AUTOMATED, LOW-COST YIELD MAPPING OF WILD BLUEBERRY FRUIT

Q. U. Zaman, K. C. Swain, A. W. Schumann, D. C. Percival

ABSTRACT. *The presence of weeds, bare spots, and variation in fruit yield within wild blueberry fields emphasizes the need for yield mapping for site-specific application of agrochemicals. An automated yield monitoring system (AYMS) consisting of a digital color camera, differential global positioning system, custom software, and a ruggedized laptop computer was developed and mounted on a specially designed Farm Motorized Vehicle (FMV) for real-time fruit yield mapping. Two wild blueberry fields were selected in central Nova Scotia to evaluate the performance of the AYMS. Calibration was carried out at 38 randomly selected data points, 19 in each field. The ripe fruit was hand-harvested out of a 0.5- × 0.5-m quadrant at each selected point and camera images were also taken from the same points to calculate the blue pixel ratio (fraction of blue pixels in the image). Linear regression was used to calibrate the actual fruit yield with percentage blue pixels. Real-time yield mapping was carried out with AYMS. Custom software was developed to acquire and process the images in real-time, and store the blue pixel ratio. The estimated yield per image along with geo-referenced coordinates was imported into ArcView 3.2 GIS software for mapping.*

A linear regression model through the origin (y = bx) was highly significant in field 1 (R^2 = 0.90; P < 0.001) and field 2 (R^2 = 0.97; P < 0.001). The correlation between actual and predicted fruit yield (validation, using the equation from field 2) in field 1(R^2 = 0.95; P < 0.001; RMSE = 3.29 Mg/ha) and field 2 (validation, using the equation from field 1) (R^2 = 0.97; P < 0.001; RMSE = 2.69 Mg/ha) was also highly significant. The best results were obtained by using site-specific calibration of <20 points for every field, using a representative range of fruit yield. Maps showed substantial variability in fruit yield in both fields. The bare spots coincided with no or low yielding areas in the fields. The yield maps could be used for site-specific fertilization in wild blueberry fields.

Keywords. *Precision agriculture, DGPS, GIS, Digital photography, Yield map.*

Wild blueberry (*Vaccinium angustifolium* Ait.) fields are developed from native stands on deforested farmland by removing competing vegetation (Eaton, 1988). The majority of fields are situated in naturally acidic soils that are low in nutrients and have high proportions of bare spots, weed patches, and gentle to severe topography (Trevett, 1962; Zaman et al., 2008). This crop is perennial in nature, having a vegetative growth season (sprout year) followed by a productive season (fruit year). Considerable spatial fruit yield variability occurs in wild blueberry fields due predominately to significant bare spots, weed patches, variable plant sizes, and soil limitations.

There is increasing grower interest to manage these fields site-specifically using variable rate technology, potentially resulting in more efficient use of agricultural inputs (fertilizer and pesticide), increased yields, and preventing environmental pollution by excess agrochemicals. Wild blueberries are low input systems with narrow optimal window of plant nutrient requirements. Detrimental fruit yield effects have been observed when excessive N has been applied (i.e. lowers floral bud numbers and harvestable yields). Unnecessary or over-fertilization in both bare spots and weed patches may also deteriorate water quality, promote increased weed growth, and reduce profit margins. Conversely, under-fertilization restricts yield and can reduce berry quality (Percival and Sanderson, 2004).

Yield maps along with topography and soil nutrient maps could be used to develop precise site-specific nutrition programs for wild blueberry production. Very limited information is available on yield monitoring technologies for wild blueberry fruit. Impact plates, load cells, optical measurements, radiometric techniques, and digital photography are some of the commonly used methods for estimating various crop yields. Malay (2000) developed a yield monitoring system for blueberries using optical sensors. The limitations of this system were that the debris common to blueberry harvest, including sticks, grass, and rocks, affected the accuracy of the CERES II yield monitor (R.D.S Technology, Gloucester, U.K.) optical sensor resulting in yield overestimation. Wild blueberries are fragile when harvested, and mechanical sensing devices can harm the berries and reduce their quality and marketability. When wild blueberries are harvested, the slow movement of the harvester (<2 km/h) and narrow width of the harvester heads (<1 m single-head harvester, <2 m double-head harvester)

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result in little weight on the belts at any given time. In addition, load cells are impractical to use because they are difficult to mount on the belt (Swinkels, 2007). Zaman et al. (2006a) estimated citrus fruit yield using ultrasonically-sensed tree canopy volume. However, the system was expensive and data processing was complicated.

A low-cost yield mapping system may be possible with the addition of photographic yield sensors on blueberry harvesters, estimating fruit yield on the ground just ahead of harvesting. Several studies have concentrated on camera-based, non-destructive, indirect fruit yield estimation and mapping (Annamalai et al., 2004; Chinchuluun and Lee, 2006; MacArthur et al., 2006). Schumann et al. (2007) developed a ground-based digital photography and ultrasonic ranging system that allowed real-time imaging, monitoring, calculation, storage, and mapping of tree characteristics and fruit yield in citrus orchards. Zaman et al. (2008) evaluated the performance of a cost-effective 10-megapixel digital color camera for wild blueberry fruit yield estimation. The coefficient of determination for correlations between blue pixel ratios and actual fruit yield ranged from 0.98 to 0.99 in two selected fields. Therefore, a cost-effective digital color camera could be used to develop an automated yield monitoring system for wild blueberry fruit estimation and mapping.

An automated real-time wild blueberry fruit yield mapping system would use a differential global positioning system (DGPS) receiver for ground speed sensing and automatic adjustment, and, together with position coordinates and digital color camera data, for the continuous calculation and storage of fruit yield data. Moreover, the performance of the camera and DGPS should be continuously monitored during the measurement process. Therefore, this study was designed to:

- Develop an automated cost-effective yield monitoring system (hardware and software).
- Evaluate the performance of the yield monitoring system to measure and map fruit yield in commercial wild blueberry fields.

Methodology

Farm Motorized Vehicle (FMV)

An automated yield monitoring and mapping system (AYMS) was developed and mounted on a specially designed Farm Motorized Vehicle (FMV) (fig.1). The FMV was constructed using locally available materials and parts to minimize the cost. The 190cc engine (Honda Inc., NS, Canada) of the FMV was capable of generating 4.47 KW with a maximum rpm of 3600. The gasoline engine with a chain-sprocket power transmission system provided the required power to the FMV. The FMV could be driven at 0- to 10-km/h ground speed. The wild blueberry fields had no tramline or rows, therefore, the slim bicycle wheels were used to minimize the crop damage during field operations.

AYMS System

Hardware Components

The AYMS consisted of a 10-mega pixel, 24-bit digital color camera (Canon Canada Inc., Mississauga, ON,

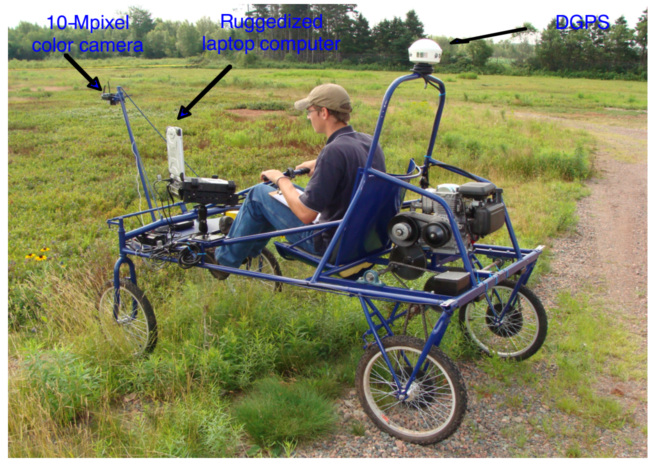

Figure 1. Configuration of automated yield monitoring system mounted on farm motorized vehicle.

Canada), Trimble Ag GPS 332 (Trimble Navigation Limited, Sunnyvale, Calif.) for geo-referencing and a ruggedized laptop computer (Panasonic Corporation, Secaucus, N.J.). The camera was mounted at the front of the vehicle, pointing downward at a height of 1.5 m with a clear view of the ground. The DGPS antenna was mounted above the camera to record the coordinates of each image simultaneously. Instead of using the limited memory space of the camera on the FMV, the large number of images from the camera was continuously stored in the 1.4-GHz ruggedized laptop computer through a RS232 communication cable, routed through the DGPS. The DGPS positions of each image were also continuously stored in the laptop through the RS-232 port at 1 Hz, using the National Marine Electronics Association (NMEA-0183) standard code sentences.

Software Development

Custom image processing software was developed in Delphi 5.0 and C programming languages for a 32-bit Windows operating system (Microsoft Corp., Redmond, Wash.), to estimate the percentage of blue pixels representing ripe fruit in the field of view of each image.

The remote camera interface (fig. 2) was capable of taking and processing the camera images in real-time and recording the DGPS readings (x, y coordinates) simultaneously in the ruggedized laptop computer through a RS-232 communication cable. Every second (1 Hz), coordinates from the previous and the current DGPS output were converted to decimal degrees, were averaged and offset, and were used to automatically estimate the timing for the next image acquisition. The distance offset was calculated with Universal Transverse Mercator (UTM) projected coordinates by utilizing the ProLat UTM (Effective Objective, Issaquah, Wash.) program function. The UTM projection was selected due to its ability to produce a flat grid of geometrically correct Cartesian ground coordinates (in meters).

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 ratios, 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 of >75 adequately discriminated the apparent blueberry fruit pixels from the remaining pixels in all images. Small clusters

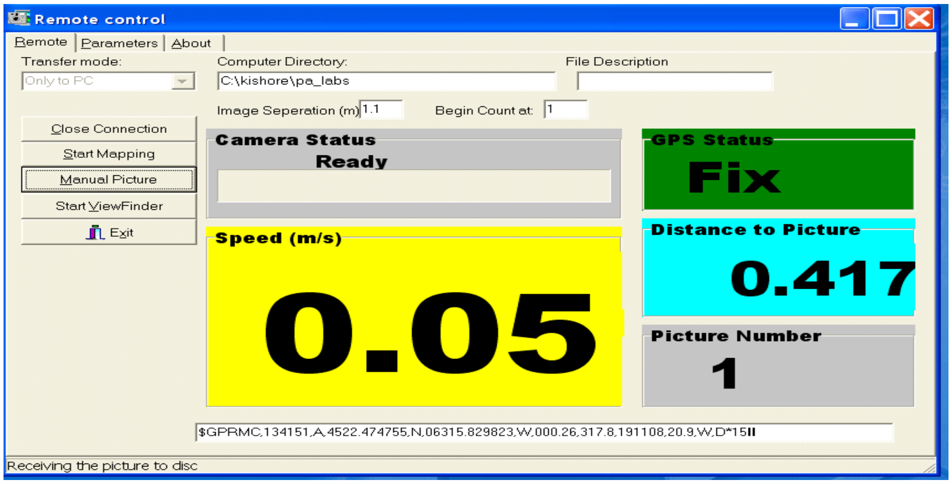

Figure 2. Software interface for automated yield monitoring system.

of pixels in the image were incorrectly identified as fruit due to specular reflection and deep shadows, but these were easily removed by applying three passes of an erosion-dilation filter. The final result of percentage fruit pixels in the quadrat region of each image was calculated automatically by running the software in batch mode and results were added to a Microsoft Access database.

The ground speed (in knots) was parsed from the DGPS string and converted to metric units, using speed (m/s) = 0.51444 × speed (knots). Ground speed was also averaged for every adjacent coordinate pair, and saved to a MS-Access database table.

Real-time percentage blue pixels and yield estimations were carried out using the linear regression model developed in C programming environment. The estimated yield per image along with geo-referenced coordinates was imported into ArcView 3.2 GIS software (ESRI, Redlands, Calif.) for further processing.

AYMS System Calibration

Two wild blueberry fields were selected in central Nova Scotia to evaluate the performance of the automated yield monitoring system. The selected fields were Debert (field 1) site (45.4418°N 63.4496°W) and cattle market (field 2) site (45.3643°N 63.2121°W). Both fields were in their fruit year in 2008, having been in the vegetative sprout year in 2007. 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, and disease management practices. A 0.5- × 0.5-m steel 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 samples. Fruit samples were collected by hand-harvesting out of the 0.5- × 0.5-m quadrat, using hand raking from the randomly selected data 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 using the AYMS setup at a height of 1.5 m placing the quadrat at the center of each selected data point in both fields. The quadrat portion of the image was masked out and percentage of blue pixels was estimated using the custom software (fig. 3). Calibration was carried out at 38 randomly selected data points (19 each) in the two wild blueberry fields.

Linear regression was used to calibrate the actual fruit yield with percentage blue pixels separately in each field. The calibration equation of field 1 was used to predict fruit yield in field 2 and calibration equation of field 2 was used to predict fruit yield in field 1 for validation of the method. Calibration and validation of regression equations/models,

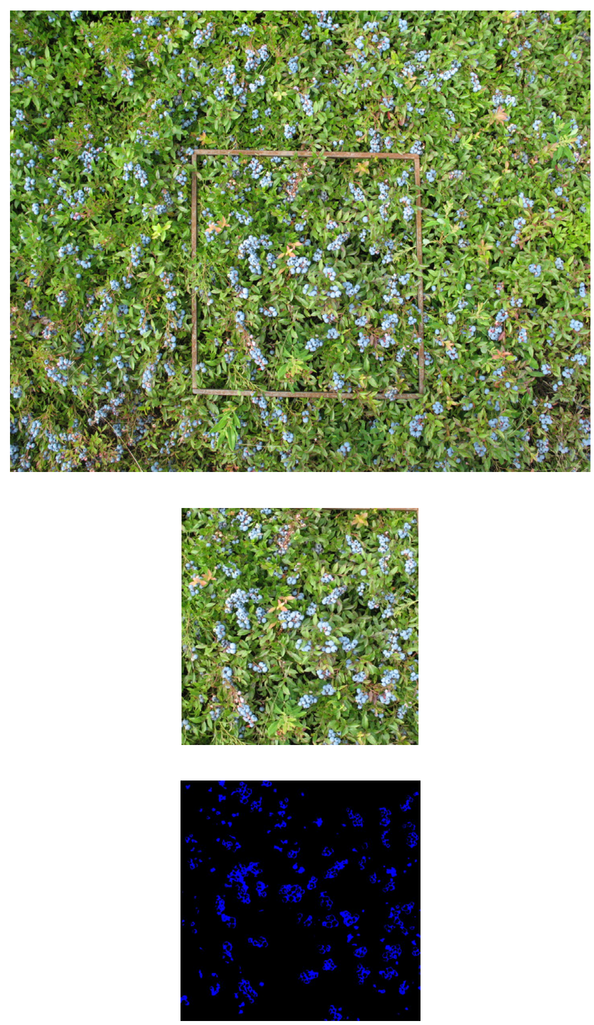

Figure 3. Steps in image processing: (a) image with 0.5- × 0.5-m quadrant, (b) masked image, (c) blue pixels in image.

coefficient of determination (R^2) and root mean square (RMSE) were calculated with SAS (SAS Institute, Cary, N.C.) software. The paired (actual fruit yield and blue pixel ratio) data for both fields were used to develop and validate the model.

Real-Time Performance Test

The performance of the software and hardware of AYMS was assessed by surveying the two fields of size 0.75 and 0.20 ha, respectively. Target ground speed, monitored on the main software screen during the surveys (fig. 2), was 0.5 m/s. Real-time yield mapping was carried out by acquiring images with AYMS on the moving FMV at a spacing of 1.1 m. The software was able to process the images to estimate the percentage blue pixels for the wild blueberry field in real-time. In order to assess the accuracy of AYMS, we correlated the percentage blue pixels of each image with manually harvested actual fruit yield from the selected quadrats in both fields. A foam marker was used for guidance to minimize error caused by overlapping the images. The camera was set to '1/1000' for 'exposure' and 'auto' for other specifications during the surveying. Variations in the natural sky illumination (sunny or cloudy) did not affect the quality of the image processing result and consequently the correlation of blue pixels with fruit yield (Zaman et al., 2008). The kriging technique was used to interpolate the estimated fruit yield data in each field. The estimated fruit yield of each field was mapped in ArcView 3.2 GIS software. The bare spots in the two blueberry fields were also mapped with a handheld ProMark3 (Thales Navigation Inc., ON, Canada) mobile mapper GPS. The fruit yield maps and bare spot maps were placed side-side by for comparison.

Results and Discussion

The linear regression model developed indicated a significant and very positive relationship between percentage blue pixels and manually harvested fruit yield in field 1 ($R^2 = 0.90$; $P < 0.001$) and field 2 ($R^2 = 0.97$; $P < 0.001$) (fig. 4). The correlation between actual and predicted fruit yield (validation, using the equation from field 2) in field 1 ($R^2 = 0.95$; $P < 0.001$; RMSE = 3.29 Mg/ha) and field 2 (validation, using the equation from field 1) ($R^2 = 0.97$; $P < 0.001$; RMSE = 2.69 Mg/ha) was also highly significant (fig. 5). The slight bias can be seen in the scatter plots (fig. 5), where fruit yield was over-estimated and under-estimated. These biases were probably from cumulative error terms (Total), some of which are listed in equation 1.

Most of these errors could be minimized by using site-specific calibrations of <20 points for every field, using a representative range of fruit yield.

The 6,348 georeferenced images (5,011 and 1,336 from field 1 and field 2, respectively) were taken on 15 and 18 August 2008 with AYMS, at a mean speed of 0.5 m/s, requiring 4.4 and 1 h to complete the survey of field 1 and field 2, respectively. The blue pixel ratio data for each field were mapped in Arcview 3.2 GIS software (fig. 6). The percent blue pixels varied from 0 (bare spots) to 9.90% and 0 to 8.19% in field 1 and field 2, respectively (fig. 6). The zero

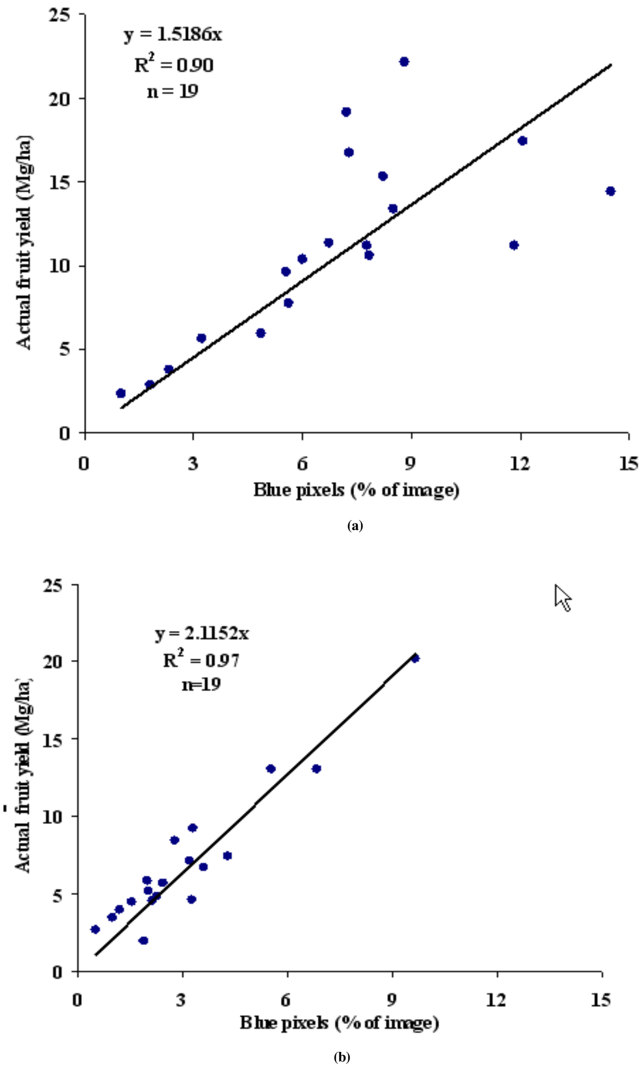

Figure 4. Relationship between percentage blue pixels and actual fruit yield per ha in the calibration data set of (a) field 1 and (b) field 2.

blue pixel ratios were due to bare spots or weeds (no blueberry plants) within blueberry fields. Blueberry fruit yield was also highly variable in field 1 and field 2, and ranged from 0 (bare spots) to 5.62 Mg/ha and 0 to 6.17 Mg/ha, respectively (figs. 7 and 8). The substantial variability in fruit yield and presence of unplanted bare spots within blueberry fields emphasize the need for site-specific agrochemical applications to increase fruit yield, farm profitability, and reduce environmental risks.

$$\gamma Total = \gamma Vm + \gamma Vl + \gamma B \quad (1)$$

where

γ = error term

Vm = underestimated in the areas where vegetation was more and berries were hidden under leaves

Vl = overestimated where the vegetation was less or negligible and mostly berries were exposed to the camera

B = error caused by the black colored berries

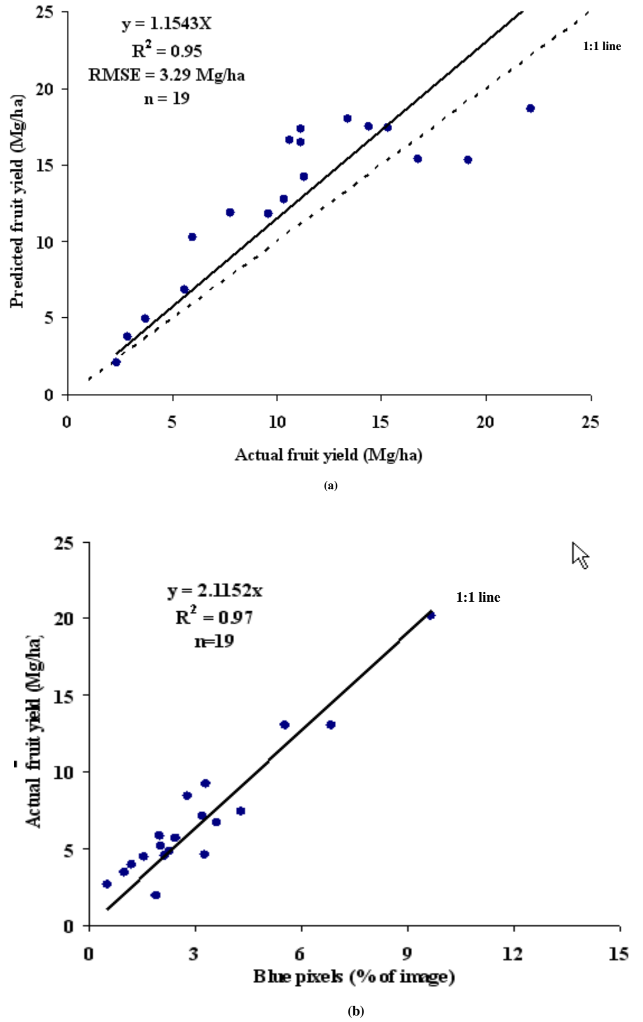

Figure 5. Measured and predicted fruit yield (a) in field 1 predicted using the equation from field 2 and (b) in field 2 predicted using the equation from field 1.

The maps of bare spots and fruit yield were placed side by side to examine the relationship between bare spots and fruit yield (figs. 7 and 8). The fruit yield and bare spot maps display that the yield and bare spots in the field coincided with each other. Mainly, bare spot areas were located close to the boundary of fields 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 agrochemicals in the fields. Zaman et al. (2008) mapped bare spot areas in different wild blueberry fields with mobile mapper GPS. The bare spots varied from 30% to 50% of the total field area and were scattered throughout the fields. The practical implication of uniform applications in wild blueberry fields is to over-fertilize/spray in large areas having significant bare spots. Approximately, 24%, 37%, 31%, 7%, and 1% areas of field 1 and 8%, 37%, 33%, 10%, and 12% areas of field 2 had zero or very low yield, low, moderate, high, and very high yield, respectively. The no yield and very low yielding areas contained bare spots within the fields (figs. 7 and 8). Ground inspections revealed that small amounts of fruit (small numbers of blue pixels) at some locations in bare spots detected by the camera were because of the presence of negligible amounts of blueberry plants at those locations in the field. Unnecessary or over-fertilization in bare spots can deteriorate water quality, promote increased weed growth and reduce profit. Zaman et al. (2005) saved 40% fertilizer with variable rate fertilization as compared to the grower's uniform rate in a Florida citrus orchard. A related study also reduced the nitrate-N concentration in leached soil solution from 28.5 and 14.0 mg/L to 1.5 and 4.5 mg/L under small and large size citrus trees, respectively, by using variable rate fertilization as compared to uniform application (Zaman et al., 2006b). Hence, variable rate application of agrochemicals based on considerable variation in fruit yield, bare spots, and weed patches could improve farm profitability and reduce environmental impacts.

Conclusions

- There was significant correlation between percentage blue pixels and actual fruit yield in field 1 (R^2 = 0.90; P < 0.001) and field 2 (R^2 = 0.97; P < 0.001).
- The correlation between actual and predicted fruit yield (validation) in field 1 (R^2 = 0.95; P < 0.001; RMSE = 3.29 Mg/ha) and field 2 (R^2 = 0.97; P < 0.001; RMSE = 2.69 Mg/ha) also was highly significant.
- Fruit yield maps showed substantial variation within both fields. The fruit yield ranged from 0 (bare spots) to 5.62 Mg/ha and 0 to 6.17 Mg/ha, respectively. The zero or very low yielding areas coincided with bare spot areas within the field.
- The best results were obtained by using site-specific calibration of <20 points for every field, using a representative range of fruit yield.

It can be concluded that there is potential to estimate and map fruit yield and detect blueberry plants and bare spots within wild blueberry fields with the automated yield monitoring system. The automated yield monitoring will be incorporated into a wild blueberry harvester for real-time mapping of fruit yield. The information obtained with the system could be used to implement site-specific management practices within the blueberry fields to optimize productivity while minimizing the environmental impact of farming operations.

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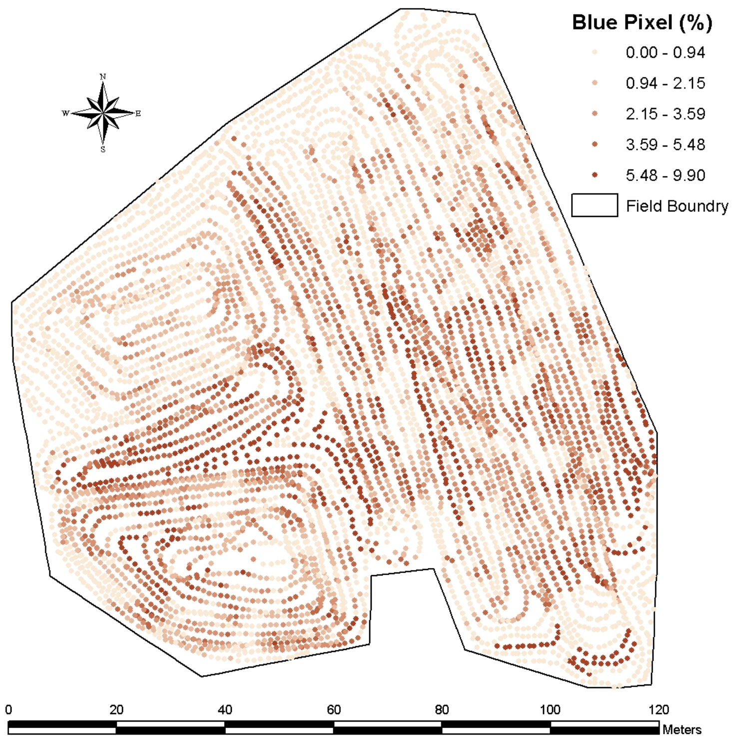

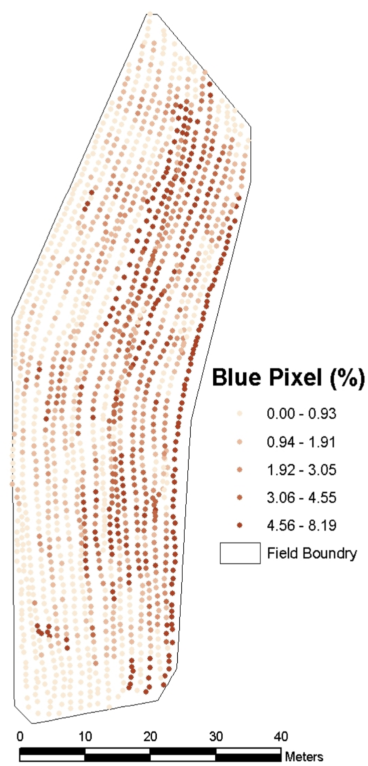

Figure 6. Maps showing blue pixel (%) of each image using automated yield monitoring system in field 1 (top) and field 2 (bottom).

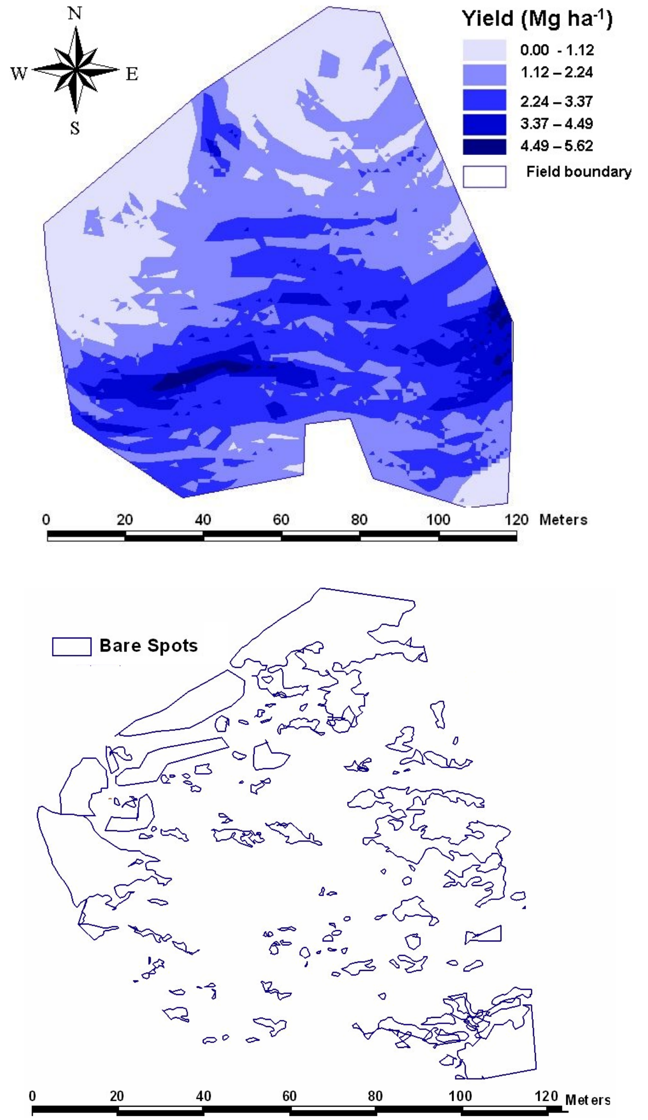

Figure 7. Maps of field 1 showing fruit yield variability using automated yield monitoring system (top) and bare spots mapped with mobile mapper GPS (bottom).

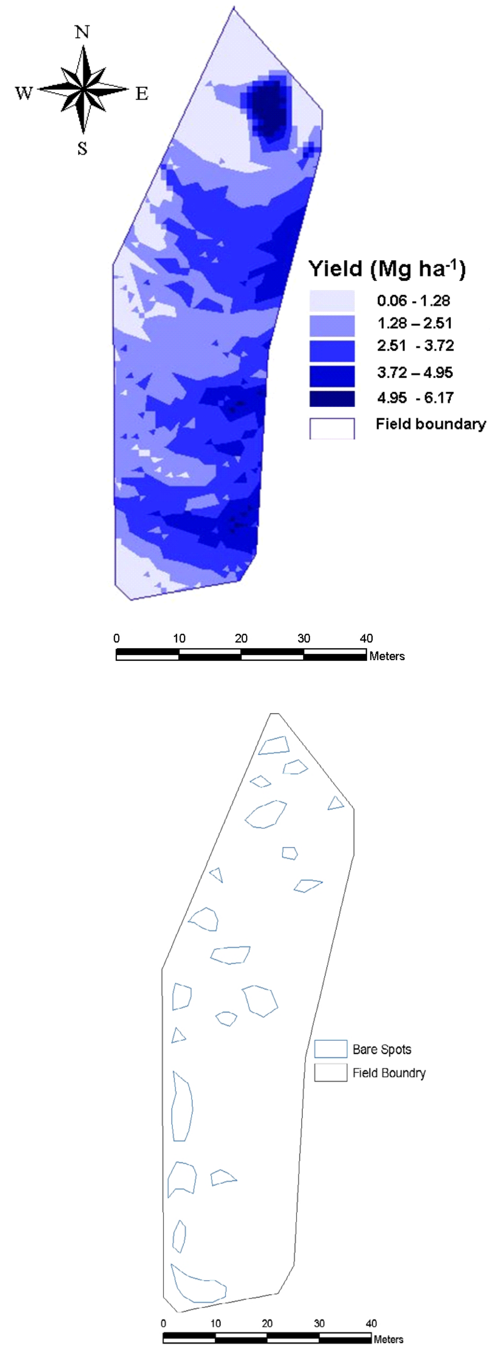

Figure 8. Maps of field 2 showing fruit yield variability using automated yield monitoring system (top) and bare spots mapped with mobile mapper GPS (bottom).

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