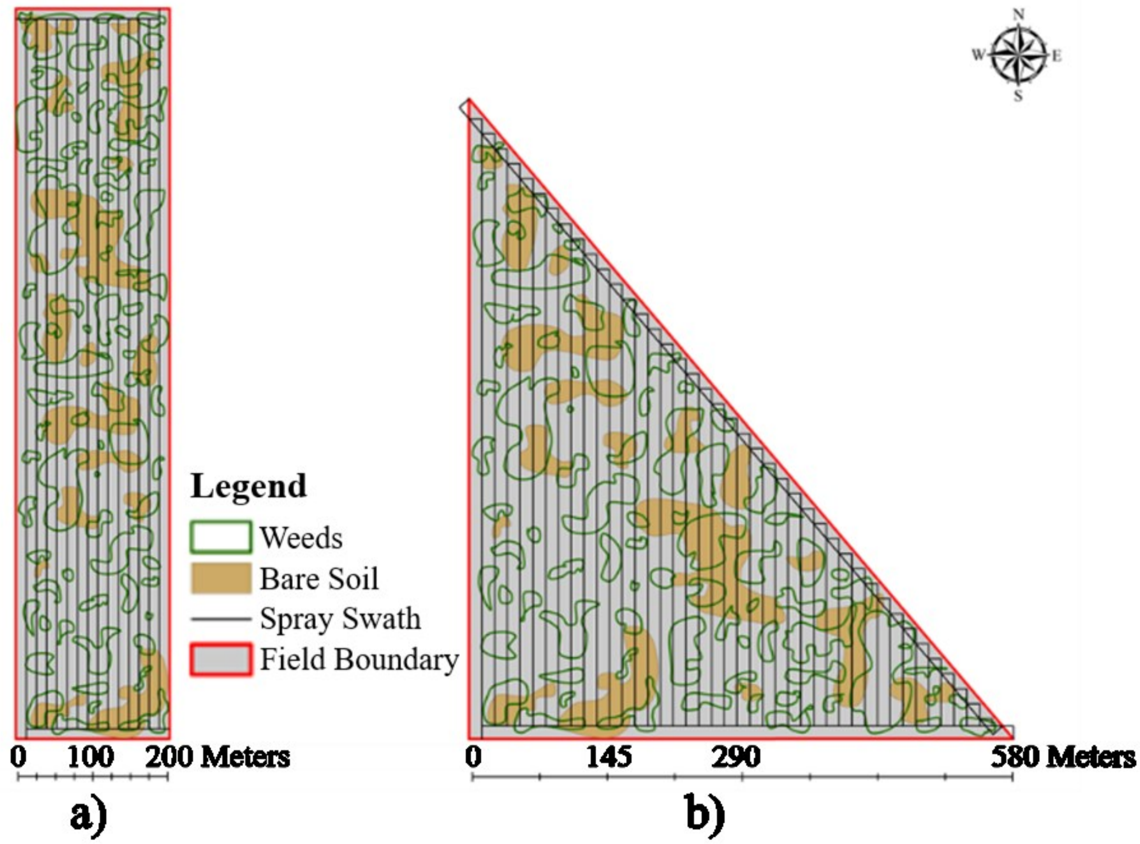

Figure 5-2: Field maps showing two different spray track configurations for a 20 ha area fields composed of 20% bare soil and 30% weed coverage.

5.3 RESULTS AND DISCUSSION

5.3.1 Simulated Field Comparison between Basic Sprayer, Swath Control Sprayer and Smart Sprayer

The 20 ha experimental fields used in this study were estimated to have 20% bare soil and 30% weed coverage (Table 5-3). It is estimated that over the two year production cycle of wild blueberries, it costs approximately \$1735 ha^{-1} for agrochemicals. However, if the agrochemicals are applied spot-specifically on target areas, the cost would reduce significantly to \$1093 ha^{-1}. Additional costs associated with the agrochemical application includes labor, diesel and equipment.

Table 5-3. Agrochemical application costs over two year production cycle.

Agrochemical	Sprayer Pass	Field area (ha)	Application area required (%)	Application area required (ha)	Uniform cost ($ ha-1)	Spot-application ($ ha^{-1})
Propyzamide (herbicide)	1	20	30	6	480	144
Hexazinone & terbicil tank mix (herbicide)	2	20	80	16	460	368
Mesotrione & fluazifop-P-butyl tank mix (herbicide)	3	20	30	6	140	42
Chlorothalonil (fungicide)	4	20	80	16	90	72
Chlorothalonil & prothioconazole tank mix (fungicide)	5	20	80	16	140	112
Propiconazole (fungicide)	6	20	80	16	50	40
Propiconazole (fungicide)	7	20	80	16	50	40
Boscalid/pyraclostrobin (fungicide)	8	20	80	16	250	200
Acetamiprid (insecticide)	9	20	100	20	75	75
Total ($ ha^{-1})					1735	1093

The cost comparison for the three types of sprayers used in this study is shown in Table 5-4. The swath overlap of the basic sprayer each time the operator made a pass across the field was estimated to be 1.23 m, resulting in two extra passes per application as compared to both the swath control and smart sprayer that featured the auto steer system. The operator travelled a total of 15,176 additional meters just in vertical spray distance (not including corners) when using the basic sprayer as compared to the swath or smart control sprayers. The increase in tractor fuel use and operator time were from the additional distance travelled (Table 5-4). Operation of the basic sprayer costs approximately \$1994 ha^{-1} over the two year production cycle as compared to \$1791 ha^{-1} with a swath control sprayer and \$1137 ha^{-1} using the smart sprayer, when total agrochemical application cost (fuel, operator and agrochemical usage) was compared. The swath control sprayer had 10.2% less input cost as compared to the basic sprayer. The smart sprayer had 43.0% less input cost than the basic sprayer for agrochemical applications in field A.

Table 5-4. Agrochemical cost comparison between basic, swath control, and smart sprayer for field A based on nine spray passes.

	Basic sprayer	**Swath control sprayer**	**Smart sprayer**
Swath overlap (m)	1.23	Negligible	Negligible
Number of individual vertical spray tracks	153	135	135
Spray distance travelled (m)	146,563	131,387	131,387
Spray volume (L)	37,568	33,678	• 14,968.0 (fungicide) • 3367.8 (herbicide) • 3742.0 (insecticide)
Overspray area (ha)	20.7	0	0
Overspray volume (L)	3889.8	0	0
Spray tank fills (#)	33.3	29.7	• 13.0 (fungicide) • 3.0 (herbicide) • 3.3 (insecticide)
Spray time (h ha^{-1})	1.9	1.8	• 0.860 (fungicide) • 0.366 (herbicide) • 0.197 (insecticide)
Fuel cost (\$ ha^{-1})	28.8	27	• 13.0 (fungicide) • 5.4 (herbicide) • 3.0 (insecticide)
Operator cost (\$ ha^{-1})	30.6	28.8	• 14.0 (fungicide) • 6.0 (herbicide) • 3.2 (insecticide)
Agrochemical cost (\$ ha^{-1})	1935	1735	• 464 (fungicide) • 554 (herbicide) • 75 (insecticide) • 1093 (total)
Application total cost (\$ ha^{-1})	1994	1791	• 491 (fungicide) • 565 (herbicide) • 81 (insecticide) • 1137 (total)
Application total savings (%)	0	10.2	43.0

Additional agrochemical application cost savings can arise for farmers by replacing a basic foam marker single boom section sprayer with a smart sprayer, especially when their fields are irregular shaped such as the triangular field B (Fig. 5-2b). The operator first travels the perimeter of the field and over-spraying or wasting application on angles that are made when not spraying square edged parts of the field perfectly (Fig. 5-3a). Furthermore, because of the 1.23 m overlap for each pass using the basic sprayer, the operator is over-applying on one side of the boom width. The over-spraying implications were reduced significantly by adopting an RTK-GPS controlled auto-steer system. Results of map comparison showed negligible overlap between consecutive spray tracks (Fig. 5-3b). The reduction in agrochemical application was also witnessed with the automatic swath manager function, which helps to shut off boom sections once they reach already-sprayed areas of the field. A further reduction in agrochemical spraying can be achieved by increasing the number of boom sections of the automatic swath system.

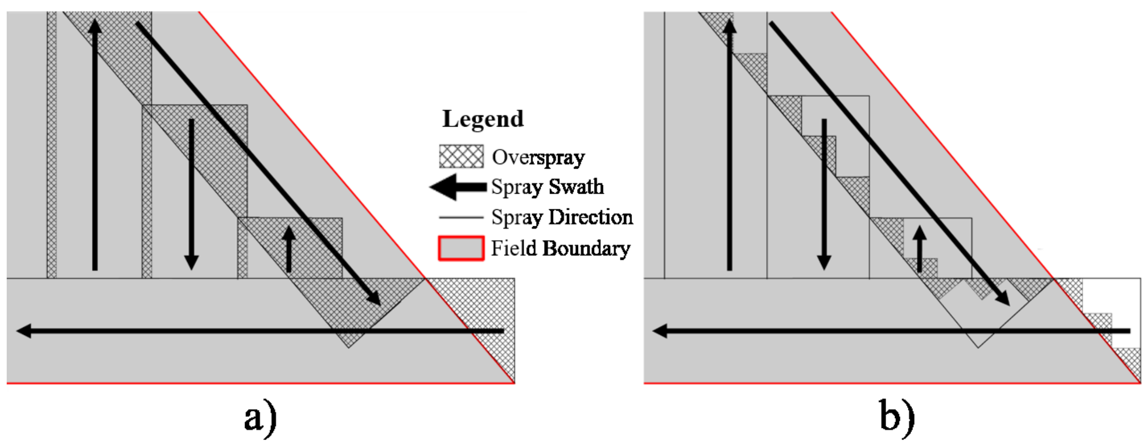

Figure 5-3: Field B close-up map showing travel direction and spray overlap using basic sprayer (a) and swath control sprayer (b).

The distance travelled while using the basic sprayer to spray field B increased by 8588 m as compared to field A because of the irregular shape of field B, although both fields had the same area (Table 5-5). The distance travelled while using the swath control sprayer and smart sprayer for field B increased by 11,435 m as compared to field A. Results reported that the basic sprayer was required to travel across field B 414 times, while the swath and smart sprayers only required 369 passes over the nine applications required. The operator travelled a total of 12,329 additional meters in vertical spray distance (not including corners) when using the basic sprayer rather than the swath or smart control sprayers on field B. Each application resulted in an overspray volume of 304.8 L ha^{-1} using the basic sprayer and 13.5 L ha^{-1} using the swath control sprayer as compared to 0 L ha^{-1} overspray using the smart sprayer. The total application cost was increased over field A by \$116 ha^{-1} when using the basic sprayer and \$16 ha^{-1} using the swath control sprayer and \$2 ha^{-1} using the smart sprayer. The total application cost was \$2110 ha^{-1} when using the basic sprayer, \$1807 ha^{-1} when using the swath control sprayer, and \$1139 ha^{-1} when using the smart sprayer. The swath control sprayer had 14.4% less input cost as compared to the basic sprayer. The smart sprayer required 46.0% less input cost than the basic sprayer for agrochemical applications applied to field B. The training required to operate the swath control and smart sprayer may require reading the operator's instructions manual (approx. 1-2 h) to understand how to use the flow rate control and the machine vision software interface. An additional 1-2 h of preliminary operational practice with the added control systems (touch screen interface for camera control, flow rate controller) may also be required for beginners. Additionally, a flow meter correction may be required for the first time which can take up to 1 h depending on the volume of water used for calibration.

Table 5-5. Agrochemical cost comparison between basic, swath control, and smart sprayer for field B based on nine spray passes.

	Basic sprayer	Swath control sprayer	Smart sprayer
Swath overlap (m)	1.23	Negligible	Negligible
Number of individual vertical spray tracks	414	369	369
Spray distance travelled (m)	155,151	142,822	142,822
Spray volume (L)	39,770	33,947	• 14,968.0 (fungicide) • 3367.8 (herbicide) • 3742.0 (insecticide)
Overspray area (ha)	32.6	1.4	0
Overspray volume (L)	6095.7	269.1	0
Spray tank fills (#)	35.1	29.7	• 13.5 (fungicide) • 3.0 (herbicide) • 3.3 (insecticide)
Spray time ($h\ ha^{-1}$)	1.97	1.86	• 0.91 (fungicide) • 0.40 (herbicide) • 0.207 (insecticide)
Fuel cost ($\$\ ha^{-1}$)	29.7	27.9	• 13.5 (fungicide) • 6.0 (herbicide) • 3.1 (insecticide)
Operator cost ($\$\ ha^{-1}$)	31.5	29.7	• 14.5 (fungicide) • 6.3 (herbicide) • 3.3 (insecticide)
Agrochemical cost ($\$\ ha^{-1}$)	2049	1749	• 464 (fungicide) • 554 (herbicide) • 75 (insecticide) • 1093 (total)
Application total cost ($\$\ ha^{-1}$)	2110	1807	• 492 (fungicide) • 566 (herbicide) • 81 (insecticide) • 1139 (total)
Application total savings (%)	0	14.4	46.0

5.3.2 Sprayer Payback Period and Benefits of Precision Agriculture Technologies to the Wild Blueberry Industry

Real-time spot-application is the most effective way of applying agrochemicals in wild blueberries. Incorporation of the precision agriculture technologies to existing sprayers can enable the sprayer to operate spot-specifically, thereby eliminating the need to purchase a new sprayer. The payback period for the swath control sprayer used in this study ranged from 2 to 1000 years over a farm size of 10 to 60 ha. For the smart sprayer, the payback ranged from 0.92 to 8.8 years based on field sizes from 10 ha to 60 ha. Results suggested that the larger growers can have their technology upgrades paid back more rapidly. One of the contributing factors in the payback period is the additional \$1500 $year^{-1}$ fee for using the swath control technology and approximately \$2000 $year^{-1}$ for the smart sprayer. Results suggested that wild blueberry producers with field sizes of 20 ha or larger can benefit greatly with the added technology. Farmers with field variability in weeds and bare soil coverage within the field can benefit from upgrading to a smart sprayer with a payback period of only 2 years with a 30 ha field as compared to almost 5 year with using only a swath control sprayer (Table 5-6).

Table 5-6. Payback period for application with an irregular shaped wild blueberry field.

Field area* (ha)	Swath control sprayer payback (yr.)	Smart sprayer payback (yr.)
10	1000	8.8
20	9.8	3.5
30	4.9	2.0
40	3.3	1.4
50	2.5	1.1
60	2.0	0.92

*split production years with half in sprout and half in crop per year

5.4 CONCLUSIONS

The three boom sprayers used in this study had agrochemical application costs ranging from \$1137 ha^{-1} to \$2110 ha^{-1} over a two year production cycle of a typical wild blueberry field. The average savings by using a swath control sprayer was 12.3% in the 20 ha fields in this study. The smart sprayer was able to save 44.5% input cost as compared to the basic sprayer used in this study. The extra cost required to purchase the equipment can be offset by applying less inputs with a payback period of 2 years for a swath control sprayer and less than 1 year with a smart sprayer with a field size of 60 ha or more. Farmers with field sizes of 20 ha or greater should consider a swath control type sprayer while those with significant weed and bare soil variability within fields should consider smart sprayer for spot-application of agrochemicals. Extra time may be initially required for training on use of the technology but results showed the potential of time saving while applying agrochemicals and the reduced trips to refill sprayer tank. Further research could involve testing a sprayer with a lower cost GPS and light bar guidance to determine if there are benefits for growers that have smaller-sized fields. Spot-applications have great potential to reduce production cost with the aided advantage of reducing environmental risks.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The overall goal of this study was to develop and evaluate a smart sprayer for spot-application of agrochemicals for wild blueberry production. An integrated automated system comprising of µEye digital color cameras, a ruggedized PC, a touchscreen monitor, custom image processing software, a VRC, a GPS, a MLC, servo valves, flow meters and individual nozzle control using solenoid valves was developed. The developed system (hardware and software) was incorporated onto a traditional sprayer along with the farm tractor for real-time spot-application of selected agrochemicals primarily used for wild blueberry production.

The key smart sprayer components were tested in the DAL-AC lab, prior to perform commercial applications in selected wild blueberry fields. Results of calibrations, performance testing, GIS mapping and field measurements revealed that the developed smart sprayer was an effective method for spot-applications of agrochemicals in wild blueberry production. Results confirmed that the smart sprayer system was more cost-effective and easier to operate with cameras mounted on the rear-sprayer boom rather than using an extra front sensor boom. The rear mounted machine vision system was able to operate fast enough to open spray nozzles with a distance of 0.18 m between the camera and the spray nozzle. Field results showed many benefits of spraying spot-specifically as compared to the conventional uniform blanket applications that end up wasting agrochemical in non-target areas such as bare soil areas in the field.

The smart sprayer performed well and adequately sprayed only on weeds (red sorrel and moss) within the selected wild blueberry fields. Results of WSPs randomly placed in target and non-target areas revealed that the spray coverage from spot-application was non-significantly different from UA in target-areas. The spot-application spray coverage was significantly lower in non-target areas when compared with UA. The spot-application resulted in a 69% reduction in chemical application with the red sorrel coverage of 28%, and with 25 cm before and after target buffer for complete application overlap.

Results of adding a light source to the machine vision system allowed the smart sprayer to operate after dark widening the application window for farmers to apply agrochemicals in low wind conditions to avoid drift affects. Polystyrene diffuser sheets were used to eliminate the hot spots created by the artificial lights. After extensive testing of the various light sources in lab, Magnafire 70 W HID lights were selected for the light source of choice because of the wide angle of even light illumination, high intensity and the lights rugged construction. The light source field test during night conditions showed that the smart sprayer saved 65% agrochemicals via targeted applications only on weeds.

Comparison of front versus rear mounted machine vision systems showed that the image processing and mechanical delay time of the flow control system was rapid enough to apply at target locations while travelling at ground speeds of 6 km h^{-1}. The added cost savings by eliminating the front boom and other accessories and conversion into a smart sprayer equipped with sensing system on the rear boom, beside spray nozzles, was an essential element for a commercial marketable product. The front boom initially was required for the image processing time, however, increase in computing capabilities enhanced the processing speeds, allowing the elimination of the front boom, making the smart sprayer compact and user friendly. Operators found that the added front sensor boom was cumbersome to maneuver in many of the rough blueberry fields. The elimination of the front sensor boom allowed the operator to concentrate on the single rear sprayer boom while spraying. The reduced sensor to discharge distance (6.6 m to 0.18 m) allowed the smart sprayer to begin properly targeting when first opening up the field to spray. The nozzle spacing was also modified from the original 0.76 m to the industry standard of 0.51 m allowing for the smart sprayer components to be easily retrofitted on an existing sprayer based on the similar nozzle spacing.

Rear mounted cameras were fast and accurate enough to apply agrochemical (Chateau®) spot-specifically, saving 77.4 to 80.3% agrochemical in non-target areas within selected fields. Non-significant differences in the yield was observed with SA and UA applications. Moss density collection revealed that the Chateau® being applied by SA or UA did not effectively lower moss density as compared to the non-treated CN. Results suggested that the moss density was the lowest during the spring most likely due to winter kill. A possible factor that could have contributed to the ineffectiveness of the herbicide is unfavorable weather conditions after application, causing the herbicide to leach into the soil or being evaporated into the air rather than staying on the surface to be used to eradicate the moss species.

Bravo®, Proline® and foliar fertilizer savings with SA ranged from 10.0 to 12.6% based on bare spot coverage within the selected fields. Plant density was not effected by the application of Bravo®, Proline® and the foliar fertilizer, however, stem height, stem diameter and number of stem branches were significantly higher with the application of foliar fertilizer applied. Wild blueberry plant health was higher by 41.0 and 57.8% points for UA and SA, respectively over the CN. There was a considerable increase in floral buds with both UA (93.8%) and SA (177.4%) of Bravo®, Proline® and foliar fertilizer as compared to CN. There was also a significant increase in harvestable yield by 85.6 and 137.8% for UA and SA, respectively over the CN.

An economic analysis comparing a basic sprayer to both a precision swath control sprayer as well as the proposed smart sprayer gave the perspective cost benefits of the technology. The wild blueberry industry is spending over $80 million CAD per year on agrochemicals in North America on a uniform basis. The development and advancement of technologies that reduce the amount of agrochemical applied can have an acceptable payback period even with small field sizes. GPS guided auto steer on spray tractors enables inexperienced operators to travel the rough blueberry ground with confidence, knowing the overlap or underlap of consecutive spray swaths is minimized. Many producers and farm managers have already found that the foam markers systems used for guidance are troublesome and expensive to maintain and without an experienced operator they don't guarantee proper spray coverage. A cost analysis comparing the different features of the sprayer technologies, i.e., base sprayer, additional technology, training, usage, repair and maintenance showed promising results for the future of precision sprayer components. The application total cost was $2052 ha^{-1} using the basic sprayer, $1799 ha^{-1} using the swath control sprayer, and $1138 ha^{-1} using the smart sprayer over a two year production cycle of the selected wild blueberry fields, selected for this study. The payback period ranged from 2.0 years (60 ha field size) to 9.8 years (20 ha field size) using the swath control sprayer. The payback period ranged from 11 months (60 ha field size) to 3.5 years (20 ha field size) when using the smart sprayer. These results revealed that the smart sprayer had significant advantage from both an environmental and economic perspective over the other two sprayers. Overall, the results of this study concluded that the developed smart sprayer was accurate, cost-effective and reliable in detecting targets (weeds, plant and bare spots) and spot spraying on as need basis. Results of evaluations confirmed the potential of significant agrochemical savings via spot-applications, which not only reduce the production cost but also increase farm profitability of the wild blueberry industry. Additionally, implementation of this smart sprayer at large scale can ensure environmental sustainability.

6.2 RECOMMENDATIONS

Results of this study emphasize the need for commercial technologies and techniques that reduce the amount of agrochemical applied to wild blueberry fields. Environmental regulation on agrochemical usage is continuously growing stricter. Exported fruit must also meet the required maximum residual level limits in the market place to provide safe food to the consumer. The producer has the essential responsibility to ensure that the wild blueberries they grow meet the export regulation guidelines. Spot-application of agrochemical can be a helpful tool for farmers to apply the necessary agrochemicals to maintain their crop and still meet the strict export maximum residual level limits.

Further improvements can be made to the image processing software by modifying the textural analysis algorithm to include shape feature recognition for wider applications. This feature could improve the in-season accuracy for discrimination of different weed and grass species. Other improvements could be adding a streamlined graphical interface that allows the user tabs that adjust the content being displayed on the screen. It would be essential for the commercial application to have software with the ability to be user programmable allowing for the increase or decrease in number of smart sprayer cameras based on the sprayer boom width.

This study was designed for the wild blueberry industry but the same technology could be applied in other cropping system that require spot-application at specific target locations. Farmers growing row crops looking to reduce the amount of herbicide application to non-target areas could benefit from adaptation of the smart sprayer technology. A technology transfer may be applicable for golf courses that need spot-treatment of different herbicides, fungicides or fertilizers based on the conditions of different fairways and greens.

6.3 CONTRIBUTIONS TO KNOWLEDGE

This PhD thesis presents the development and field evaluation of a smart sprayer system for the wild blueberry cropping system. An integrated machine vision system with custom image processing software equipped with a custom control box and fast acting solenoid valves for individual nozzle control was developed and mounted on a farm tractor for spot-applications of agrochemicals. Many researchers have tested spot-sprayers for a variety of different crops. However, the wild blueberry cropping system has had little focus from a research and development perspective of smart spraying technologies.

An engineering design process was utilized that started with defining the problem of excess agrochemicals being applied uniformly to wild blueberry fields. Idea generation and brainstorming involved a literature search of related technology used to address over application of agrochemicals in non-target areas in other cropping systems. A list of possible solutions to the problem was developed and after choosing the most feasible option, a prototype was developed based on the design criteria. The prototype was tested and evaluated with a series of lab and field tests. After a sequence of refinements and re-evaluations, each step of the engineering design process has been an important stage in improving the design and functionality of the smart sprayer system. The original smart system involved an added front sensor boom and a complex series of cabling and control systems. The smart sprayer was refined by removing the front boom and eliminating many of the extra wiring and components by developing a remotely mounted custom solenoid relay control box. The smart sprayer system in its latest stage is fairly simplistic in terms of components required for converting from a typical commercial agricultural boom sprayer. This simplification and refinement of the smart sprayer through the various stages of the engineering design process have led to a unique and practical solution for spot-applications of agrochemical for the wild blueberry cropping system.

A few decades ago many wild blueberry fields could be grown without the need for intense and precise herbicide and fungicide applications. However, with some weed and grass species becoming more resistant to herbicide applications and the increased yields from fungicide applications, the farmers are applying more and more inputs to their fields. At the same time many farmers are realizing the issues with uniform blanket applications that can lead to soil erosion and environmental contamination. The uniform application of agrochemical is also costing the North American wild blueberry industry a significant amount of money ($80 million CAD per year). Some of the largest horticultural producers and processors in Atlantic Canada have set the goal of reducing agrochemical input by 20 to 40% to remain competitive in the global economy. This trend has sparked its initiative to develop a smart sprayer technology to lower the amount of inputs while still maintaining maximum output yields.

Knowledge of the various components included with the smart sprayer could be adapted for use and application for other cropping systems for lowering input requirements. The same technology could be adapted for use with fertilizer spreaders to apply more appropriate rates based on the real-time field variations that commonly exist. A database collected from the smart sprayer could be compiled each year to determine the effectiveness of the agrochemicals being applied. The data could also be compared to yield maps to determine relationships between the different inputs, and their impact on the yield to propose best management practices.

The wild blueberry industry aims to increase harvestable yields at lower production cost, which can be achieved by adopting this technology. This PhD project is unique, as it directly addresses one of the major industrial problems. This research has found that spot-applications of agrochemicals on target locations has the ability to increase harvestable yields while at the same time lowering agrochemical inputs. Results has shown a significant reduction in producer cost required for agrochemical input using the smart sprayer as compared to the uniform amounts of agrochemicals applied on commercial wild blueberry fields. Adoption of this smart sprayer for commercial agrochemical applications can increase profit margins for wild blueberry farmers, with the added advantage of achieving sustainable production, which is of paramount importance in the evolving world.

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APPENDIX A: SMART SPRAYER DEVELOPMENT AND EVALUATION IMAGES

Figure A-1: Wild blueberry field showing substantial field variability requiring the need for spot-specific applications.

Figure A-2: Custom plumbed flow valve system for boom section control.

Figure A-3: Flow rate and individual nozzle calibration experimental setup.

Figure A-4: Experimental setup showing procedure for determination of mechanical delay time.

Figure A-5: Wiring individually controlled solenoid valves for each nozzle on smart sprayer.

Figure A-6: Operators view of controllers used during initial smart sprayer design and testing.

Figure A-7: Front machine vision boom and rear sprayer boom folded in for road travel to research fields.

Figure A-8: Smart sprayer tank fill-up using commercial chemical mixing station.

Figure A-9: Fungicide application in selected field using front machine vision system.

Figure A-10: Herbicide application in selected field with front machine vision boom.

Figure A-11: Square quadrat for determining percent weed coverage from selected plots.

Figure A-12: Herbicide application in selected field using front machine vision system.

Figure A-13: Herbicide application in selected field with front machine vision system.

Figure A-14: Machine vision system experimental testing after dark with added light source.

Figure A-15: Rear mounted machine vision system.

Figure A-16: GoPro® camera mounted on rear sprayer boom for real-time video acquisition during field testing.

Figure A-17: Refined smart sprayer system installed on Case 185 farm tractor.

Figure A-18: Field testing smart sprayer system installed on Case 185 farm tractor for spot-application of herbicide.

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