

# **SENSOR FUSION ON A WILD BLUEBERRY HARVESTER FOR FRUIT YIELD, PLANT HEIGHT AND TOPOGRAPHIC FEATURES MAPPING TO IMPROVE CROP PRODUCTIVITY**

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## **ABSTRACT**

Site-specific crop management can improve profitability and environmental risks of wild blueberry crop having large spatial variation in soil/plant characteristics, topographic features which may affect fruit yield. An integrated automated sensor fusion system including an ultrasonic sensor, a digital color camera, a slope sensor, a real-time kinematics GPS (RTK-GPS), custom software and ruggedized computer was developed. The system was incorporated into a commercial wild blueberry harvester, to measure plant height, fruit yield, slope and elevation in a simultaneous manner with harvest. Two wild blueberry fields were selected in central Nova Scotia of Canada to evaluate the performance of the system. The field boundary, bare spots, weeds and grass patches were mapped with a RTK-GPS prior to start the experiment.

Linear regression was used to calibrate the actual fruit yield with the percentage of blue pixels ( $R^2 = 0.91$  to  $0.92$ ;  $P < 0.001$ ;  $n = 40$ ) using  $0.91 \times 0.70$  m quadrates at selected points from both fields. The output voltage of ultrasonic sensor was significantly correlated with manually measured plant height ( $R^2 = 0.95$ ;  $P < 0.001$ ;  $n = 40$ ). Comprehensive surveys were conducted in both fields to measure plant height, fruit yield, slope and elevation rapidly in real time at the same time of harvest. The maps for the measured parameters were developed in ArcGIS 10 showed substantial variability in measured parameters across the fields, suggesting less fruit yield and more plant height in low lying areas and vice versa. A negative relationship among fruit yield and plant height ( $r = -0.20$ ) also supported the results identified by the maps. Overall, the results of calibration and

mapping indicated that the sensor fusion system was accurate, reliable and efficient to map plant height, fruit yield, slope and elevation in real time. This information can be used to develop site-specific nutrition program, based on easily measured field parameters, to optimize productivity while minimizing the environmental impacts.

**Keywords:** Sensor fusion, crop productivity, wild blueberry, RTK-GPS, ultrasonic sensor and digital photography.

## INTRODUCTION

The North American wild blueberry industry may significantly benefit from precision agriculture (PA) technologies that allow site-specific monitoring and management of agricultural inputs. This crop is unique as it is native to North America and has never been cultivated. Wild blueberry has a biannual production cycle where it undergoes vegetative growth in the first year and produces fruit followed by pruning in second year (Eaton, 1988). Newly deforested areas or discarded farmland with pre-existing wild blueberry coverage or transplanting are usually used for commercial development of fields. Newly developed fields have a significant proportion of bare spots which varies from 30% to 50% of the total field area (Zaman et al., 2008). The unique features of the wild blueberries cropping system as compared to other closed canopy crops emphasize the need for the development of new PA systems comprises of low-cost sensors and controllers for accurate applications to maximize profit and minimize environmental impacts.

Currently, wild blueberry producers apply fertilizer uniformly considering the whole field as a homogeneous unit. However, soil properties, plant characteristics, topographic features vary substantially within a field which significantly affects fruit yield and quality (Farooque et al., 2012). Mapping resulting variability in fruit yields is a logical starting point for site specific nutrient management and it is very effective for potential management zone identification (Farooque et al., 2012). Yield along with fertility, topographic features, crop characteristics and land characteristics maps developed by sensing and control system can be used to generate prescription maps for site-specific fertilization.

Sensor integration is a widely adopted technique in PA systems to measure and map soil and plant characteristics in real time for variable rate technologies. Sensor fusion involves a wide spectrum of sensors, hardware and software for data acquisition, automated recording, analogue and digital processing of data and up to symbolic analysis all within framework to assess the spatial variations within field. Mobile ground or proximal sensors are an emerging technology designed to overcome many of the limitations associated with the current instrumentation of satellite- or aircraft-based sensing systems (Bausch and Delgado 2003). Satellite or airborne platforms deliver spectral information; however, they may not be available in time for critical management

decisions to be implemented. Also, remote sensing data is constrained by weather conditions, obtaining up-to-date aerial photography is very expensive, the quality is variable, and data processing is also intensive and complicated. Ground sensing technologies are able to get around the problem of weather conditions, and their close proximity to the canopy reduces or eliminates soil reflectance interference. Coupled with a differential GPS, these ground sensors are able to deliver data of high spatial resolution that can be integrated with material delivery systems to facilitate real time applications of agrochemicals (Holland et al. 2006).

Many researchers have studied the spatial variation in soil properties, plant characteristics and fruit yield for different cropping systems using ground based sensing and control systems. Lan et al. (2009) developed a ground-based, multi-source information collecting system and tested the feasibility of the system on cotton; it consisted of NDVI sensor, crop canopy analyzer for LAI, hyperspectro-radiometer, multispectral camera and crop height sensors. Rosell Polo et al. (2009) used a low-cost tractor-mounted scanning Light Detection and Ranging (LIDAR) system capable of making non-destructive recording of tree-row structure in orchards and vineyard. Moshou et al. (2006) investigated proximal optical sensing to diagnose disease infestations on wheat and to discriminate between pathological and nutritional stresses. Mazzetto et al. (2010) integrated optical and analogue sensors for monitoring canopy health and vigor for vineyard.

Many researchers have attempted to characterize and quantify the spatial variation in soil properties, plant characteristics and fruit yield for different cropping systems using multiple sensor and control systems (Moshou et al. 2006, Lan et al. 2009, Rosell Polo et al. 2009, Mazzetto et al., 2010, Zaman et al., 2011). However, to date little attention has been paid to wild blueberry production system. In the present study, a ground based sensor fusion system (software and hardware) comprised of a ultrasonic sensor, a digital color camera, a slope sensor and a RTK-GPS was developed and incorporated into a wild blueberry harvester to propose practical ground sensing solutions and match crop monitoring needs. The objective of this work was to evaluate the performance of the sensor fusion system (SFS) in wild blueberry fields with regard to plant height, fruit yield, slope and elevation estimation in real time.

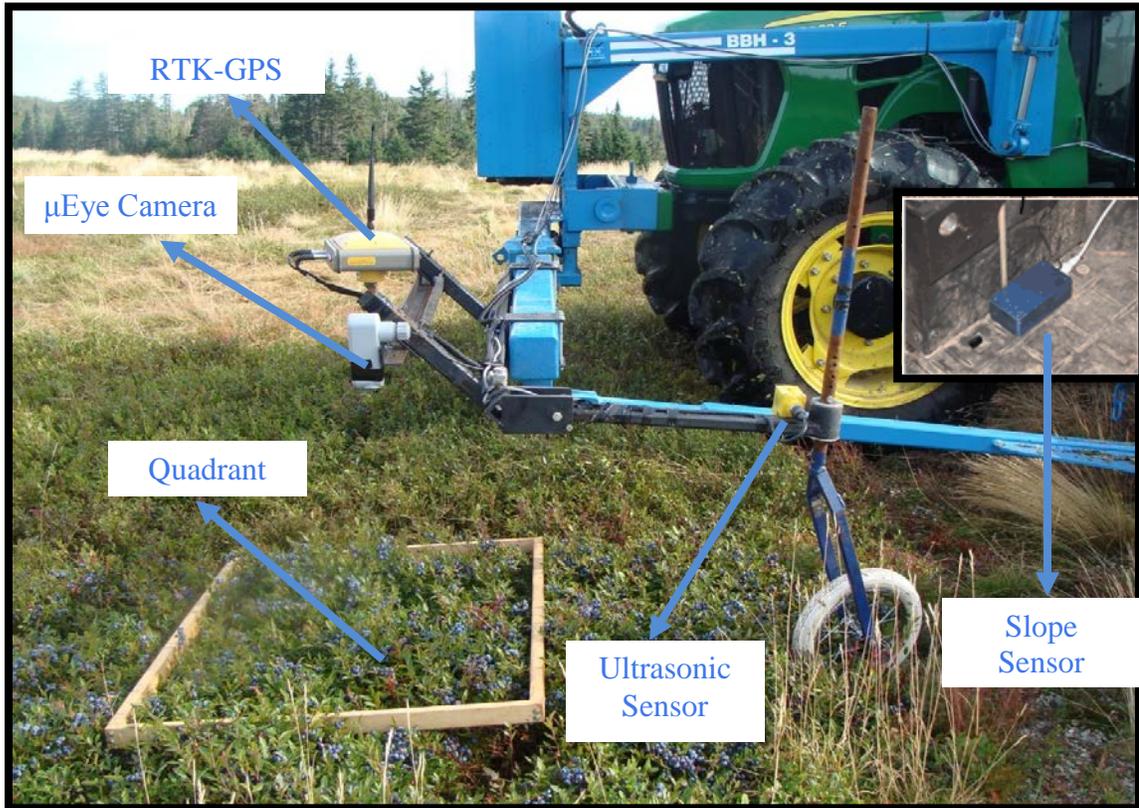
## **MATERIALS AND METHODS**

### **Development of Sensor Fusion System**

#### **Hardware components**

The SFS consisted of a  $\mu$ Eye 1220SE/C digital color cameras (IDS Imaging Development System Inc., Woburn MA, USA), a HiPer® lite+ RTK-GPS (Topcon positioning systems Inc., Livermore, CA, USA) for geo-referencing, a tilt sensor (Memsic 2125; Parallax Inc., Rocklin, CA, USA) in order to permit sensing the tilt of a vehicle in any orientation on a slope, an ultrasonic sensors (Q45U; Banner Engineering Corp., Minneapolis, MN, USA) mounted on a steel frame constructed using locally available materials and parts to minimize the cost, and ruggedized computer Latitude E6400 XFR (Dell Inc., Round Rock, TX,

USA) was developed (Fig. 1) to incorporate into commercial wild blueberry harvester for mapping fruit yield, plant height and topographic features.



**Fig. 1.** Configuration of a sensor fusion system mounted on a wild blueberry harvester.

The camera and RTK-GPS were mounted at the front of the harvester at a height of 0.95 m with a clear view of the ground. The ultrasonic sensor was mounted 0.8 m above the ground surface on the steel frame (Fig. 1). A bicycle wheel was used in the steel frame to keep the height of the sensor constant during the operation of SFS. The National Marine Electronics Association (NMEA-0183) standard code sentences of RTK-GPS was used for the calculation of the coordinates of ultrasonic sensor, the center of camera images, and slope sensor simultaneously. The camera is comprised of a 1/3 inch CMOS sensor, a C-mount for lens (LM4NCL, Kowa Optimed Inc., Torrance, CA, USA) and a global shutter. The camera lense had 3.5 mm focal length and was set up with fixed aperture (f/4.0) and infinity focus. The images from the cameras were acquired according to the speed of harvester and processed data were stored with calculated coordinates in the ruggedized computer. The calculated coordinates and elevation data were continuously stored in the ruggedized computer through the serial port at 5 Hz. The slope sensor was mounted inside the cabin of tractor to measure the tilth of the tractor in any orientation. In this study we used the pre-calibrated slope sensor by Zaman et al. (2010). The details about the configuration of the slope sensor can be adopted from Zaman et al. 2010.

## Software development

Custom image processing software was developed in C++ using Visual Studio 2010 (Microsoft, Redmond, WA, USA) for a 32-bit Windows operating system to estimate the percentage of blue pixels representing ripe fruit in the field of view of image taken by the camera. The software interface was capable of capturing a 24-bit RGB  $720 \times 480$  image (total covered field area of  $0.91 \text{ m} \times 0.70 \text{ m}$ ) and processing the percentage of blue pixels, ultrasonic sensor recording for plant height estimation, elevation recording and pre-calibrated tilt sensor recording for measurement of slope and recording the RTK-GPS readings simultaneously in the ruggedized computer through a serial communication cable in real time. Exposure time and digital gain for camera were automatically controlled to adjust for variable outdoor light conditions. The acquired images can be saved in a BMP file format. Coordinates from the previous and the current RTK-GPS output were converted to decimal degrees and used to automatically estimate the timing for the next image, and ultrasonic sensor data acquisition.

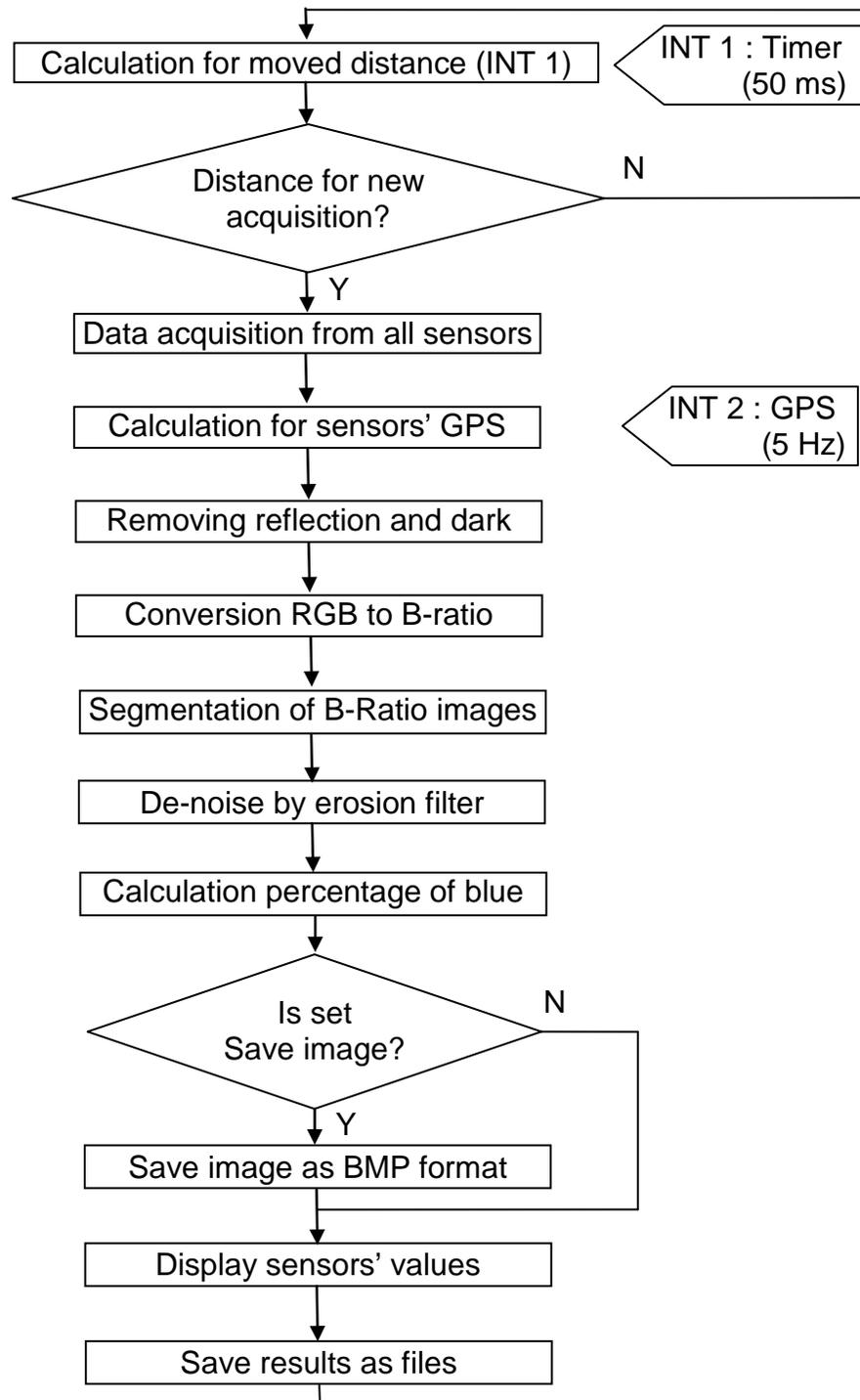
The custom software was used to enhance and count the blue pixels in the quadrat region of each image, using red-green-blue (RGB) pixel ratio, and expressing the result as a percentage of total quadrat pixels. The ratio used was  $(B*255)/(R+G+B)$ , and a manually obtained threshold ( $> 80$ ) adequately discriminated the apparent blueberry fruit pixels from the remaining pixels in an image. Overestimated tendency due to the reflection and dark shadows was corrected by removing over and under intensity pixels ( $(R+G+B) > 500$  or  $< 40$ ). Small noisy clusters of pixels in the image which were incorrectly identified as fruit were removed by applying one pass of  $2 \times 2$  erosion filter. The result of percentage of blue pixels in the quadrat region of each image was calculated automatically by running the software in real time mode. The final results of plant height, blue pixels, slope and elevation along with the geo-referencing using SFS were saved as comma-separated values files (Fig. 2).

The SFS data along with geo-referenced coordinates was imported into ArcGIS 10 computer software (ESRI, Redlands, CA, USA) for further processing.

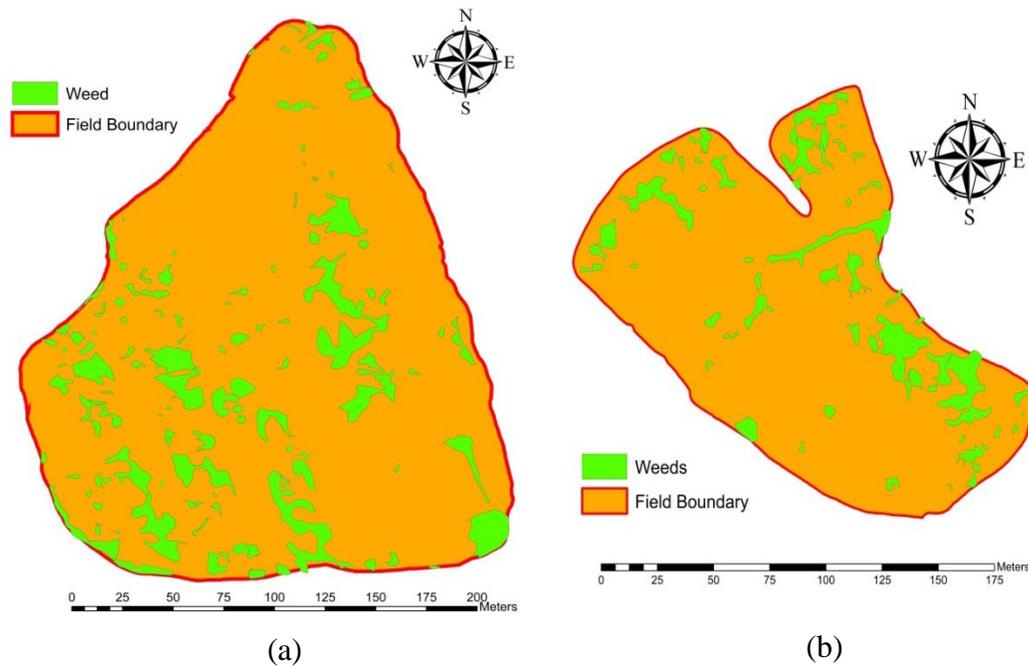
## Calibration of the Sensor Fusion System

### The experimental sites

Two wild blueberry (*Vaccinium angustifolium* Ait.) fields were selected in central Nova Scotia to evaluate the performance of the SFS. The selected fields were Cooper site ( $45.480573^\circ\text{N}$ ,  $63.573471^\circ\text{W}$ ) and Small Scott site ( $45.600641^\circ\text{N}$ ,  $63.086512^\circ\text{W}$ ) (Fig. 3). Both fields were in their fruit year in 2011, having been in the vegetative sprout year in 2010. The fields have been under commercial management over the past decade and have received biennial pruning by mowing for the past several years along with conventional fertilizer, weed, pest and disease management practices.



**Fig. 2.** Flow chart showing computer program for the sensor fusion system real time in wild blue blueberry field.



**Fig. 3.** Field layout for (a) Cooper site (b) Small Scott site.

A  $0.91 \times 0.70$  m wooden frame quadrat was constructed and placed at selected locations in both fields to define the area of interest in the image and for collection of fruit yield. Fruit samples were collected by hand-harvesting out of the  $0.91 \times 0.70$  m quadrat, using hand raking from the randomly selected points in each field. Blueberries were separated from debris including leaves, grass and weeds for each sample and weighed at the time of harvest.

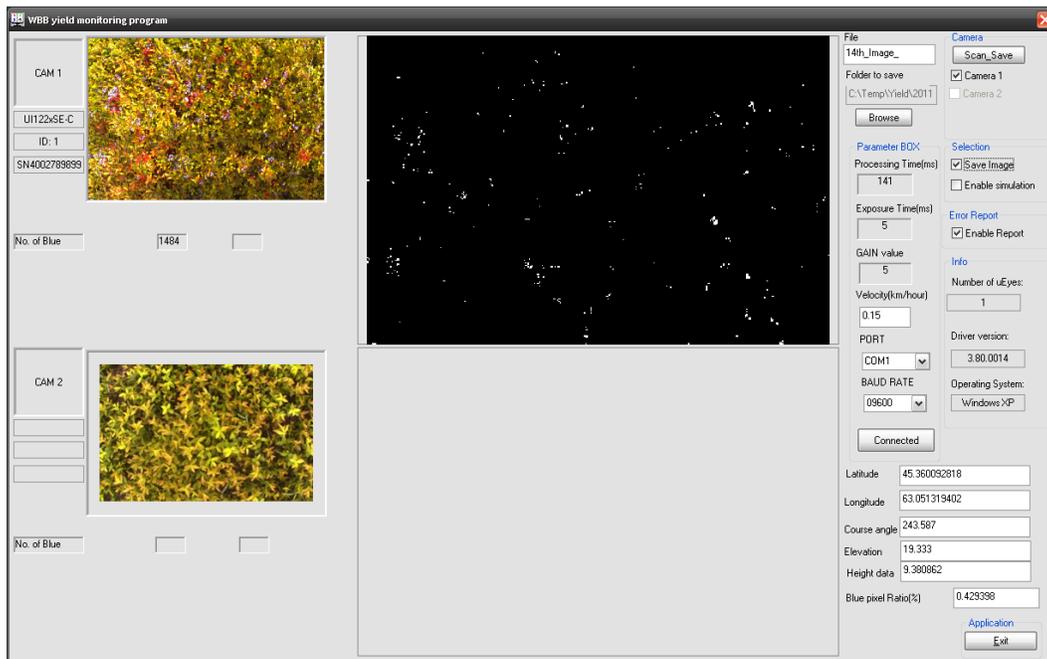
The images were taken from the selected points using the camera mounted on the wild blueberry harvester by placing the same quadrat at random locations in both fields. The quadrat portion of the images was masked out and percentage of blue pixels was estimated using the custom software. Calibration was carried out at 40 randomly selected data points (20 points in each field) in the two wild blueberry fields. The ultrasonic sensor was calibrated to measure the distance from the ultrasonic sensor to the target prior to use for plant height estimation in real time using SFS. The corresponding voltages were recorded using a U3-HV (LabJack Corp., Lakewood, CO, USA) I/O unit at the time of distance measurements for comparison. Manual plant height readings were taken from selected points using a ruler in both fields. Ultrasonic sensor was used to record the sensor reading (voltage) from same selected points. The measured height (from ground to canopy) and voltage were compared by linear regression using SAS 9.1 software (SAS Institute, Cary, NC, USA) to examine the performance accuracy of the ultrasonic distance measurements. Calibration was carried out at 13 randomly selected data points. For slope sensor we used the calibration equation developed by Zaman et al. (2010) to estimate the slope in real time.

## STATISTICAL ANALYSIS

Linear regression was used to calibrate the actual fruit yield and plant height with the percentage of blue pixels and ultrasonically sensed plant height respectively, in each field. The calibration equation of Cooper site was used to predict fruit yield in Small Scott site and calibration equation of Small Scott site was used to predict fruit yield in Cooper site for validation. Calibration and validation of regression equations/models, coefficient of determination ( $R^2$ ) and root mean square (RMSE) were calculated with SAS 9.1. The paired (actual fruit yield and percentage of blue pixels) data for both fields were used to develop and validate the model. Geographical information system (GIS) was applied to generate detailed maps in ArcGIS 10 to analyze the spatial variability in fruit yield, plant height and slope visually. The maps were produced at the same scale and equal number of classes in order to allow easier comparison.

### REAL TIME FIELD PERFORMANCE OF SFS

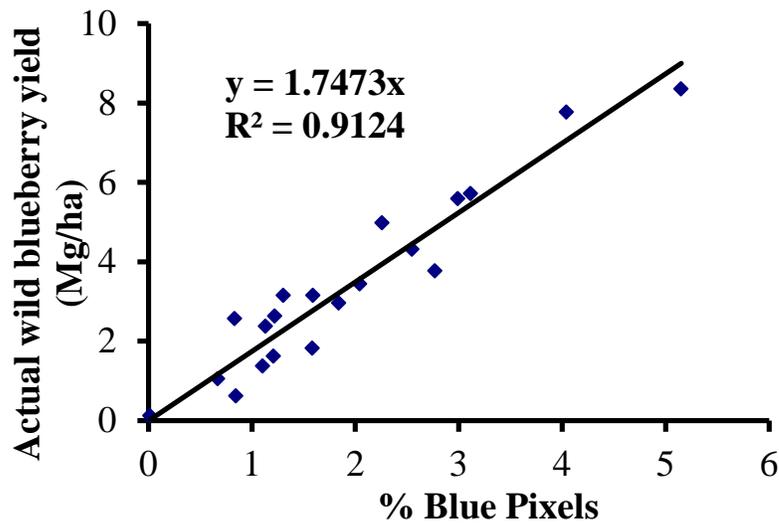
The performance of the software and hardware of SFS was assessed by surveying the two fields of size 3.2 ha (Cooper site) and 1.9 ha (Small Scott site), respectively. The ranges of target ground speed, monitored on the main software screen during the surveys (Fig. 4), were 1.5 ~ 1.7 km/h. Real time yield, plant height and topographic features mapping was carried out by acquiring images, ultrasonic sensor, and slope sensor reading with SFS on the moving wild blueberry harvester mounted on John Deere 85 horsepower tractor. The software was able to process the images to estimate the percentage of blue pixels, ultrasonic sensor to predict plant height, slope sensor to calculate slope, and RTK-GPS for elevation in real time at the same time of harvest.



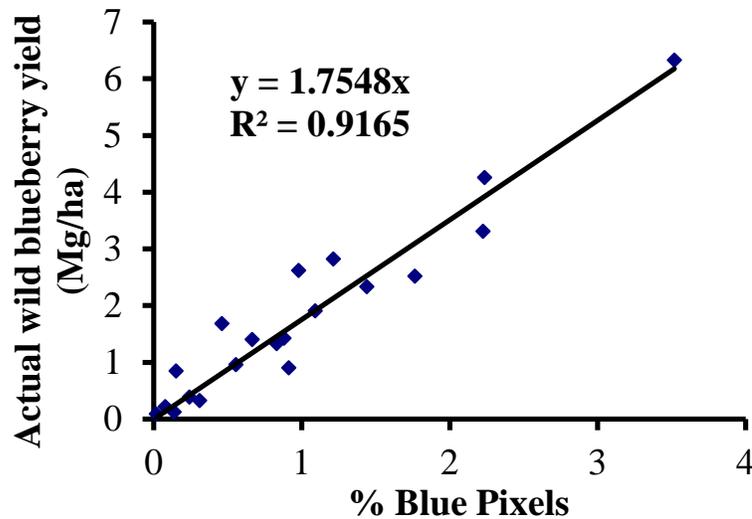
**Fig. 4.** Custom software interface for sensor fusion system.

## RESULTS AND DISCUSSION

The percentage of blue pixels, representing the fruit yield in the harvested quadrat region of the image in both fields, was calculated with custom software. The zero percentages of blue pixels were due to bare spots or weeds (no blueberry fruit) within blueberry fields. The presence of bare spots in wild blueberry fields is due to natural colonization of plants developed from native stands on deforested farmland by removing competing vegetation (Eaton, 1988). The percentage of blue pixels was significantly correlated with manually harvested fruit yield in Cooper site ( $R^2 = 0.91$ ;  $P < 0.001$ ) and Small Scott site ( $R^2 = 0.92$ ;  $P < 0.001$ ) (Fig. 5).



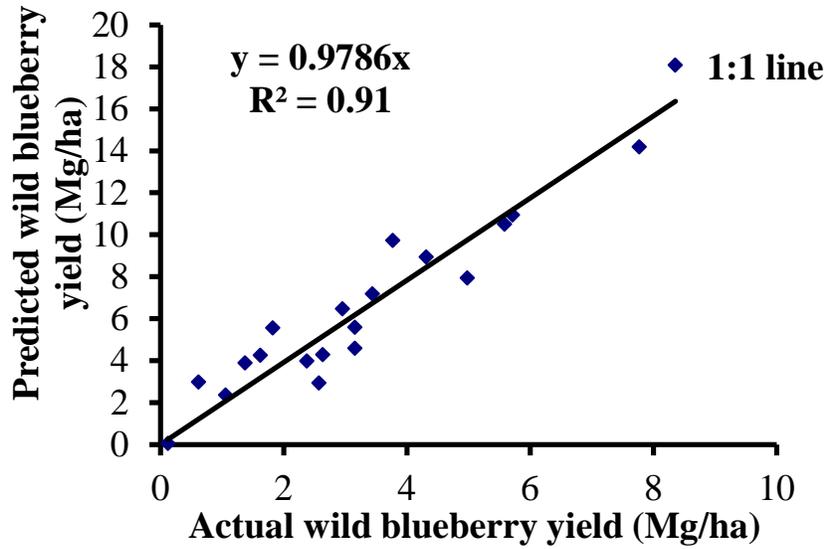
(a)



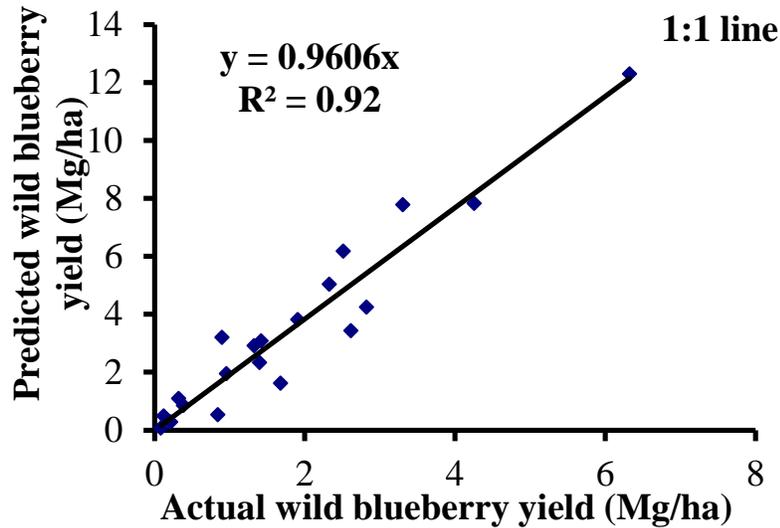
(b)

**Fig. 5.** Relationship between percentage of blue pixels and actual fruit yield per/ha in the calibration data set of (a) Cooper site and (b) Small Scott site.

The correlation between actual and predicted fruit yield (validation, using the equation from Small Scott site) in Cooper site ( $R^2 = 0.91$ ;  $P < 0.001$ ; RMSE = 1.78 Mg/ha) and Small Scott site (validation, using the equation from Cooper site) ( $R^2 = 0.92$ ;  $P < 0.001$ ; RMSE = 1.47 Mg/ha) was also highly significant (Fig. 6). The slight bias can be seen in the scatter plots where fruit yield was over or under-estimated. The reason for over-estimation might be the vegetation was less or negligible and mostly berries were exposed to the camera and under-estimation was because the vegetation was more and berries were hidden under leaves.



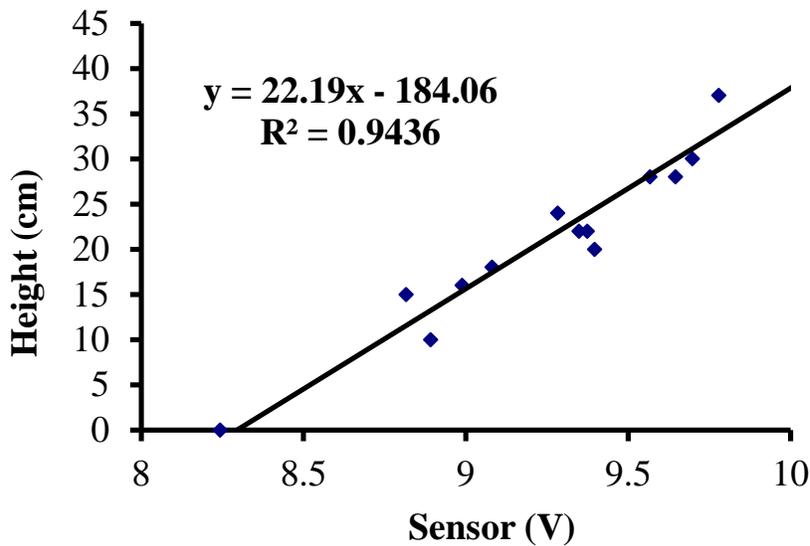
(a)



(b)

**Fig. 6.** Measured and predicted fruit yield (a) in Cooper site predicted using the equation from Small Scott site and (b) in Small Scott site predicted using the equation from Cooper site.

Ultrasonics were calibrated for height measurement and the linear calibration model showed that distance measured from sensor to plant was correlated highly significantly with the sensor voltage ( $R^2 = 0.94$ ;  $P < 0.001$ ). Ultrasonic sensor calibration equation for distance measurement (Fig. 7) incorporated into software to permit sensor for estimation of plant height accurately in real time. Custom software retrieved the elevation data from RTK-GPS mounted on the SFS along with the geo-referenced data. Significant correlation among the percentage blue pixels and actual fruit yield, sensor voltage and actual plant height and pre-calibrated slope sensor suggested that  $\mu$ Eye color camera, ultrasonic sensor, and slope sensor can be mounted on the wild blueberry harvester to estimate fruit yield, plant height and topographic features in real time.

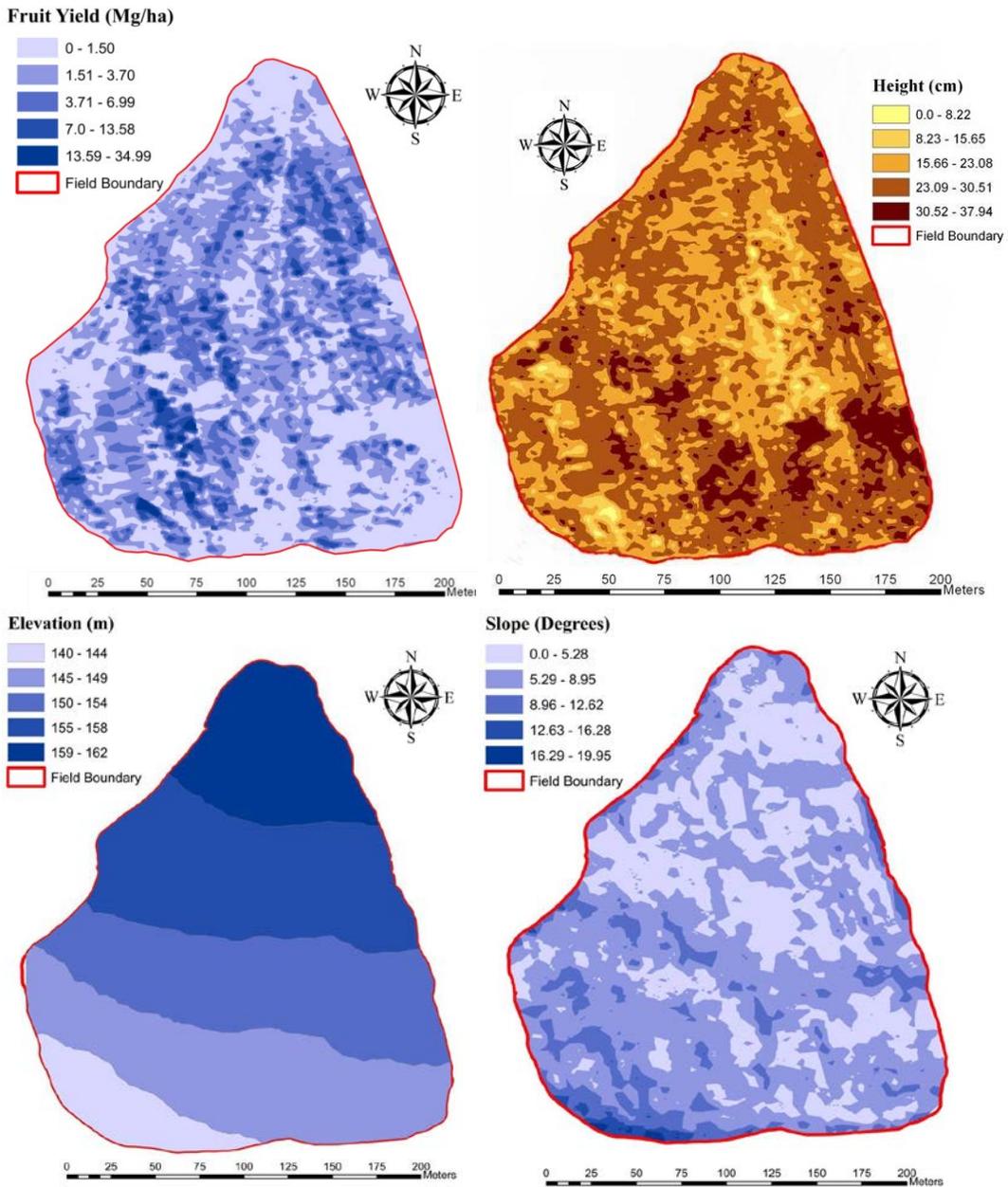


**Fig. 7.** Relationship between ultrasonic sensor and actual distance measured from sensor to target plant.

The percentage of blue pixels converted to fruit yield, ultrasonics to plant height data for each field were mapped in ArcGIS 10 software (Fig. 8). Due to space constraints, only the maps of Cooper site are discussed here (Fig. 8). The fruit yield varied from 0 (bare spots) to 34.99 Mg/ha and plant height ranged from 0 (bare spots) to 38 cm, slope varied from 0 to 20 degrees and elevation ranges from 140 to 162 m (Fig 8). The substantial variability in fruit yield, plant height, slope, elevation and presence of bare spots/weeds within blueberry fields emphasize the need for site-specific fertilization to increase fruit yield, farm profitability, and mitigate environmental risks.

The kriged maps of fruit yield, plant height, slope and elevation (Fig. 8) showed gradual and non random spatial variability with significantly different values across the field for Cooper site (Fig. 8). The map comparison of plant height with fruit yield suggested that in general fruit yield was lower in the areas where the plant height was higher (Fig. 8). The negative but non-significant relationship ( $R = -0.20$ ) among the fruit yield and plant height also supported the correlation identified by the maps. The visual inspections also revealed the lower yield in the areas with more plant height suggesting more vegetative growth,

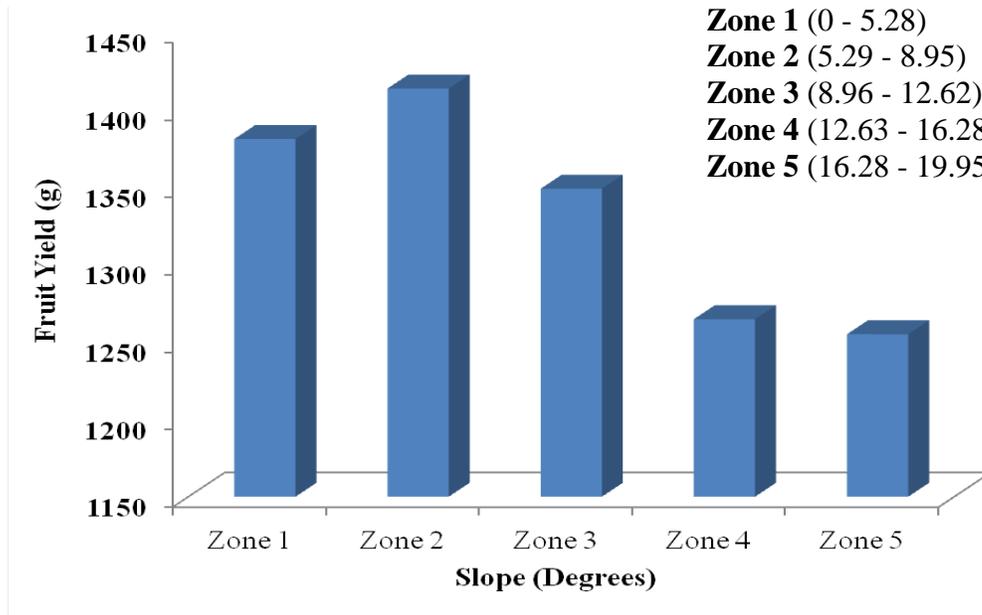
emphasizing the need to apply fertilizer on as needed basis. The map comparison suggested that there was less influence of elevation on the plant height and fruit yield as these parameters were present in all regions of elevation.



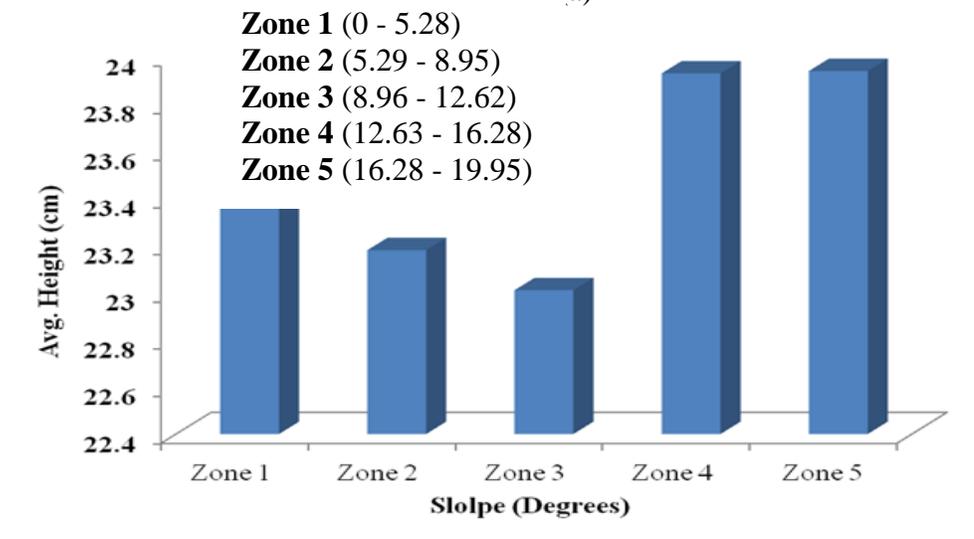
**Fig. 8:** Kriged maps of fruit yield, plant height, elevation and slope data for Cooper site using SFS.

The kriged maps suggested that fruit yield was higher in flat areas and vice versa (Fig. 8). The zonal statistics was performed in order assess the variation in fruit yield and plant height in different slope zones across the field. The zonal statistics indicated the higher yield and less plant height in less slopy areas and vice versa (Fig. 9) suggesting the need to develop management zones

for variable rate technologies based on slope variation. The low fruit yield on the steep slope areas may be due to erosion of nutrients from steep slopes and accumulation in low lying areas. The zonal statistics also supported the negative relation between fruit yield and plant height. These results were in agreement with the findings of Farooque (2010).



(a)

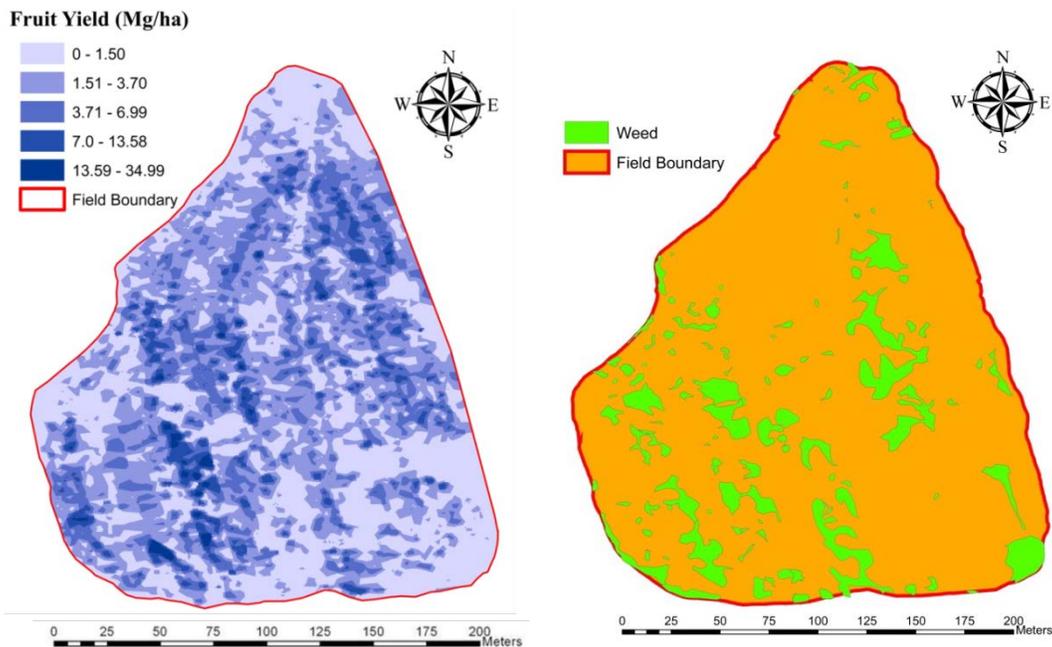


(b)

**Fig. 9.** Bar graphs showing the variation of fruit yield and plant height with respect to slope for Cooper site.

The maps of bare spots/weeds and fruit yield were placed side by side to examine the relationship between bare spots and fruit yield (Figs. 10). Mainly, bare spot/weeds areas were scattered within field and associated with zero or very low yield. The low yield in some parts of the field might be partially due to weeds in those areas of the field. Another reason for variation in fruit yield might be the

variability in soil properties and nutrients within the field. The similar spatial patterns in bare spots and fruit yield within these fields could be useful to develop prescription maps for variable rate applications to reduce fertilizer usage in the fields. Zaman et al. (2008) mapped bare spot areas in different wild blueberry fields with a mobile mapper GPS. The bare spots varied from 30 % to 50 % of the total newly developed field area and were scattered throughout the fields. Unnecessary or over-fertilization in bare spots areas may also deteriorate water quality, promote weed growth and increase production cost. Under-fertilization restricts yield and can reduce berry quality (Percival and Sanderson, 2004). Hence, variable rate fertilization based on considerable variation in fruit yield, bare spots/weeds, plant height, and slope could improve farm profitability and reduce environmental impacts. Farooque et al. (2012) suggested defining bare spots as a separate class while delineating management zones for variable rate fertilization would results in significant amount of fertilizer saving.



**Fig. 10.** Maps of cooper field showing fruit yield variability using sensor fusion system (left) and bare spots/weeds mapped with RTK-GPS (right).

The  $\mu$ Eye camera mounted on SFS took 55,640 images with the estimated fruit yield of 10,232 kg/ha, while the actual yield collected in the harvester bin and weighed was 9,100 kg/ha for Cooper site suggesting 11.07 % losses of berries while harvesting. The total number of taken images was 33,068 with the estimated fruit yield of 3,408 kg /ha. The actual fruit yield collected by the harvester was 3,110 kg/ha indicating 8.74% losses of berries for Small Scott site. There were less yield losses of berries in Small Scott as compare to Cooper site. The possible reason for the less fruit loss was due to low yield at Small Scott site suggesting that the wild blueberry field have less losses of berries during harvesting in low yielding field and vice versa. These results suggested that there is need to conduct research at the harvester picking efficiency in different yielding (low, medium and high) areas to quantify the wild blueberry yield losses. This

would help the wild blueberry industry to generate more revenue and increase profitability for the farmers.

## **CONCLUSIONS**

The results of this work suggested that the sensor fusion system (hardware and custom software) proved very efficient at measuring and mapping fruit yield, plant height and topographic features estimation in wild blueberry fields. The results of this work have indicated that the mapping of wild blueberry fruit yield, plant height, and topographic features were valuable for understanding the fertility status in the monitoring fields. Based on the results of this study it can be concluded that there is potential to estimate and map fruit yield, plant height and topographic features within wild blueberry fields with the SFS in real time. This information could be used to implement site-specific management practices within the blueberry fields to optimize productivity while minimizing the environmental impact of farming operations.

## **ACKNOWLEDGEMENTS**

This work was supported by the Oxford Frozen Foods Limited, Agri-Futures (ACAAF) Nova Scotia, Wild Blueberry Producers Association of Nova Scotia and Nova Scotia Department of Agriculture Technology Development Program, Agriculture and Agri. Food Canada (Canadian Horticulture Council). The authors would like to thank Gary Brown and Doug Wyllie (farm managers Bragg Lumber Company), Dr. Mumtaz Cheema, Fahad Khan and Shoaib Saleem (graduate students), and Mathew Morrison and Asena Yildiz (summer students) for their assistance during the experiment. Authors would also like to thank Peter Swinkles and Carol Bragg (Doug Bragg Ent.) for providing harvester and technical support during the experiment.

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