Progress Report

Precision Harvesting Technologies to Improve Berry Yield and Quality

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DBE
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Improving Berry Picking Efficiency during Harvesting Using Precision Agriculture Technologies and Bio-Systems Modeling

Dr. Zaman and his Precision Agriculture (PA) Research Team launched an initiative to develop innovative harvesting technologies in Atlantic wild blueberries. This proposal was a part of a multi-disciplinary research effort at the Engineering Department, Faculty of Agriculture, Dalhousie University in collaboration with Doug Bragg Enterprises (DBE), Collingwood, Nova Scotia. This collaboration between industry and research scientist was initiated to develop innovative and viable techniques that should enhance berry picking efficiency, assist with the stabilization of yields over time and increase farm profitability. While this project is submitted with the collaboration of wild blueberry industry to increase harvestable berry yield and quality, the DBE harvester is being used to harvest 80% of the total acreage of wild blueberry in the Atlantic Provinces. The combination of research and technology transfer activities situated within the project are in the process of resulting in the continued development of more efficient, sustainable, and environmentally friendly harvesting technologies, the continued training of graduate students, post-doc fellows, wild blueberry producers and industry personnel, and a more competitive wild blueberry industry.

The research project "Improving efficiency of commercial wild blueberry harvester using precision agriculture technologies" was completed in September 2016. This research would help to ensure the long term stability of industry and make growers more profitable over time. The research contains training of HQPs component in the form of graduate and undergraduate student and postdoctoral fellow, and the continuing "lifelong" applied education of producers and industry representatives. Therefore, it is anticipated that this research would improve the current knowledge base of wild blueberry industry, potentially provide innovative technologies to reduce harvesting losses, and increase blueberry supply, and improve socio- and economic conditions in rural Atlantic Canada and Quebec. The PA team at Dalhousie Agricultural Campus is actively involved in transferring viable technologies including publications in scientific journals, growers' magazines, radio and TV talks, presenting in national, international and industry meetings, and demonstrating the technologies in farmers' field days. Results of current research project would increase harvestable berry yield and reduce operator stress.

Introduction

Northeastern North America is the world's leading producer of wild blueberry *(Vaccinium angustifolium* Ait.) with over 93,000 ha under management and producing 145 million kg of fruit valued at $600 million annually. The crop is unique as it is native to North America and has never been cultivated. Fields are predominately managed on two-year cycles with the perennial shoots pruned in alternative years to maximize floral bud initiation, fruit set, yield, and ease of mechanical harvest. Wild blueberry crop has been harvested using a hand rake that was originally designed as a cranberry scoop for the past 100 years. The increase in fruit yields over last few decades, shortage of labor and consequently the increase of wages have increased the demand for mechanized harvesting (Yarbrough, 1992). Although, the research on development of the mechanical harvester started in early 1950s, a viable mechanical harvester was not produced until the 1980s (Hall *et al*., 1983). Hall *et al*. (1983) estimated that the Bragg blueberry harvester attains 68% (in weedy fields) to 75% (smooth weed free fields) of total berry yields.

Currently, the mechanically harvested blueberry area is more than 80% of the total wild blueberry area in Canada and only the fields in rough terrain are still hand raked (PMRA, 2005). In last two decades, increased management practices using selective fertilizers and pesticides have resulted in healthy and tall plants, high plant density, tall weeds and significant increase in fruit yield. The increased harvesting losses of wild blueberry crop during harvesting due to change in crop and field conditions have pushed the growers and processors within the industry to set a goal, to increase the harvestable yields of wild blueberries by 33% to justify ever increasing cost of agrochemicals. Currently, there are 15 to 25% fruit yield losses during the harvesting with existing commercial blueberry harvester. Increased harvesting efficiency of the harvester would reduce fruit losses and contribute $31,200,000 to Atlantic Provinces and Quebec economy every year (WBPANS, 2010).

Improvements to the existing harvester using novel, automated and integrated precision agriculture (PA) systems to increase agricultural production will require; (i) identification of sources responsible for increased losses and reduced berry quality; (ii) improve harvestable berry recovery; (iii) replace old technology with innovative integrated harvesting system; (iv) find a suitable combination of ground speed and harvester head revolution with minimum losses after detailed evaluation of harvester using PA technologies and mathematical modeling procedures; (v) redesign the commercial blueberry harvester components to increase berry picking efficiency.

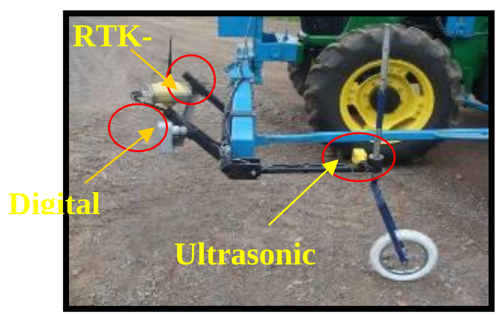
The two primary objectives of this research initiative were to; (i) develop sensor fusion system for quantification of blueberry fruit yield losses; (ii) develop models for identification of sources of losses to improve harvesting efficiency in order to increase fruit yield; and (iii) train highly qualified personnel, producers and industry representatives.

Significant Research Results

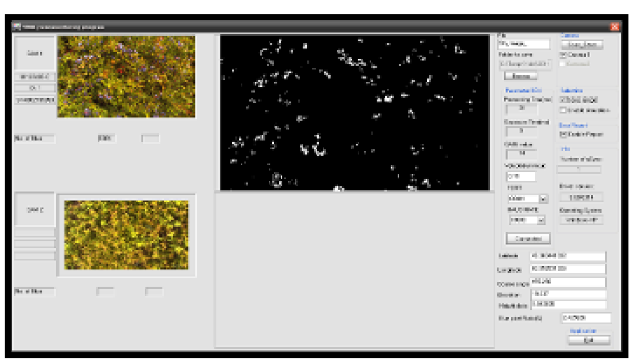
1. **Sensor Fusion System**

Development of Automated Sensor Fusion

An integrated automated sensing system including ultrasonic sensor, digital color camera, slope sensor, RTK-GPS, custom software and laptop computer was developed. The system was incorporated into a blueberry harvester to map plant height, slope, elevation and fruit yield simultaneously. The information obtained from the system will be used to identify factors affecting harvesting efficiency of wild blueberry harvester. Commercial wild blueberry fields at different sites in Atlantic Provinces were surveyed to evaluate the performance of the system. Information obtained from the system could be used to increase berry picking efficiency of blueberry harvester. This information could also be used to optimize productivity while minimizing the environmental impact of farming operations in fields.



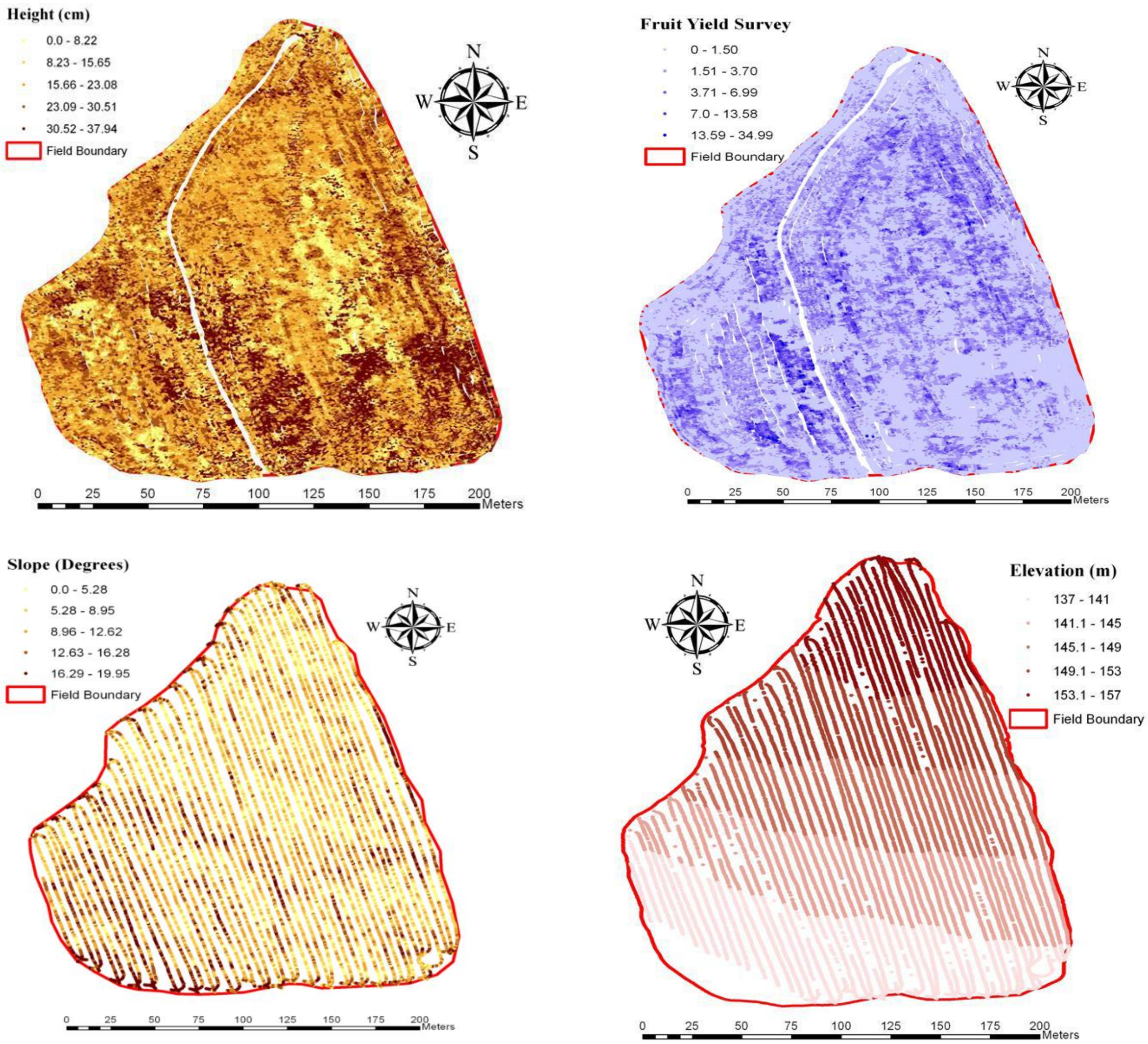
Yield monitoring system, ultrasonic sensor and RTK-GPS incorporated into harvester



Custom software to estimate fruit yield, plant height and topographic features

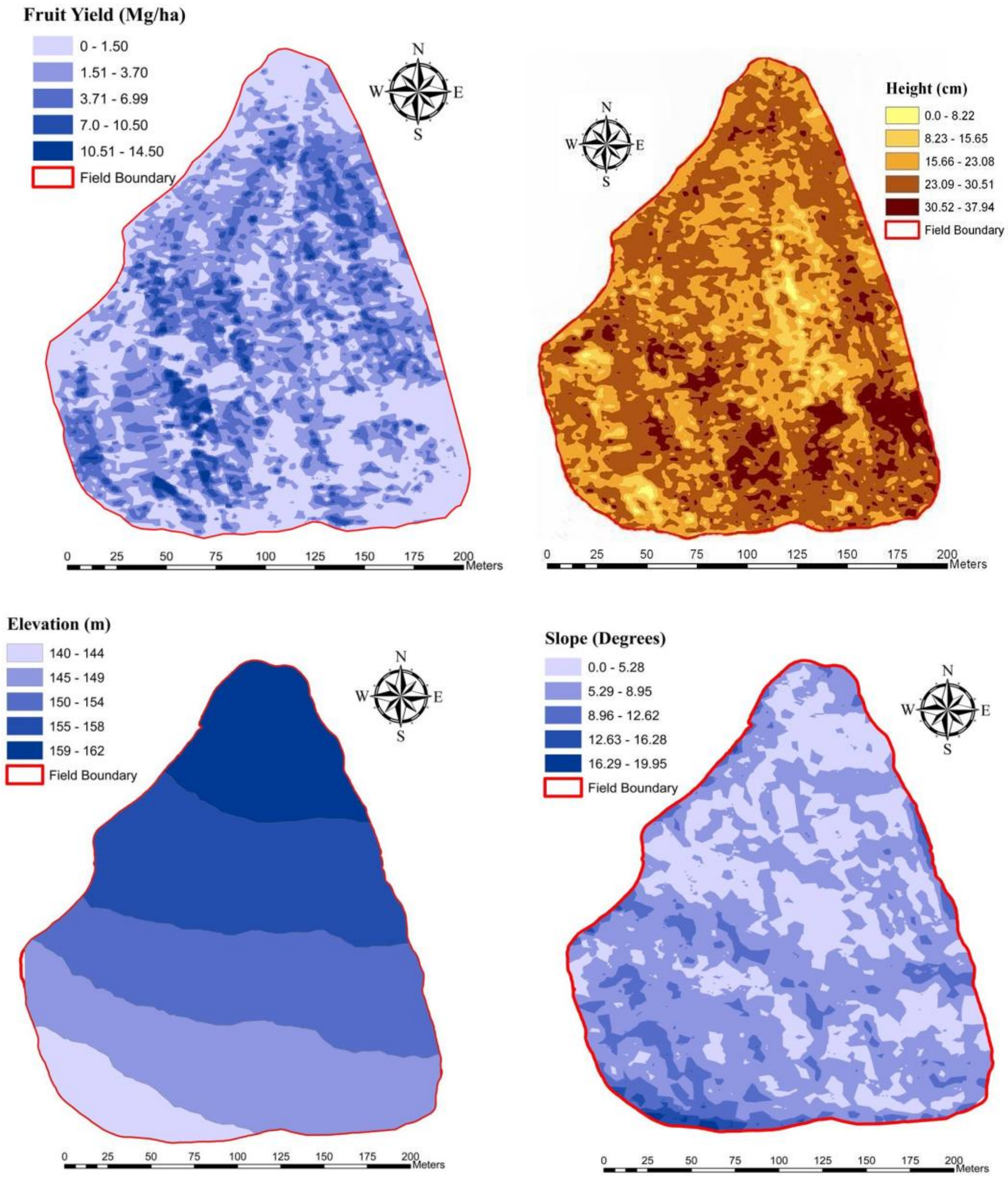
The developed system was tested and evaluated in selected wild blueberry fields i.e., Frankweb, Nova Scotia (4.10 ha); Londonderry, Nova Scotia (3.2 ha); Small Scott, Nova Scotia (1.6 ha) and Tracadie, New Brunswick (1.9 ha) to map plant height, slope, elevation and fruit yield in real-time. Customized Windows-based software on a laptop computer was developed to merge the plant height, elevation, slope, and fruit yield data with corresponding RTK-GPS spatial coordinates.

Surveys were conducted to measure and map crop parameters and topographic features during July, 2013, and fruit yield was measured and mapped during harvesting season (August to mid-September, 2013) in selected wild blueberry fields. The integrated system took more than 30,000 data points for Small Scott and Tracadie fields; and more than 55,000 sampling points for Frankweb and Londonderry fields to estimate plant height, slope, elevation and fruit yield in real-time. Due to space constraint results of Cooper site are presented here.



Raw data maps of fruit yield, plant height, slope and elevation obtained from sensor fusion system.

The μEye camera mounted on commercial wild blueberry harvester estimated fruit yield of 10,232 kg, while the actual yield collected in the harvester bin weighed at 9,100 kg for Cooper site suggesting 11.07% loss of berries during harvesting. The digital color camera indicated 8.74% pre-harvest loss of berries for Small Scott site. These results suggested that there is need to conduct research on the harvester picking efficiency in different yield (low, medium and high) areas to quantify the wild blueberry fruit losses during harvesting.



Kriged maps of fruit yield, plant height, elevation and slope with sensor fusion system.

The characterization and quantification of the soil properties, topography (slope and elevation), fruit yield and plant parameters allows to generate zones, to identify if there is any effect of these parameters on the harvesting efficiency of the harvester. Variations in soil properties, plant characteristics and topographic features corresponding with the variability in fruit yield will provide strong evidence in determining the factors affecting localized yield and increasing yield losses during harvesting.

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. The negative but non-significant relationship ($r = -0.20$) between the fruit yield and plant height also supported the correlation identified by the maps. The substantial variation in mapped parameters and presence of bare spots/weeds within blueberry fields suggested that these parameters could be playing a significant role in wild blueberry fruit losses during harvesting.

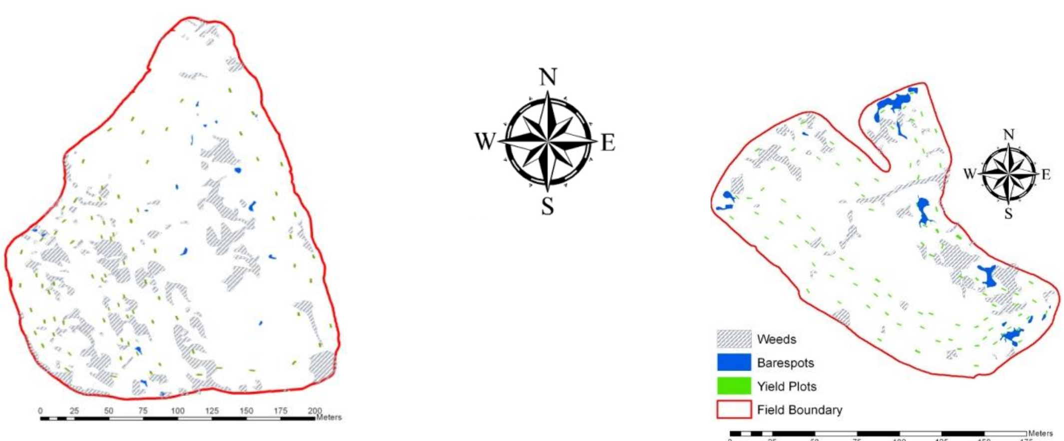
The sensor fusion system (hardware and custom software; SFS) was developed and incorporated into wild blueberry harvester after lab testing and calibration of analog and digital sensors to map variability in plant height, fruit yield and topographic features in real-time. SFS mounted on harvester was evaluated in commercial blueberry fields in Atlantic Canada. Calibration and mapping results indicated that the developed system was an accurate, reliable and efficient to map plant height, fruit yield, slope and elevation in real-time. Results indicated that that there was a need to conduct research on harvester picking efficiency in different yield (low, medium and high) areas to quantify blueberry losses. This would help wild blueberry industry to generate more revenue and increase profitability. *Research results were published in scientific journal Computer and Electronics in Agriculture and presented in international conference and industry meetings. This research was part of PhD thesis research (completed).* These research results will directly support the automation of blueberry harvester to improve berry picking efficiency and reduce operator stress.

2. **Quantification of Fruit Losses During Harvesting to Improve Berry Picking Efficiency**

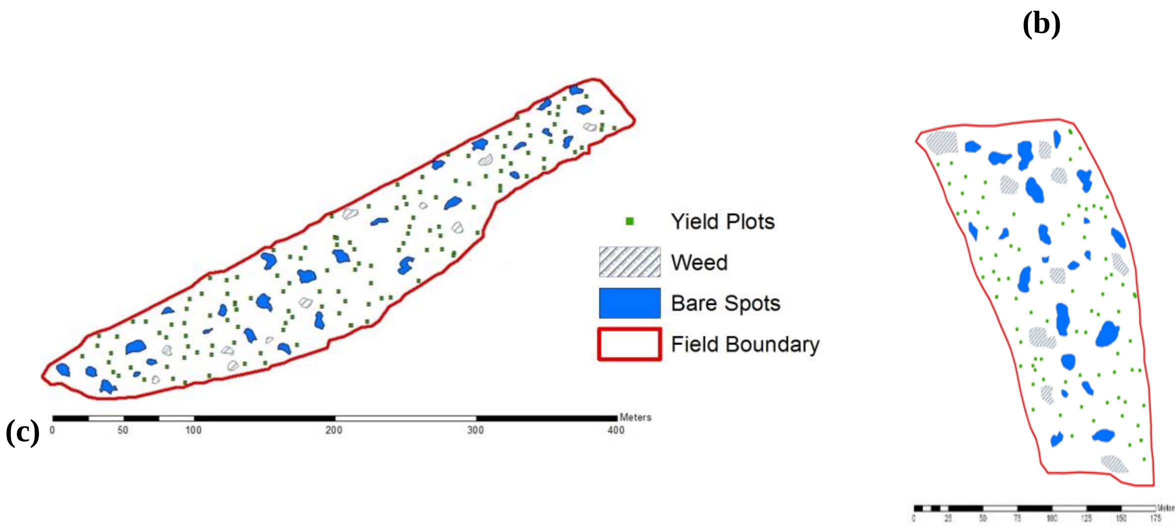
Wild blueberry fields were selected to evaluate the berry picking efficiency of commercial wild blueberry harvester. The harvester was operated at specific levels of ground speed at 1.20, 1.6 and 2.0 km h^{-1} and header rpm 26, 28 and 30. The total fruit yield, un-harvested berries on the plants, berries on the ground, and berries through blower were collected from each plot within selected fields. The pre-harvest fruit losses were collected from each plot prior to harvest. The slope, plant height and fruit zone were also recorded manually from each plot. Results of this study showed a treatment combination of 1.2 km h^{-1} and 26 rpm can result in significantly lower losses as compare to higher ground speed and header rpm in blueberry fields with yield over 3500 kg ha^{-1}. *Results were published in scientific journal Applied Engineering in Agriculture and presented in international conference and industry meetings. This research was part of PhD thesis research (completed).* This information will help to develop an automated system (hardware and software) to adjust ground speed and header rpm automatically according to the variation in fruit yield to increase harvestable berry yield.

Evaluation of Berry Picking Performance Efficiency of Harvester

Wild blueberry fields were selected (Frankweb, Nova Scotia; Londonderry, Nova Scotia; Small Scott, Nova Scotia and Tracadie, New Brunswick) to evaluate the berry picking efficiency of the commercial wild blueberry harvester. Eighty one yield plots were selected randomly in each field. The harvester was operated at specific levels of ground speed at 1.20, 1.6 and 2.0 km h^{-1} and header rpm of 26, 28 and 30. The pre-harvest fruit losses were collected from each plot prior to harvest. The slope, plant height, and fruit zone were also recorded manually from each plot. The experimental plots were set up in selected wild blueberry fields based on variations in slope (flat field, mild and steep slope), plant height (low, medium high) and fruit yield (low, average and high), to quantify the harvester berry picking losses.



(a)

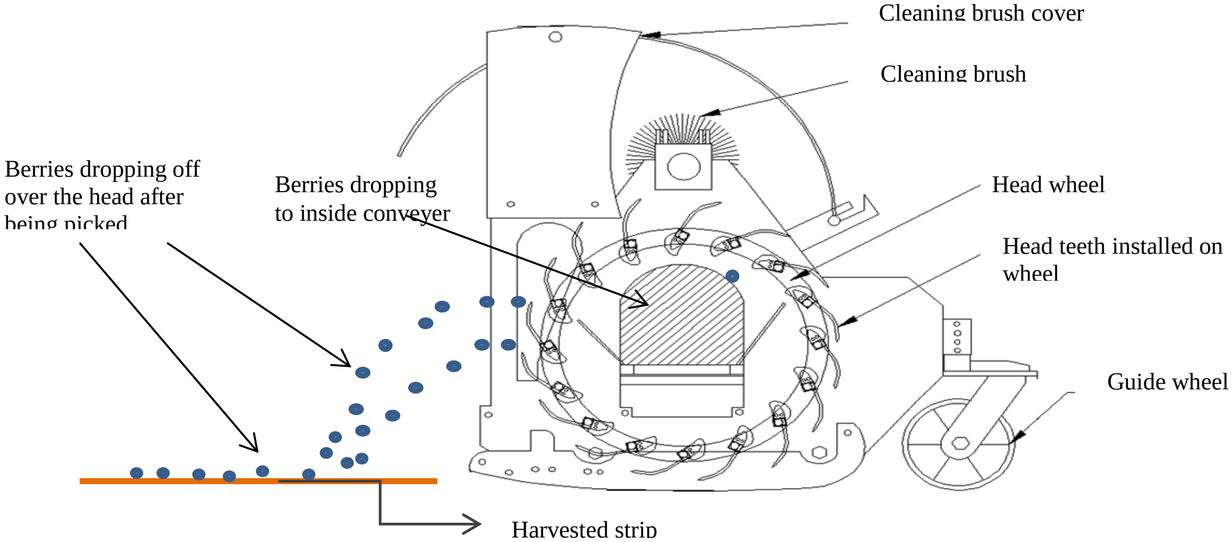


Layouts of selected wild blueberry fields

The data collected for fruit losses was analyzed using statistical; geo-statistical, bio-systems modeling and mapping tools to calculate the fruit losses at various combinations of ground speed and revolutions and to identify the factors responsible for losses.

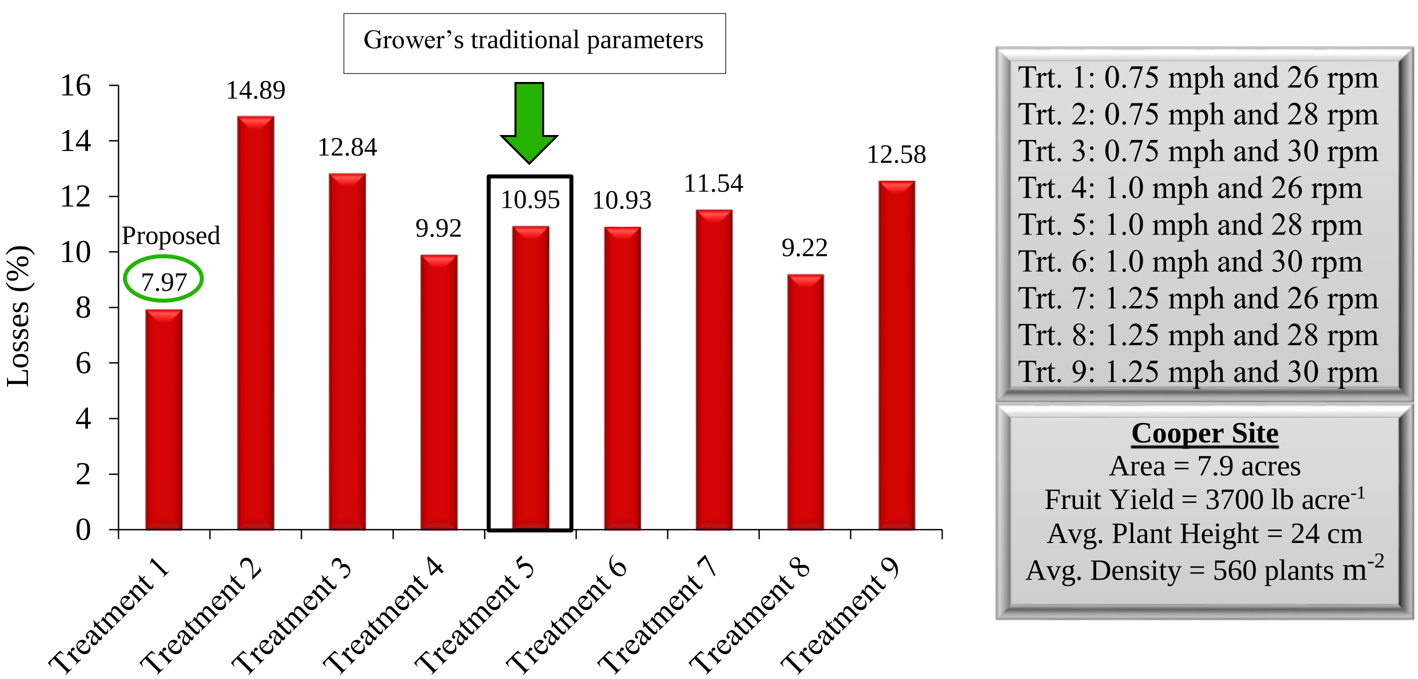
Collection of losses on the ground and un-harvested berries on the plants and fruit losses through blower and total fruit yield from the harvested plot.

The results of this study suggest that the pre-harvest fruit losses are found to be higher during the late season suggesting that early season harvesting could be helpful in reducing pre-harvest fruit losses. Higher percentage of losses on the ground suggested that the berries were picked by the harvester but not effectively conveyed to the inside conveyer for transportation to the storage bin on the back of the harvester. The losses on the ground emphasized the need to operate the harvester at lower ground speed and header rpm to provide a gentle upward movement of reel teeth bars through the plants to enhance berry picking efficiency.

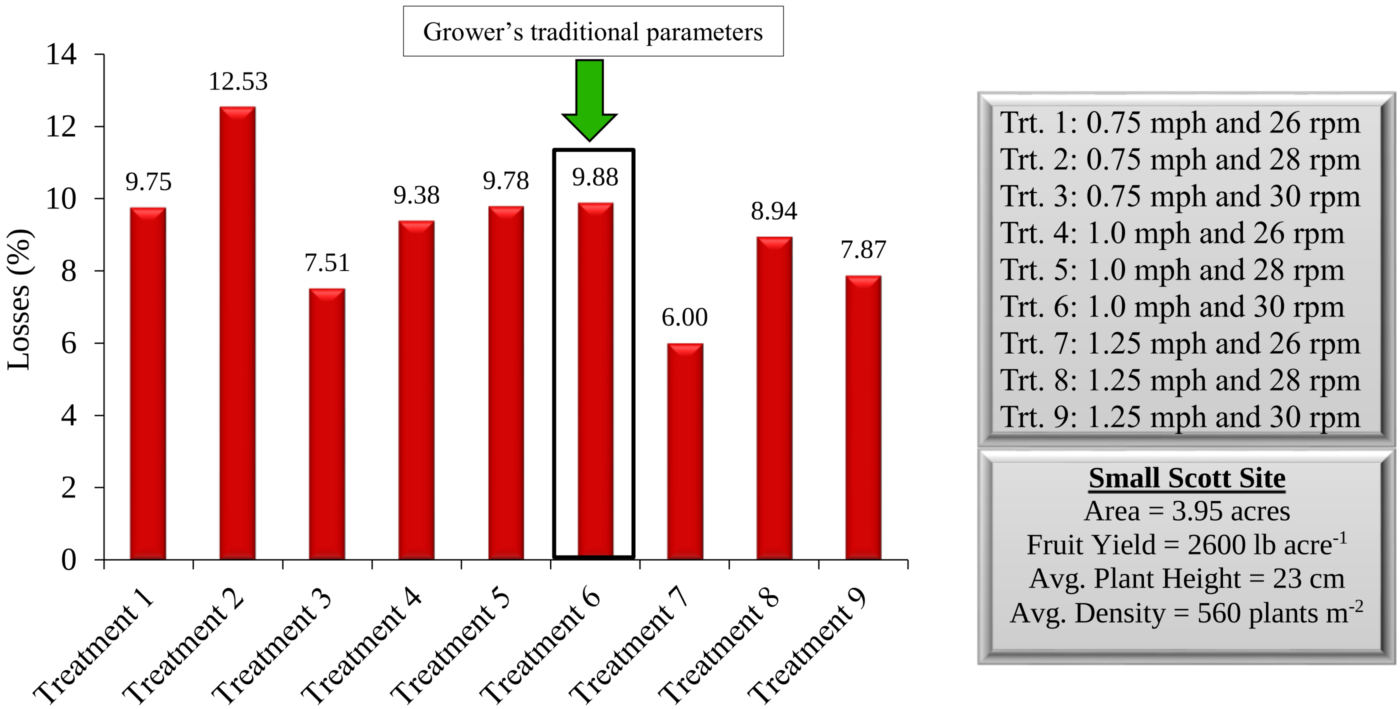


Berries dropped over the harvester strip after being picked by the harvester head during harvesting.

Fruit loss during harvesting is a linear function of the fruit yield, as fruit yield increases the fruit losses increases and vice versa. Based on the ANOVA results it can be concluded that ground speed, header rpm and their interaction can cause significant differences in the picking efficiency of the wild blueberry harvester.



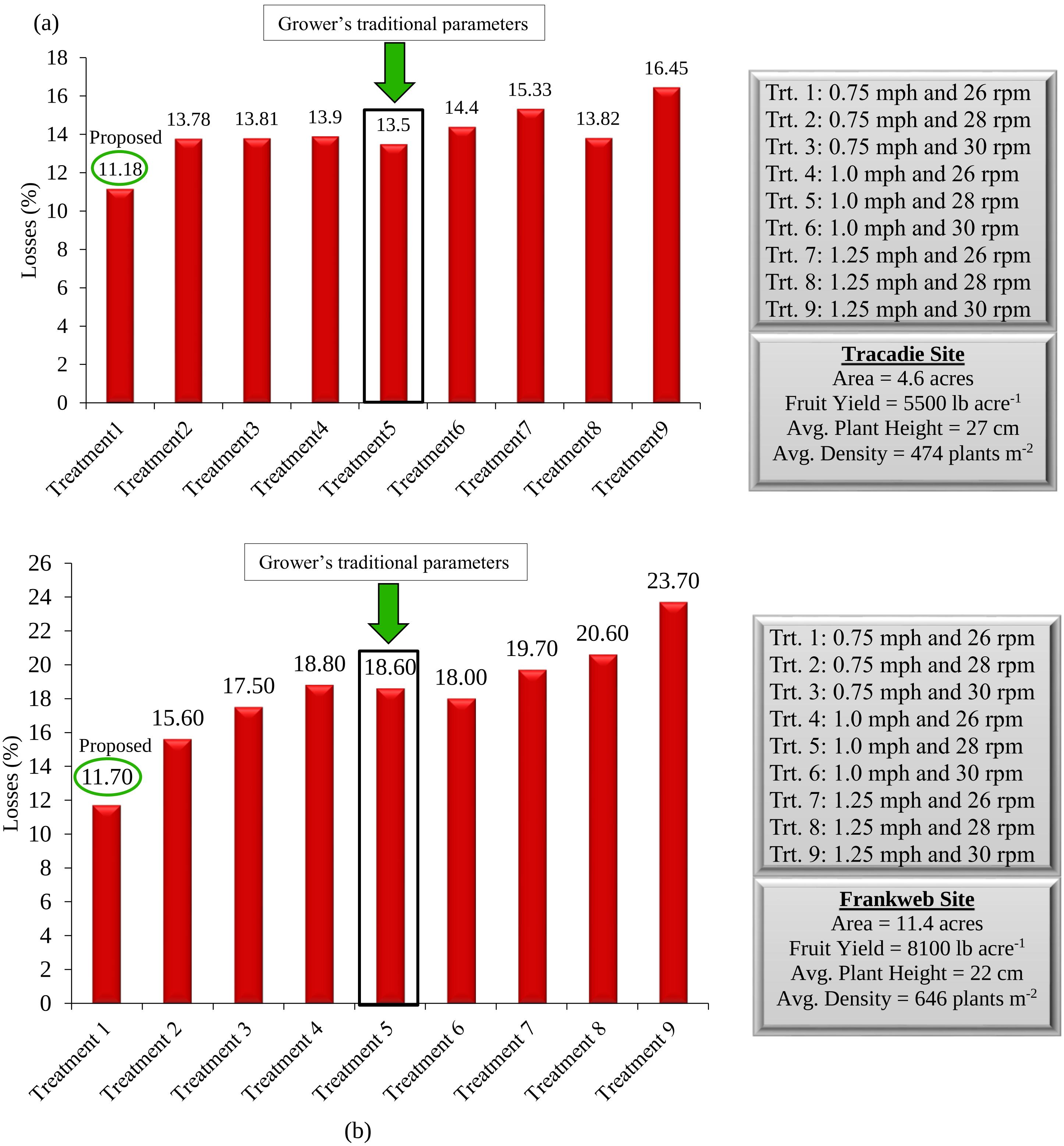
(a)



(b)

Mean comparison for total fruit losses (%) at different treatment combination for (a) Cooper site, and (b) Small Scott site.

The results of means comparison showed a treatment combination of 1.2 km h^{-1} and 26 rpm can result in significantly lower losses as compare to higher ground speed and header rpm in wild blueberry fields with yield over 3500 kg ha^{-1}. In low yielding fields (<3500 kg ha^{-1}) a combination of 2.0 km h^{-1} and 26 rpm can do a better job to increase the berry picking efficiency of the commercial wild blueberry harvester. Other factors including operator skills, field conditions, time of harvesting, weather conditions, bare spots and weed coverage, crop maturity, crop characteristics and improper maintenance of the harvester can change the picking efficiency and berry recovery of the harvester. By choosing an ideal combination of ground speed and header rpm can minimize the fruit losses to increase farm profitability.



Mean comparison for total fruit losses (%) at different treatment combination for (a) Tracadie site, and (b) Frankweb site.

3. **Modification/Evaluation of Different Harvester Heads to Reduce Fruit Loss**

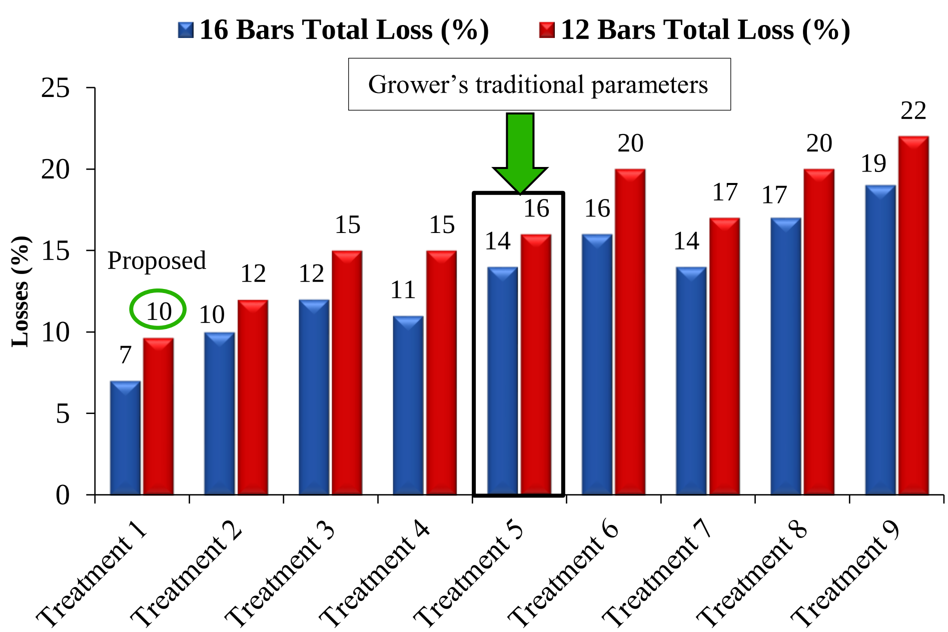
Different components (number of teeth bars, spacing in bars, spacing in teeth, head diameter, inner conveyor width) of traditional harvester head (22" dia. and 16 teeth bars) were modified and evaluated in lab and field using innovative techniques to increase harvestable yield. Design analysis of different harvester heads (traditional and modified) was performed to calculate tip velocities, tangential and radial forces, patterns and paths of operating harvester along with the capacities of the internal and external conveyer of harvester, to examine their impact on picking efficiency and berry quality.

Wild blueberry fields were selected in Atlantic Provinces. Fruit losses (losses on the ground, losses on the leaves, blower losses, pan losses, and pre-harvest losses) and fruit yield were collected at different crop conditions (small and tall plants, low to high plant density, low and high yield, different fruit zone and dia.) from selected fields. Variation in plant height, fruit yield and slope were mapped with multiple sensors and related to field losses. The information obtained will help to develop integrated harvesting technologies and adjust machine parameters automatically in order to reduce fruit losses.

a) Comparison of Harvester Heads (12 bar and 16 bar)

Traditional blueberry harvester has sixteen bars head. The DBE has been trying to improve the design of harvester head in order to reduce fruit losses during harvesting. Based on the preliminary results of this project and design analysis of principle components of existing sixteen bars harvester, a twelve bars harvester head with more spacing between bars was developed to improve berry picking efficiency. Both harvester heads were operated at different combination of ground speeds (1.2, 1.6, and 2.0 km h^{-1}) and header rpm (26, 28, and 30 rpm).

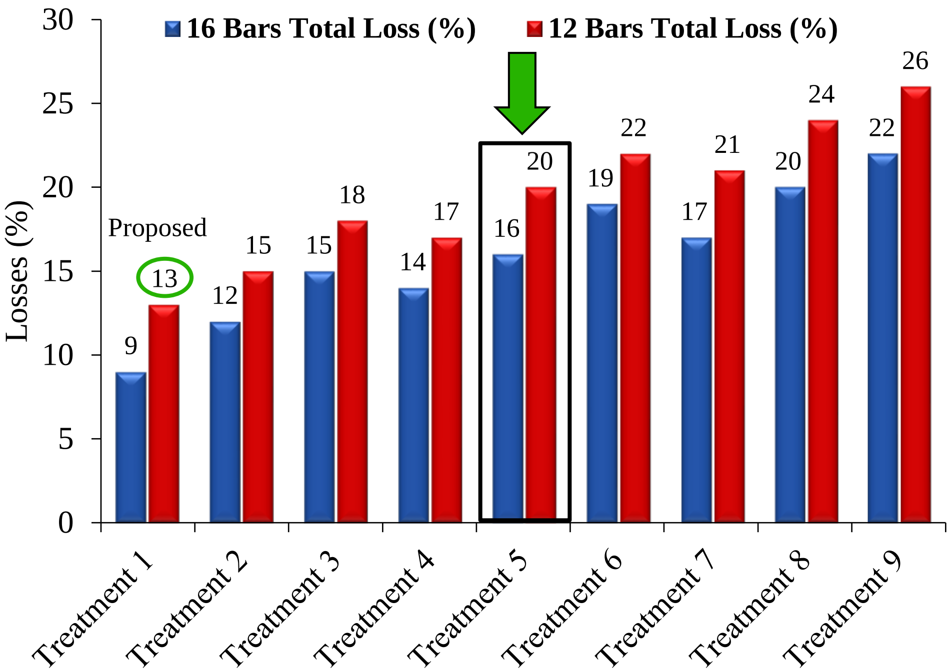
Results indicated that twelve bars harvester head caused 15.18% and 28.82% higher losses (%) as compared to sixteen bars head. The 12 bar head provided more space for plants which causes the head to take bigger bites. The 12 bar head combed through each plant 6 times, while the 16 bar head combed through each plant 9 times. The capacity of the 12 bar head was 25% lower than 16 bar head. The 16 bar head kept the berries more securely inside the header. The 12 bar head pulled 12% and 39% more plants when compared with 16 bar head during dry and wet conditions, respectively. Field experimentation, visual observations and video clips proved that there were significantly higher losses with 12 bar head. *Presented in international conference and industry meetings.*



Trt. 1: 0.75 mph and 26 rpm
Trt. 2: 0.75 mph and 28 rpm
Trt. 3: 0.75 mph and 30 rpm
Trt. 4: 1.0 mph and 26 rpm
Trt. 5: 1.0 mph and 28 rpm
Trt. 6: 1.0 mph and 30 rpm
Trt. 7: 1.25 mph and 26 rpm
Trt. 8: 1.25 mph and 28 rpm
Trt. 9: 1.25 mph and 30 rpm

Robbie Glenn Site
Area = 8.0 acres
Fruit Yield = 3385 lb $acre^{-1}$
Avg. Plant Height = 23 cm
Avg. Density = 560 plants m^{-2}

Mean comparison of total fruit losses (%) with 12 bars and 16 bars heads for Robbie Glenn Site.

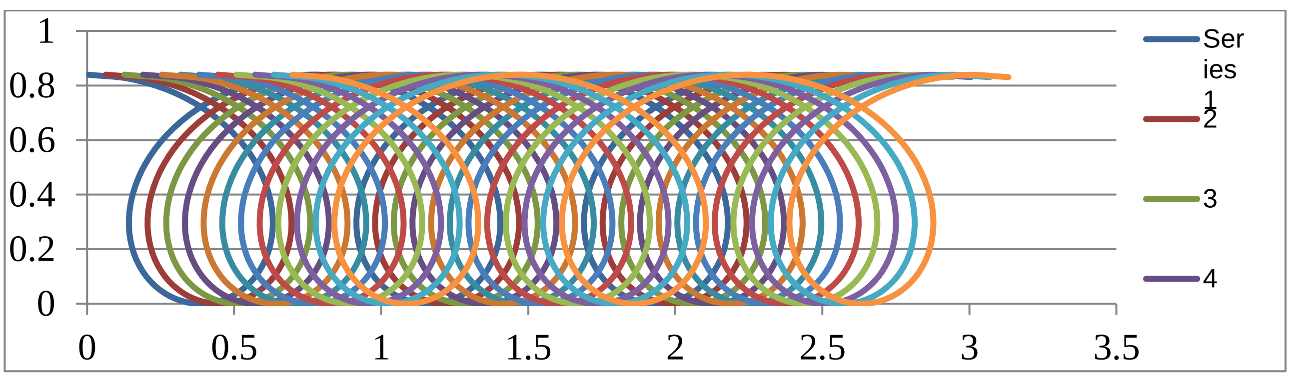


Trt. 1: 0.75 mph and 26 rpm
Trt. 2: 0.75 mph and 28 rpm
Trt. 3: 0.75 mph and 30 rpm
Trt. 4: 1.0 mph and 26 rpm
Trt. 5: 1.0 mph and 28 rpm
Trt. 6: 1.0 mph and 30 rpm
Trt. 7: 1.25 mph and 26 rpm
Trt. 8: 1.25 mph and 28 rpm
Trt. 9: 1.25 mph and 30 rpm

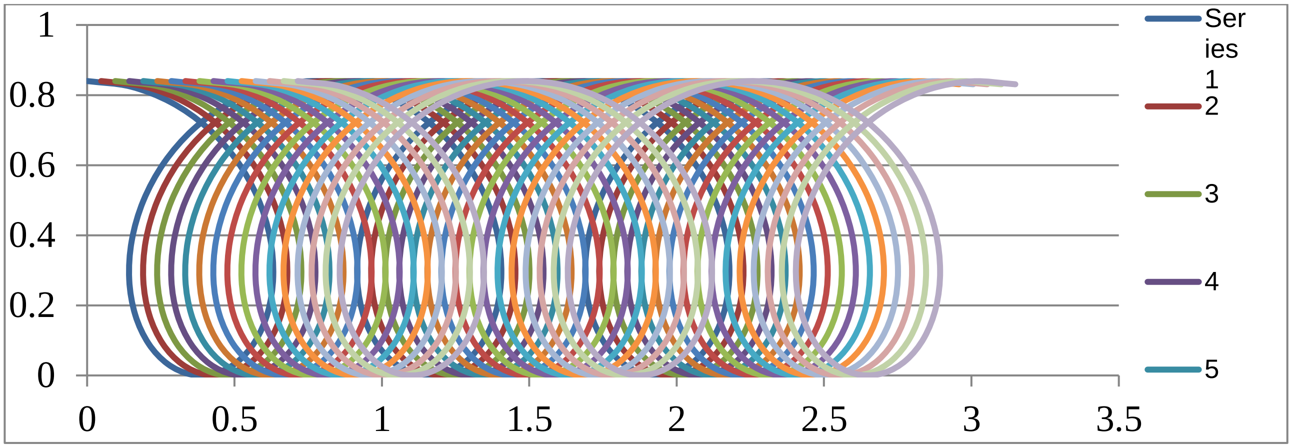
<u>Hardwood Hill Site</u>
Area = 5.1 acres
Fruit Yield = 6973 lb acre^{-1}
Avg. Plant Height = 19 cm
Avg. Density = 646 plants m^{-2}

Mean comparison of total fruit losses (%) with 12 bars and 16 bars heads for Hardwood Hill Site.

12 bar head combed 6 times through each plant



16 bar head combed 9 times through each plant



Head Capacity Comparison

16 Bar Head		12 Bar Head	
Max Yield Harvestable (Kg/ha)	25568	Max Yield Harvestable (Kg /ha)	19176
5% Leaves by Volume	24290	5% Leaves by Volume	18217
10% Leaves by Volume	23011	10% Leaves by Volume	17259
15% Leaves by Volume	21733	15% Leaves by Volume	16300

The capacity for the 12 bars head is 25% lower than 16 bars head

Conclusion:

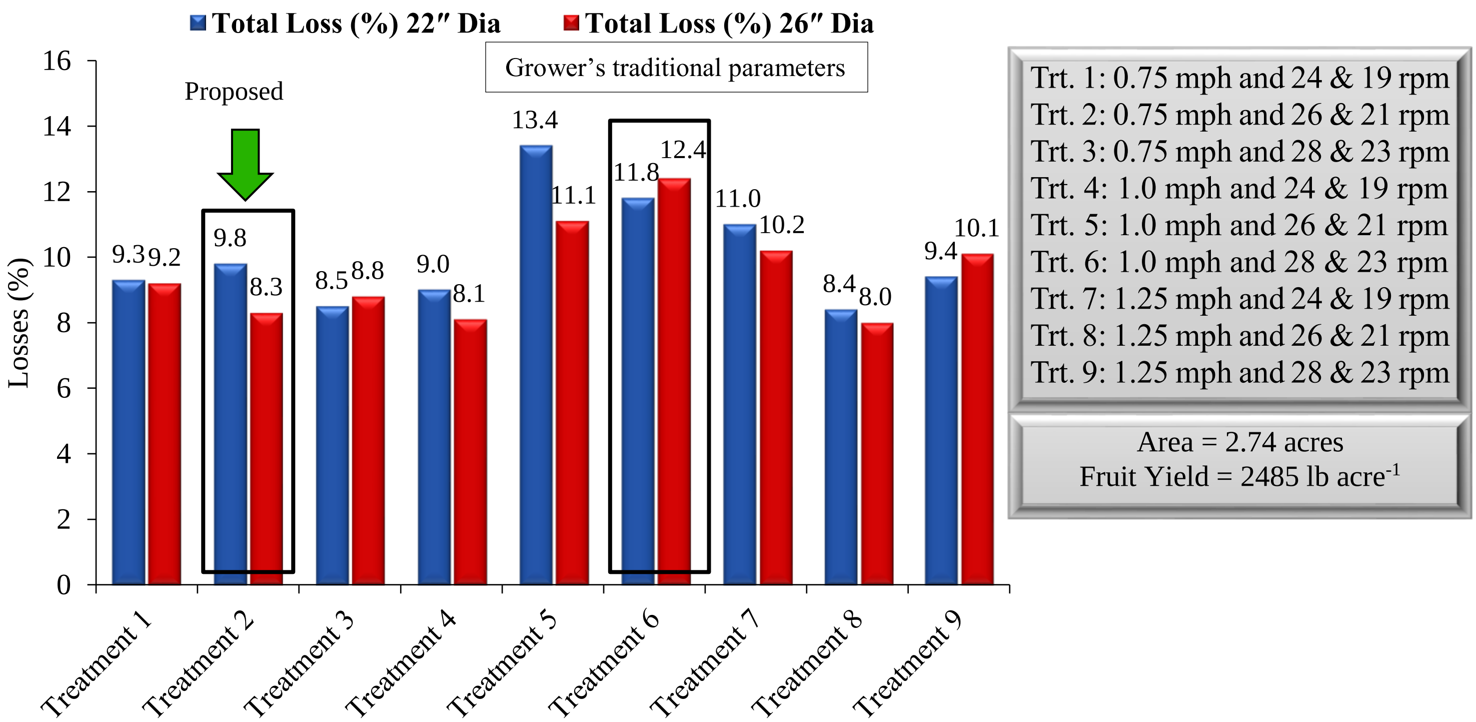
- ✓ The 12 bar head provides more space for plants which causes the head to take bigger bites
- ✓ The 12 bar head combed through each plant 6 times, while the 16 bar head combed through each plant 9 times
- ✓ The capacity of the 12 bar head is 25% lower than 16 bar head
- ✓ The 16 bar head keep the berries more securely inside the header
- ✓ The 12 bar head pulled 12% and 39% more plants when compared with 16 bar head during dry and wet conditions, respectively

We propose harvester should be operated at a combination of 0.75 mph and 26 rpm in wild blueberry fields with yield over 3000 kg ha^{-1} to reduce berry losses.

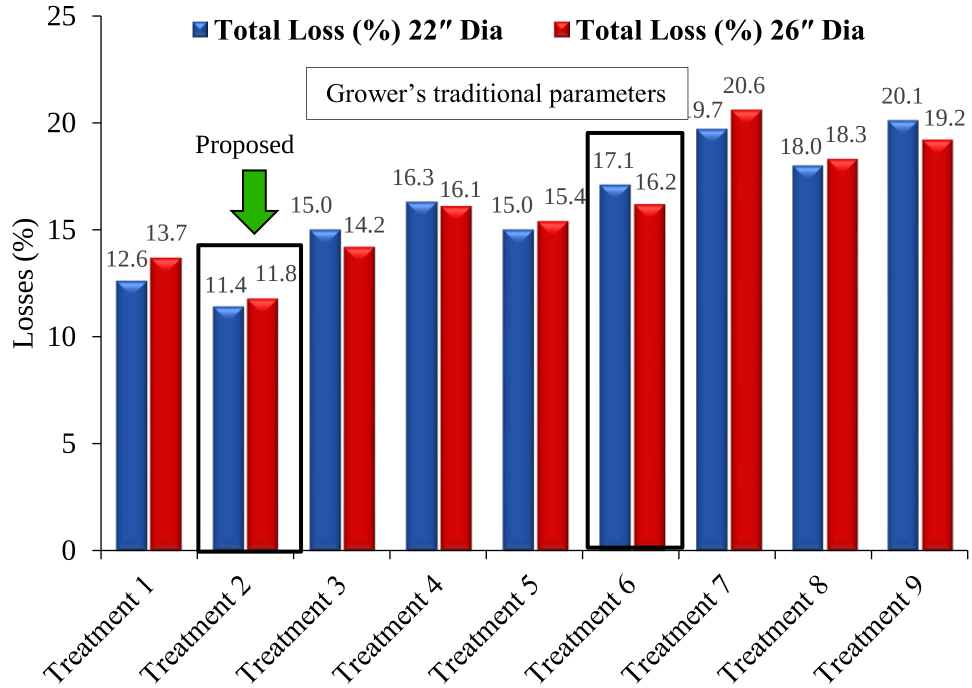
b) Comparison of Harvester Heads (22” dia. and 26” dia.)

Traditional harvester was modified, based on previous results of lab (design analysis) and field experiments using PA technologies to improve berry picking efficiency of harvester. Traditional head (22” dia) was modified by increasing the diameter of head and inner diameter of conveyer. Both harvester heads were operated at different combination of ground speeds (1.2, 1.6, and 2.0 km h^{-1}) and header rpm for 22 dia head (26, 28 and 30 rpm) and comparable head rpm (20, 22 and 24 rpm) for 26” head. Results indicted less fruit loss with 26’ diameter head in traditional fields than 22” dia. head. The 26” diameter head pulled less plants than 22” head during harvesting.

Larger circumference with 26” head allowed for debris to be more thoroughly cleaned from picker teeth. (Stretched bar spacing on the 26” diameter head). Improved cam action resulted in a gradual picking action with 26” head. The inner head conveyor width was increased from 8” to 12” on 26” diameter head, allowing for a larger carrying capacity. The wider conveyor seems to allow for better berry handling when travelling on steep slopes (less dropped berries). The 26” dia head worked well on rough terrain and required less adjustment in head height without digging ground surface. *Results were presented in industry meetings and reported in routinely progress report.*



Mean comparison of total fruit losses (%) for 22” dia and 26” dia heads at different treatment combination



Trt. 1: 0.75 mph and 24 & 19 rpm
Trt. 2: 0.75 mph and 26 & 21 rpm
Trt. 3: 0.75 mph and 28 & 23 rpm
Trt. 4: 1.0 mph and 24 & 19 rpm
Trt. 5: 1.0 mph and 26 & 21 rpm
Trt. 6: 1.0 mph and 28 & 23 rpm
Trt. 7: 1.25 mph and 24 & 19 rpm
Trt. 8: 1.25 mph and 26 & 21 rpm
Trt. 9: 1.25 mph and 28 & 23 rpm

Area = 9.59 acres
Fruit Yield = 6781 lb $acre^{-1}$

Mean comparison of total fruit losses (%) for 22” dia and 26” dia heads at different treatment combination

Teeth Bar Spacing

22‘ Diameter Head

Spacing between the teeth bars - **1.37** inches

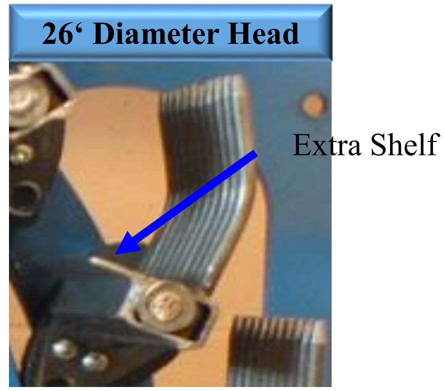
26‘ Diameter Head

Spacing between the teeth bars - **1.63** inches

Head Capacity Comparison

Part	26’ Head	22’ Head
Harvester Head (kg/ha)	218312.41	98602.43
Interior Conveyor (kg/ha)	34223.43	25164.17
Exterior Conveyor (kg/ha)	21426.52	21426.52
Overall Maximum (kg/ha)	21426.52	21426.52

The capacity for the 26’ Head is **26% higher** than the 22’ Head.

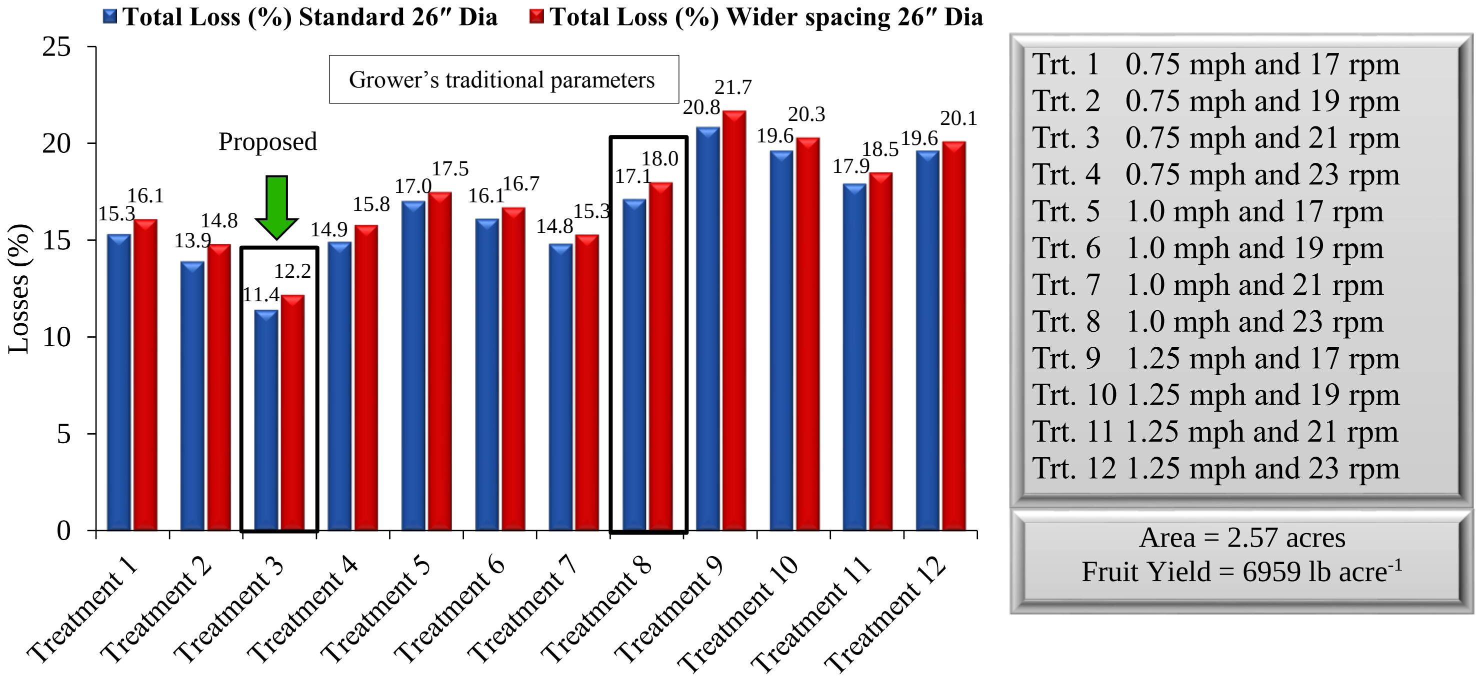


Conclusion

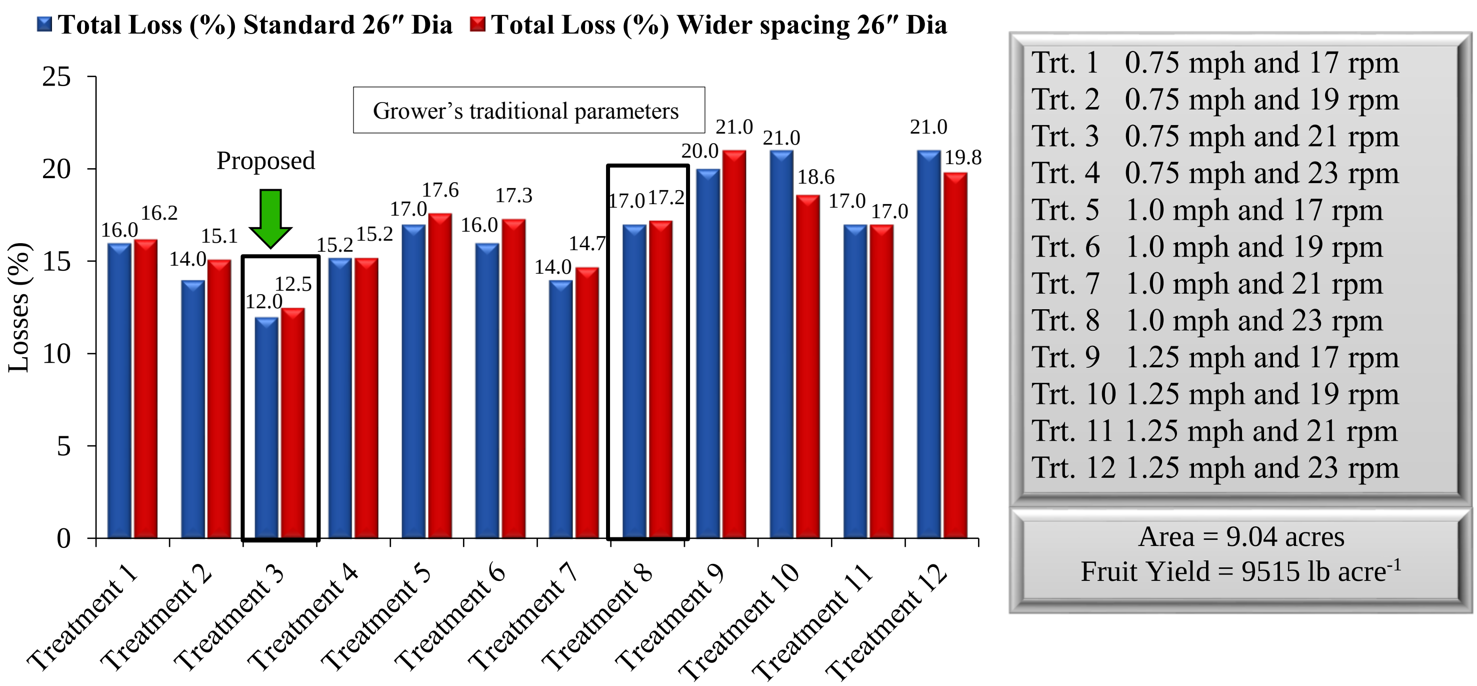
- ✓ Less fruit loss with 26’ diameter head in traditional fields than 22” dia. head.
- ✓ The 26” diameter head pulled less plants and debris than 22” head while harvesting.
- ✓ Larger circumference with the 26” head allowed for debris to be more thoroughly cleaned from the picker teeth. (Stretched bar spacing on the 26” diameter head).
- ✓ Improved cam action resulting in a gradual picking action from an increased diameter with the 26” head.
- ✓ The inner head conveyor has increased in width from 8” to 12” on the 26” diameter heads allowing for a larger carrying capacity.
- ✓ The increased inner head conveyor has better debris handling (not as much an issue with the conveyor plugging with debris when wet).
- ✓ The wider conveyor seems to also allow for better berry handling when travelling on steep slopes (less dropped berries).
- ✓ The larger 26” diameter head seems to be easier to operate over rough terrain and required less adjustment in head height to successfully harvest the berries without digging into the ground surface.

c) Comparison of Harvester Heads (26” dia. head with standard teeth and increased spacing)

Another attempt was made to modify 26” dia. harvester head, based on the previous results of lab (design analysis) and field experiments. The 26” dia head was modified by increasing the spacing in between teeth on bars of head. The data is being analyzed using statistical, geostatistical and GIS techniques and will be presented in meetings. The information obtained through detailed study of machine parameter related to field, crop and climatic conditions will improve harvestable fruit yield.



Mean comparison of total losses (%) for 26” dia and 26” dia wider spacing heads at different combination.

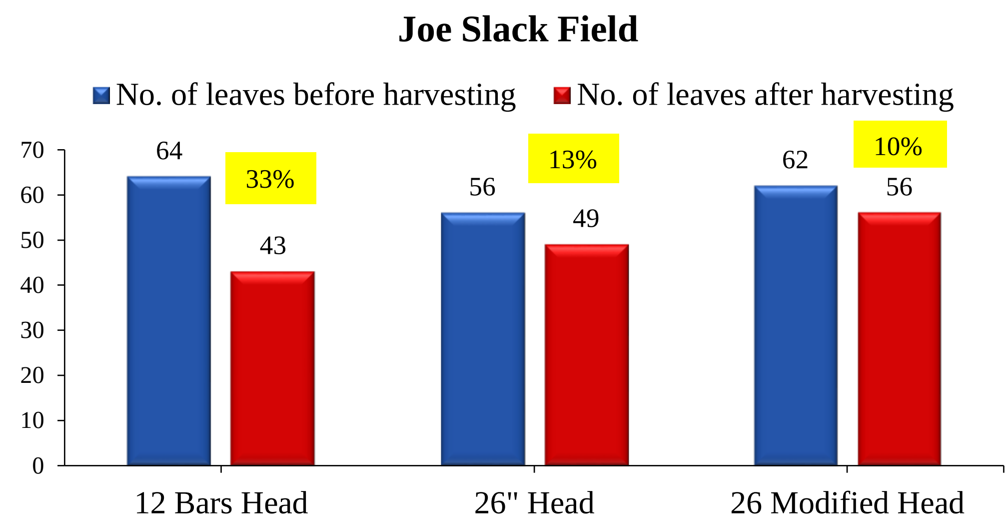


Mean comparison of total losses (%) for 26” dia and 26” dia wider spacing heads at different combination.

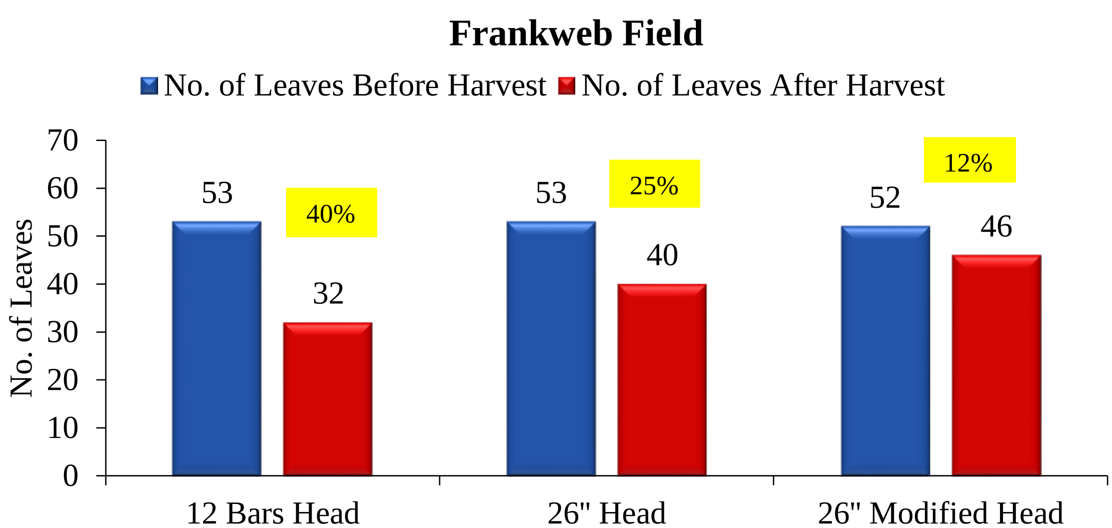
d) Three Wild Blueberry Harvester Heads (22” and 26” bars and 26” with wider teeth spacing; 67, 65 and 63) for Plant Damage

Performance efficiency of different harvester heads was evaluated for plant damage during harvesting. Data was collected before rainfall and after rainfall for comparison. Results of preliminary comparison between 22”-12 bar and 22”-16bar heads indicated that 22”-12 bar head pulled more plants as compared to 22”-16 bar head. The 26-16 harvester head designed with increased diameter (26 in.) performed better as compared to 22”-16 bar head in both dry and wet conditions. The reason for better performance with increased diameter head could be the increased spacing between bars of 26”-16 bar head, which allowed relatively less aggressive action resulting in lesser plant pulling as compared to 22”-16 bar head.

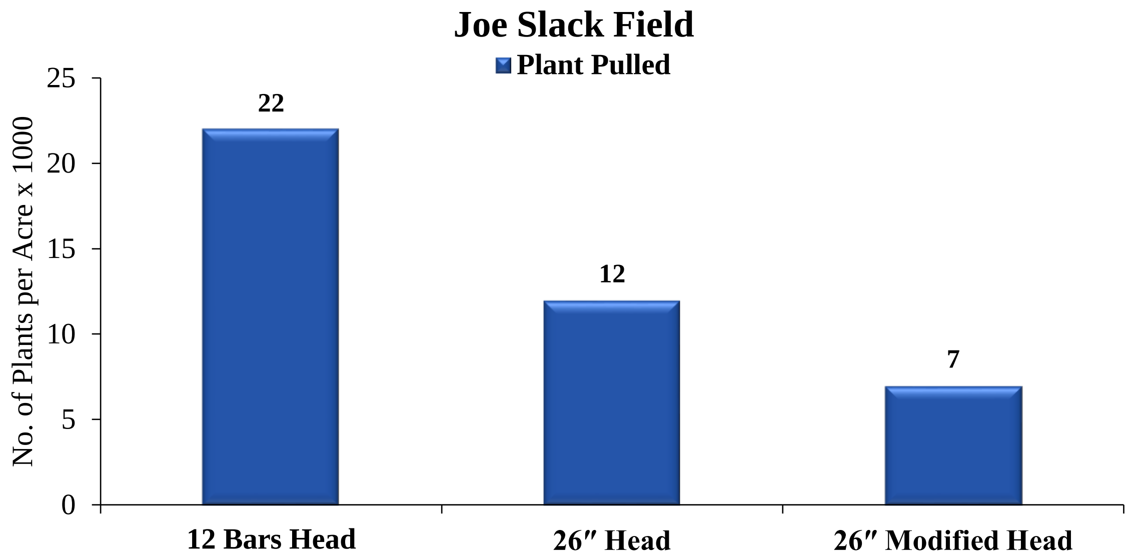
Data for 26” head with wider teeth spacing is being analyzed using statistical, geostatistical techniques and GIS software for comparison. The results of this study will help to improve berry picking efficiency and reduce plant damage during harvesting. The automated harvesting system will be developed using for real-time adjustment of head height and machine parameters to increase harvestable fruit yield. *Results will be presented in industry meetings and published in progress report.*



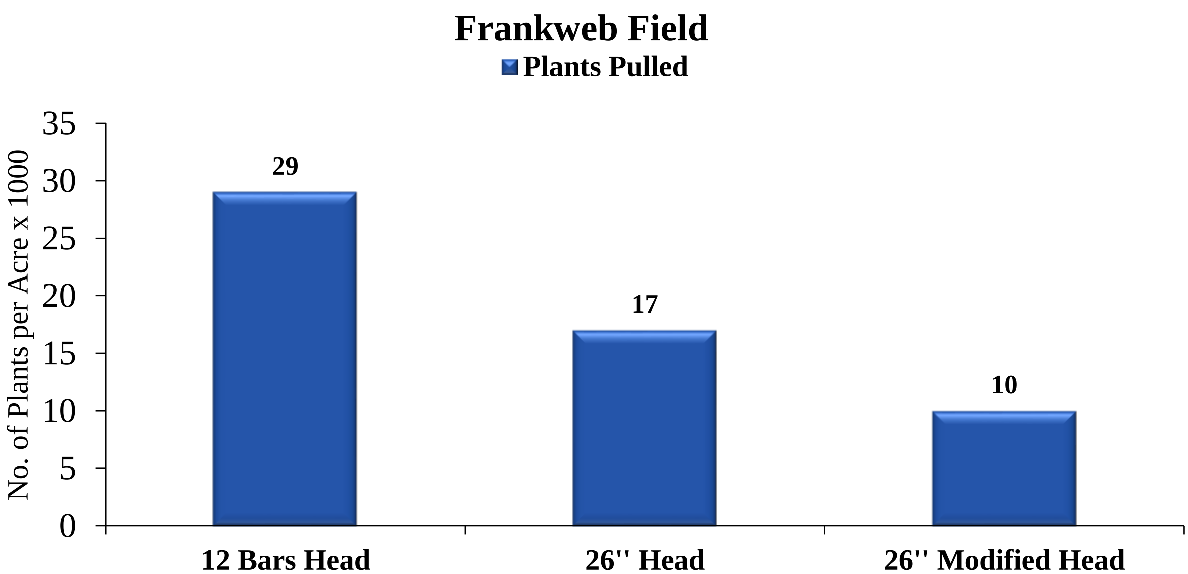
Defoliation of plants with three different heads for Joe Slack field.



Defoliation of plants with three different heads for Frankweb field.

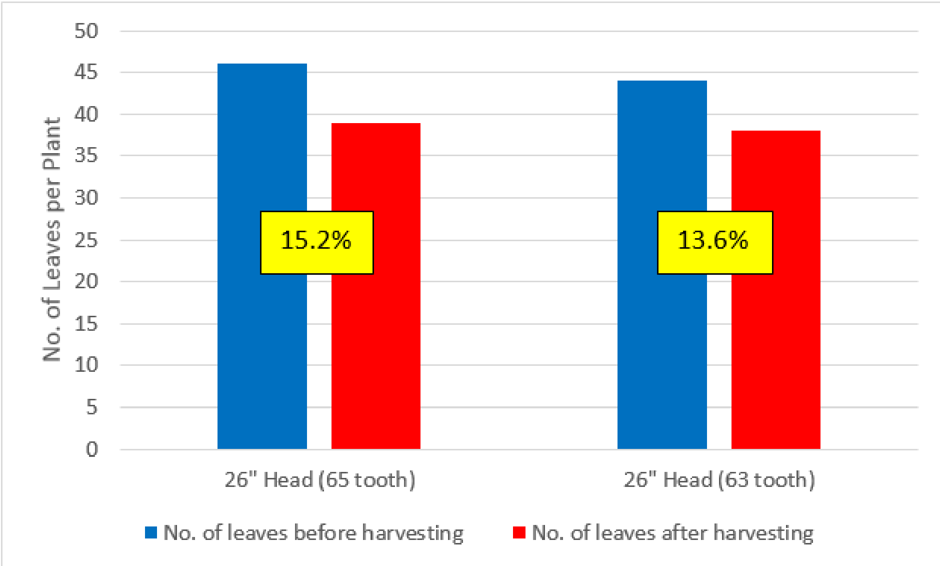


No. of plants pulled by three different heads for Joe Slack field.



No. of plants pulled by three different heads for Frankweb field.

The 26-16 harvester head with 65 and 63 tooth bar was designed and evaluated for berry quality improvement. Preliminary results indicated leaf loss was less with 63 tooth bar harvester head. However, visual observation revealed there was more small size berry loss with 63 than 65 tooth bar during harvesting.



Conclusion

- ✓ Less "plant pulling" with wider teeth spacing 26" 16 bar head than 22" 12 bar head 26" 16 bar head.
- ✓ Less leaf loss with wider teeth spacing 26" head than 22" 12 bar head 26" dia. head.
- ✓ More small sized berries left on the stem and ground while with the wider teeth spacing.
- ✓ Potential for better debris cleaning from the brush with the wider teeth spacing.
- ✓ Potential for less fruit bud damage with wider teeth spacing.
- ✓ Larger circumference with the 26" head allowed for debris to be more thoroughly cleaned from the picker teeth. (Stretched bar spacing on the 26" diameter head).
- ✓ Improved cam action resulting in a gradual picking action from an increased diameter with the 26" head.
- ✓ The inner head conveyor has increased in width from 8" to 12" on the 26" diameter heads allowing for a larger carrying capacity.
- ✓ The increased inner head conveyor has better debris handling (not as much an issue with the conveyor plugging with debris when wet).
- ✓ The wider conveyor seems to also allow for better berry handling when travelling on steep slopes (less dropped berries).

The larger 26" diameter head with 65 tooth bar seems to be easier to operate over rough terrain and required less adjustment in head height to successfully harvest the berries without digging into the ground surface.

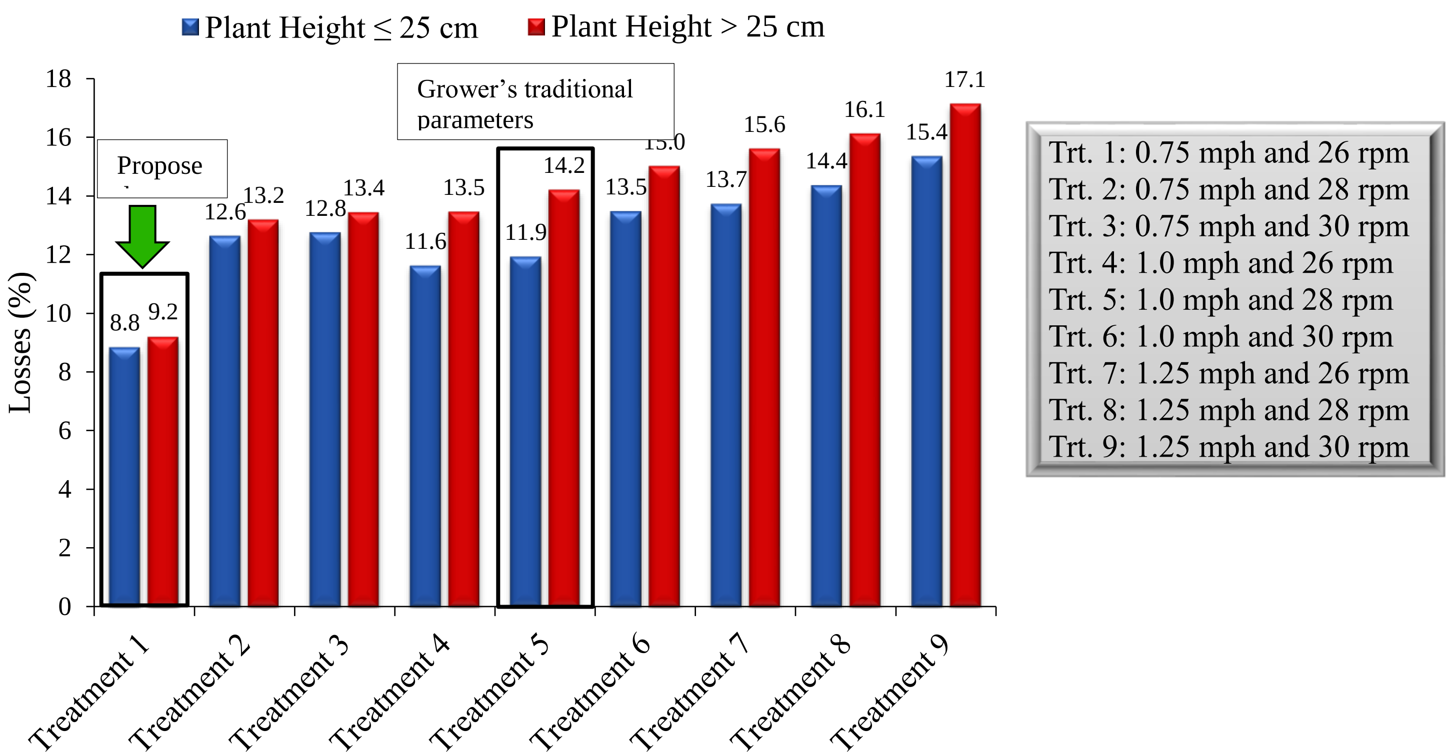
4. Effect of Plant Characteristics on Berry Picking Efficiency of the Harvester

The effect of plant characteristics on picking efficiency of wild blueberry harvester was evaluated in wild blueberry fields in Atlantic Provinces. Plant height (PH) and plant density (PD) were classified into four different categories i.e. tall plant - low plant density, tall plant - high plant density, short plant - low plant density and short plant - high plant density. Combined effect of ground speed (1.2, 1.6 and 2.0 km h^{-1}) and header revolutions (26, 28 and 30 rpm) on berry losses at each category of PH and PD was identified. Berry losses were collected from each plot within the selected fields. Fruit losses were higher in taller (>25 cm) plants and low plant density (<12) than short plants and high plant density areas of the selected fields. A suitable combination of ground speed and header rpm in optimum plant characteristics at appropriate head height can minimize fruit losses.

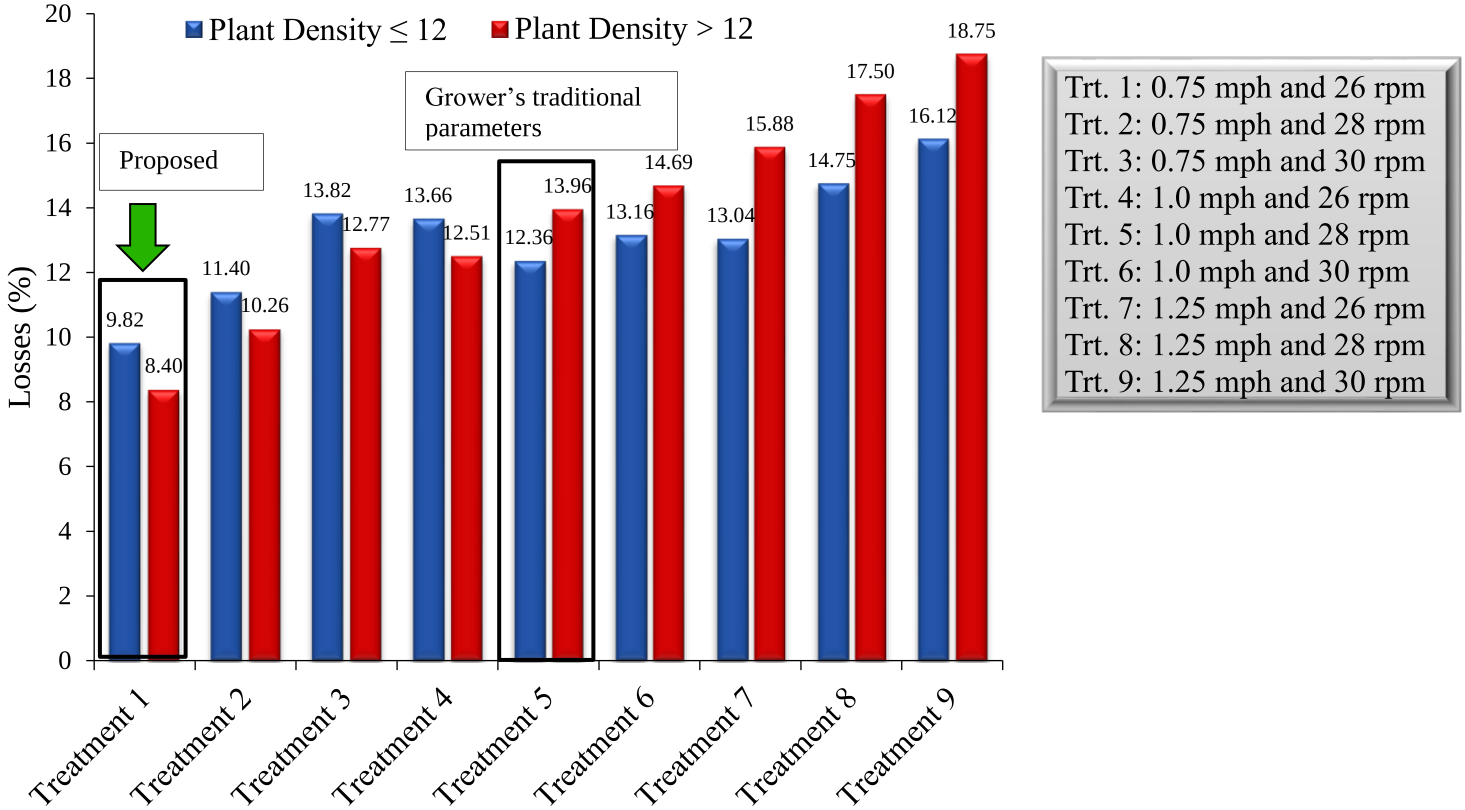
The effect of fruit characteristics (fruit yield, fruit zone and fruit dia.) on berry losses at different machine parameters was examined in wild blueberry fields. Results indicated lower losses in high fruit zone areas of the field, while higher losses were observed in low fruit zone areas. This information will help to develop automated system to adjust head height on-the-go according to the variation in plant/fruit characteristics. *Manuscript was submitted in scientific journal Applied Engineering in Agriculture and results presented in international conference and industry meetings.*

The combined effect of plant characteristics and machine parameters on picking performance of harvester was analyzed using accurate predictions of artificial neural network (ANN) model. Processed data were categorized into four classes of berry losses (<10%, 10-15%, 15-20% and >20%), to determine the optimum crop characteristics and machine parameters for effective berry picking during harvesting. Fruit losses were lower (<10%) in in high yield (FY > 3000 kg ha^{-1}), short plants (PH < 25 cm), high PD (PD > 12plants/0.0225 m^2) and higher FZ (FZ > 17cm) plots, within selected fields. The best operating combination for this category was 1.2 km h^{-1} and 26 header rpm. Berry losses increased with an increase in ground speed and head rpm in higher FY, PH and FZ plots. Higher berry losses (> 20%) were observed in high yielding plots with short plants and low plant density at 2 km h^{-1} and 30 header RPM. Results concluded that the picking efficiency can be increased by operating the harvester at a ground speed of 1.2 km h^{-1} and 26 header rpm of harvester in spatially variable plant characteristics (Table). *Currently a manuscript is under review in a scientific journal Applied Engineering in Agriculture. This research was part of Master thesis research (completed).*

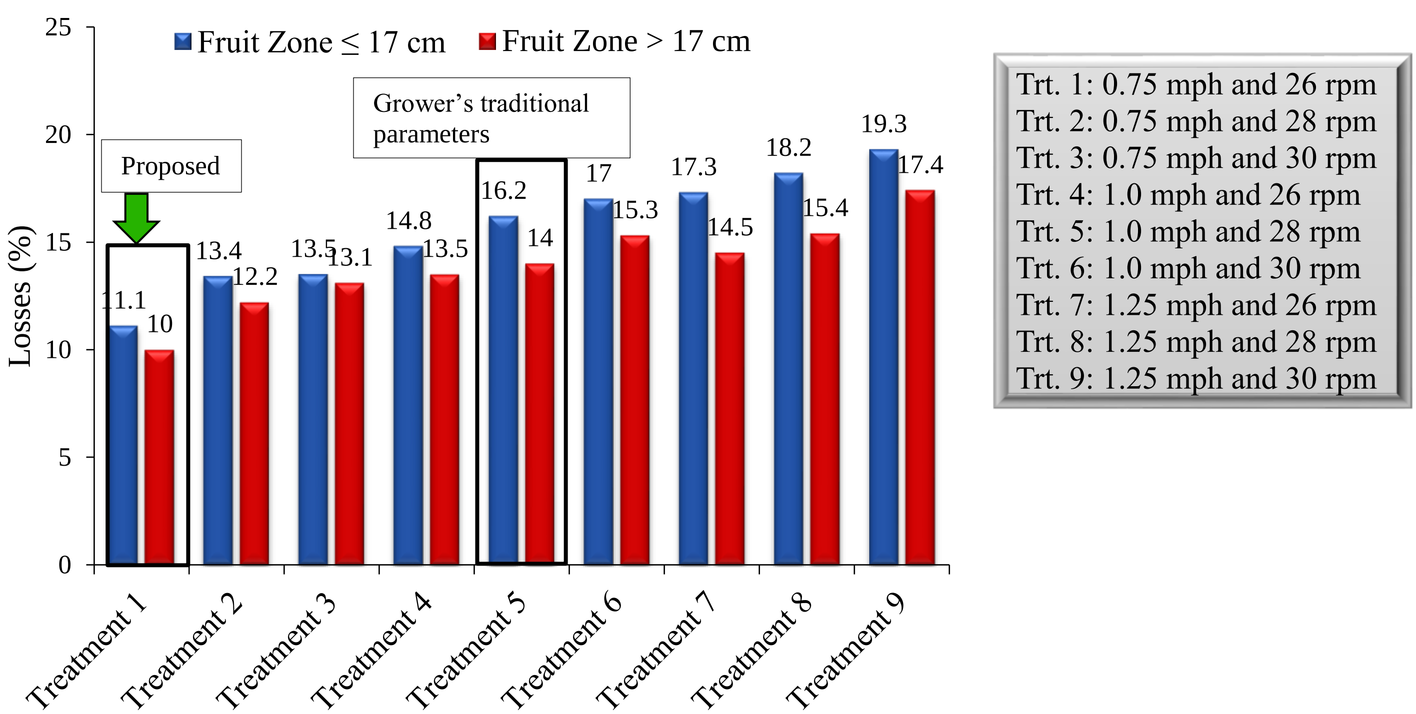
This information will help to develop an automated system (hardware and software) to adjust ground speed and header rpm automatically according to the variation in fruit yield to increase berry yield.



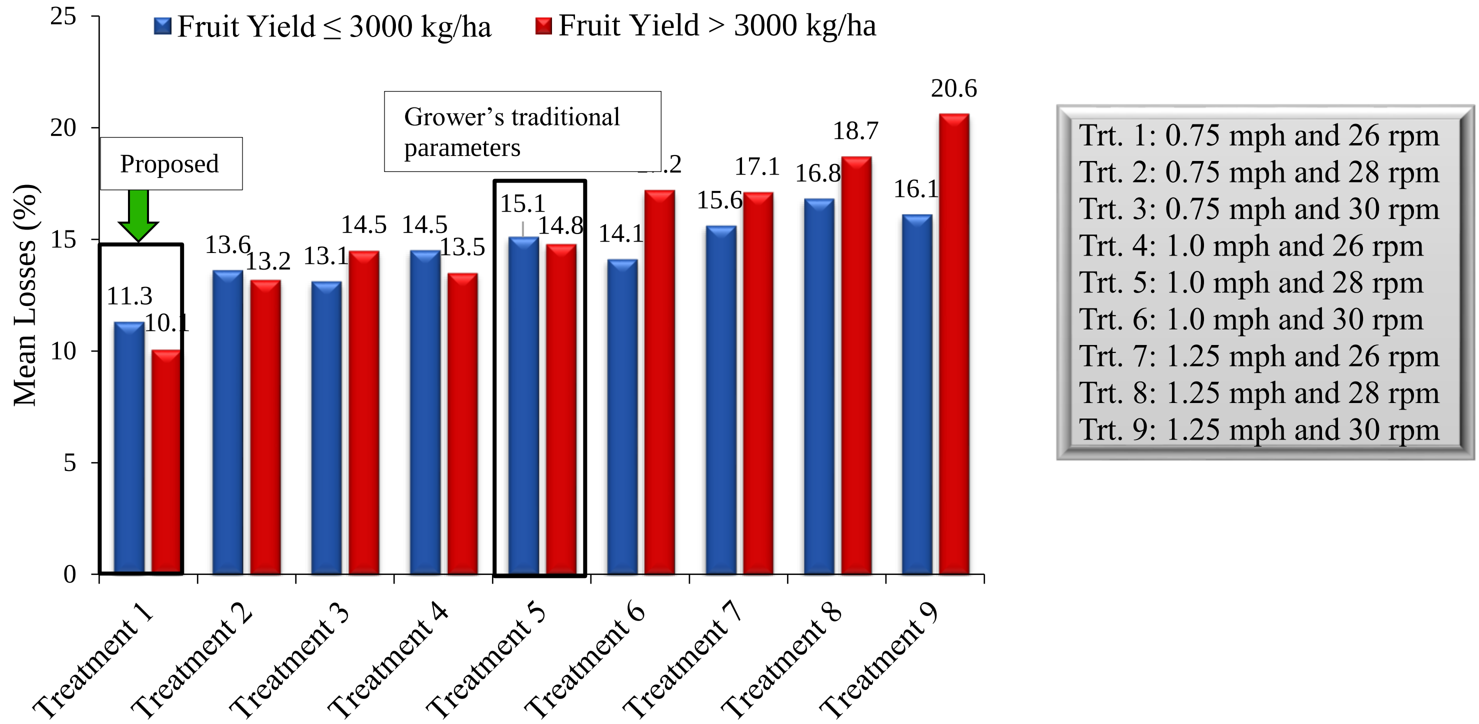
Mean comparison of fruit losses (%) for two plant heights at different treatment combinations.



Mean comparison of fruit losses (%) for two plant heights at different treatment combinations.



Mean comparison of fruit losses (%) for two fruit zones at different treatment combinations.



Mean comparison of fruit losses (%) for two fruit zones at different treatment combinations.

Optimum combination of machine and crop parameters.to reduce fruit loss using ANN model

Training

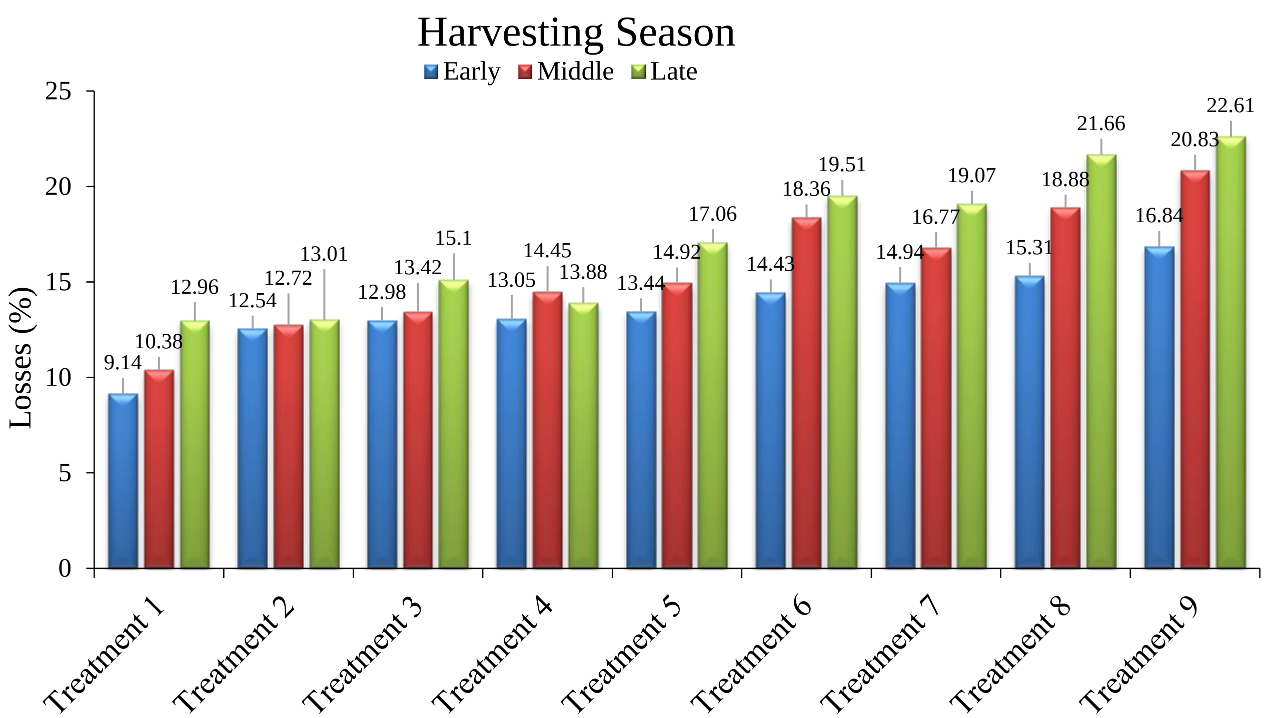
Class	**Speed ($km\ h^{-1}$)**	**RPM**	**FY ($kg\ ha^{-1}$)**	**PH (cm)**	**PD (*)**	**FZ (cm)**	**Mean Loss (%)**
<10%	**1.2**	**26**	4326	23.46	13.53	21.13	7.8
10-15%	1.2	28	5918	23.92	10.78	22.28	12.47
15-20%	1.6	28	6546	29.23	12.70	27.81	17.26
>20%	2	30	5521	17.24	9.92	15.43	23.13

Validation

Class	**Speed ($km\ h^{-1}$)**	**RPM**	**FY ($kg\ ha^{-1}$)**	**PH (cm)**	**PD (*)**	**FZ (cm)**	**Mean Loss (%)**
<10%	1.2	26	4543	22.85	12.90	21.16	8.29
10-15%	1.2	28	5879	21.11	10.91	20.27	12.06
15-20%	1.6	28	6477	28.65	12.22	26.92	17.02
>20%	2	30	5436	17.93	11.79	14.08	22.56

5. Quantification of Fruit Losses at Different Harvesting Times

Wild blueberry fields were selected in Atlantic Provinces to examine the impact of different harvest timings on berry picking efficiency of harvester. Fruit losses data were collected at three different levels of ground speed (1.2, 1.6 and 2.0 km h^{-1}) and header revolution (26, 28 and 30 rpm) for each category of season (early, middle and late season from each field. Results revealed fruit losses were higher in late season compared to early and middle season harvesting. Results also showed that higher ground speed in concomitance with higher header rpm resulted in substantial increase in fruit losses in each harvesting season, but these losses were more prominent in late season due to over-ripened berries. Selecting an appropriate combination of ground speed and header rpm is very important to enhance harvesting efficiency by reducing berry losses when dealing with early, middle and late season harvesting. *Presented in international conference and industry meetings. This research is part of Master thesis research).*



Mean comparison of fruit losses (%) for different time of harvesting season.

6. Coupling Biological, Mechanical and Environmental Data to Develop Integrated Harvesting Techniques Using Bio-system Modeling

Bio-system modeling (ANN) to couple mechanical, biological and environmental processes enabled us to identify the senstive factors responsible for increased losses. This approach implemented various aspects of harvesting, *i.e.*, quantification, prediction, classification, optimization of efficiency and quality damage during harvesting. Processed ANN modeling data comprising of soil, plant, fruit and environmental characteristics, and fruit losses is ready for the development of a farmer's friendly small computer program by considering spatial and temporal variations to enhance berry recovery. Peltarion Synapse software was used to develop WorkArea0.dll file. This file served as brain to recommend efficient harvesting settings (ground speed and header rpm).

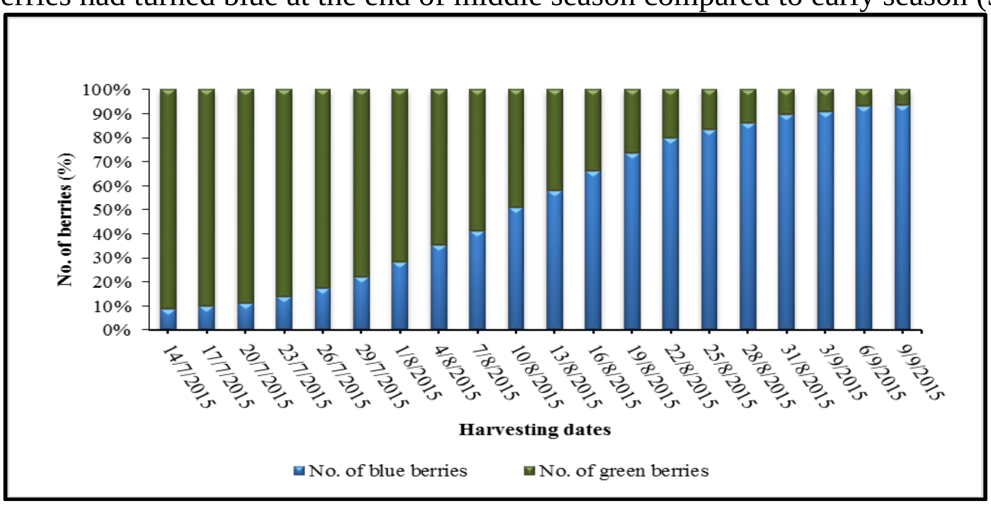
The collected data were normalized, and 70% of the data were utilized for training, and 30% for validation of the developed models using ANN and MR techniques. Results of mean square error (MSE) and root mean square error (RMSE) suggested that the tanh-sigmoid transfer function between the hidden layer and output layer was the best fit for this study. The developed models were validated internally and externally and the best performing configuration/architecture was identified based on MSE, RMSE, CE and coefficient of determination (R^2). The optimum number of iterative steps (epoch) to process data and predict fruit losses was examined by plotting the error rate against epoch number. Results suggested that the iterative steps of 15000 was enough to predict fruit losses during mechanical harvesting. Results suggested that tanh sigmoid

mathematical function was the best to process the data collected. The optimal configurations of the model to predict fruit losses were selected based on MSE, RMSE, CE and R2.
Results revealed that the prediction accuracy of the MR models was lower ($R^2 = 0.46$; RMSE = 0.14) than the ANN model ($R^2 = 0.84$; RMSE = 0.075) for training dataset. Results reported that the ANN model predicted fruit losses with higher ($R^2 = 0.63$; RMSE = 0.11) accuracy when compared with MR model ($R^2 = 0.37$; RMSE = 0.15) for external validation dataset. Overall, the results of the study suggested that the ANN model was able to predict fruit losses during harvesting accurately and reliably. This study can help to identify the factors responsible for fruit losses and to suggest optimal harvesting scenarios to improve berry picking efficiency and recovery.

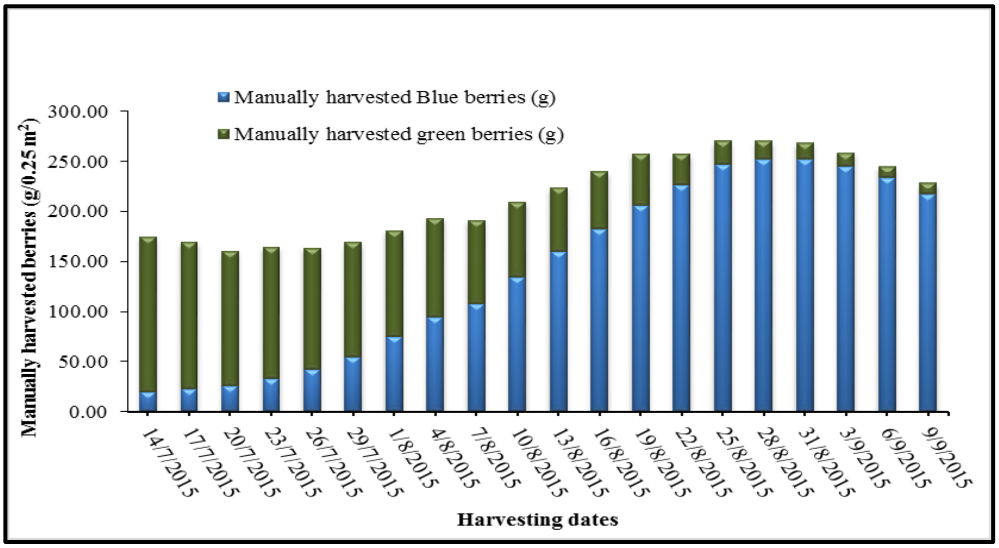
Results suggested that the ANN model could thus effectively be used for predictive modeling and optimization of fruit losses during mechanical harvesting of wild blueberries. Based on the results of this study, it is suggested to include environmental factors, time of harvest, soil properties, plant densities, fruit diameters and stem thickness to input variables in future studies while modeling the harvesting dynamics of the wild blueberry cropping system. We developed a C# (Microsoft, Redmond, Wash.) program for wild blueberry industry. The farmers are able to login, add their inputs (yield, PH, PD), and software will suggest best settings of machine to reduce fruit loss. *This research is a part of PhD and Master thesis research. Manuscript was published in Applied Engineering in Agriculture Journal and presented in international conference and industry meetings.*

7. FRUIT RIPENING IN RELATION WITH TIME OF HARVESTING USING DIGITAL PHOTOGRAPHIC TECHNIQUE

Ripening of wild blueberry at the time of harvest is the leading factor for fruit quality. Currently, there are no protocols available for the farming community related to wild blueberry fruit ripening and maturity. Two wild blueberry fields were selected to examine the berry ripening levels using digital photographic technique on different harvesting times (early, middle and late). Completely randomized block design with four blocks and each block was further divided into three classes of early, middle and late. Fruit images from each block at early, middle and late seasons were acquired and processed to count blue pixels from each image, using image processing software. A significant correlation was found between percentage of blue pixels and actual fruit yield in Field A ($R^2 = 0.96$; $P < 0.001$) and Field B ($R^2 = 0.97$; $P < 0.001$). The correlation between actual and predicted fruit yield were also highly significant. The absolute and relative measures further strengthened the model. The results also indicated that the effect of time of harvesting on wild blueberry yield was significant and blueberry yield increased gradually during early harvesting, reached maximum in late harvesting and then started to decrease in late harvesting. Comparison results indicated that 90% of green berries had turned blue at the end of middle season compared to early season (58%).



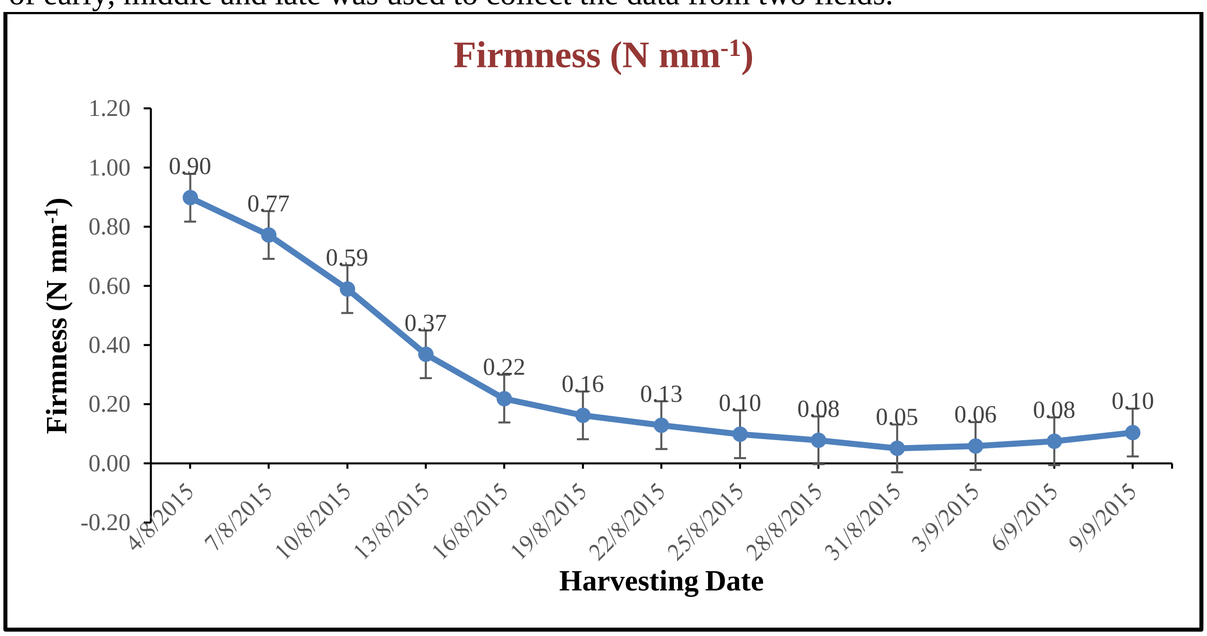
Comparison of green and blue berries at different harvesting dates.



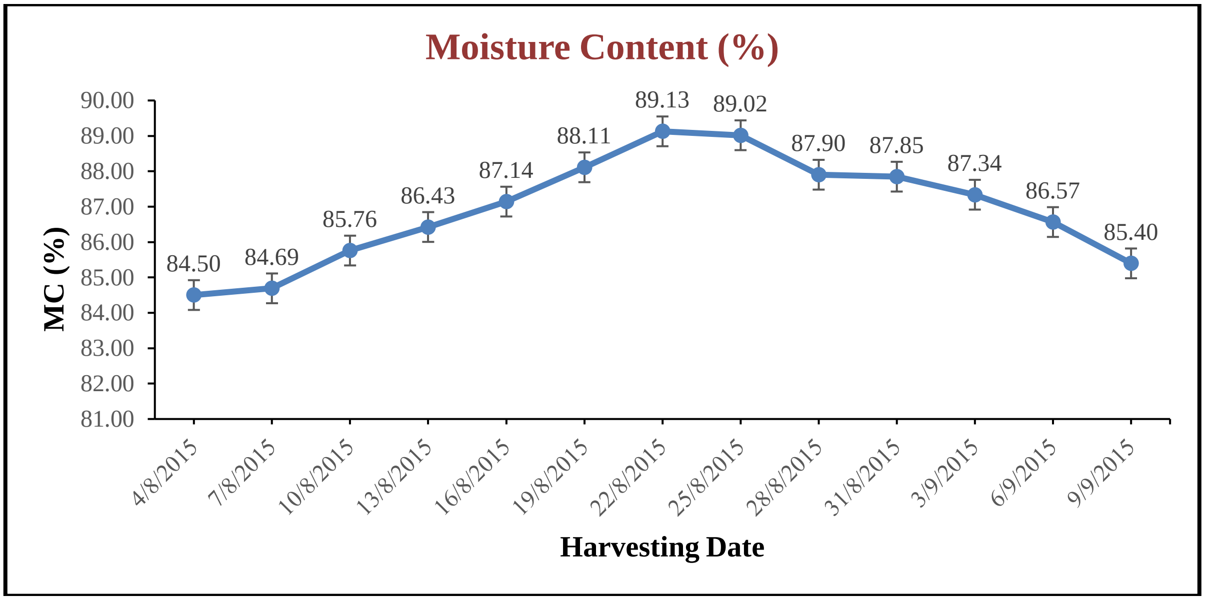
Comparison between manually harvested green and blueberries at different harvesting dates

8. IMPACT OF TIME OF HARVESTING ON PHYSICAL AND CHEMICAL CHARACTERISTICS OF WILD BLUEBERRY RIPENING

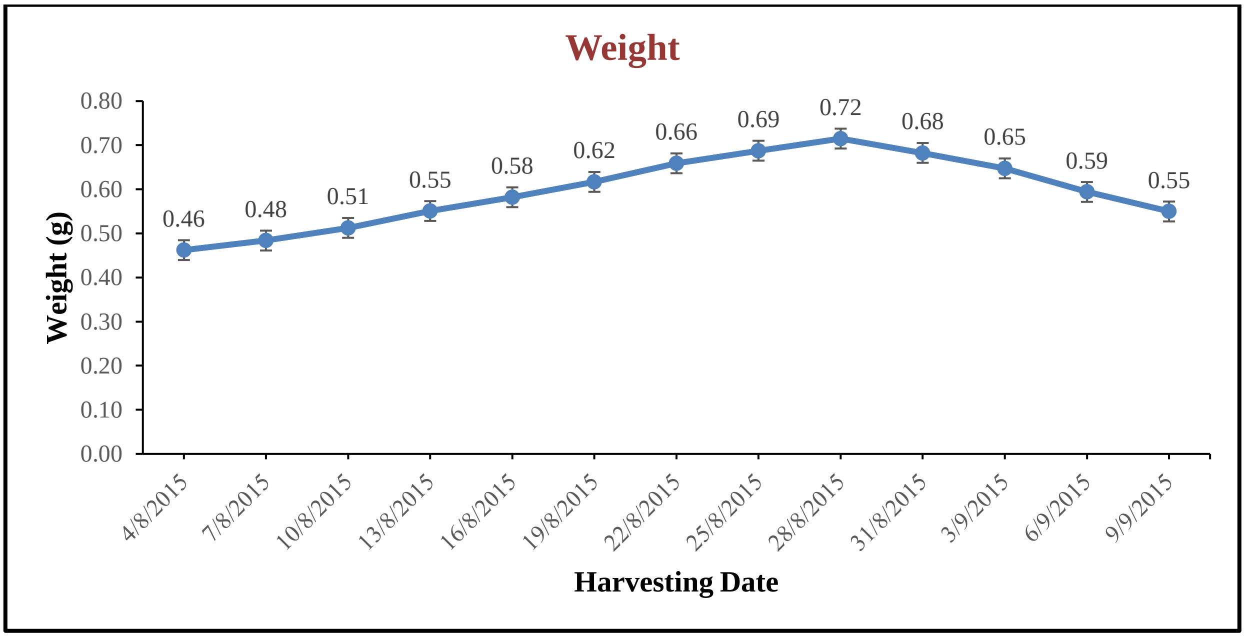
Maturity of wild blueberry at the time of harvest is the leading factor for fruit quality. Prior to this study, there were no identified protocols related to wild blueberry maturity and time of harvest that could be used to minimize fruit loss and /or improve fruit quality. Two wild blueberry fields were selected in Atlantic Provinces to examine the impact of different harvesting times (early, middle and late) on berry ripening characteristics (anthocyanin content, firmness, total soluble solids, total titratable acidity and moisture content). Completely randomized block design with four blocks and each block was further divided into three classes of early, middle and late was used to collect the data from two fields.



Wild blueberry fruit firmness on different harvesting dates.



Wild blueberry fruit moisture content on different harvesting dates.



Average weight of wild blueberries at different harvesting dates.

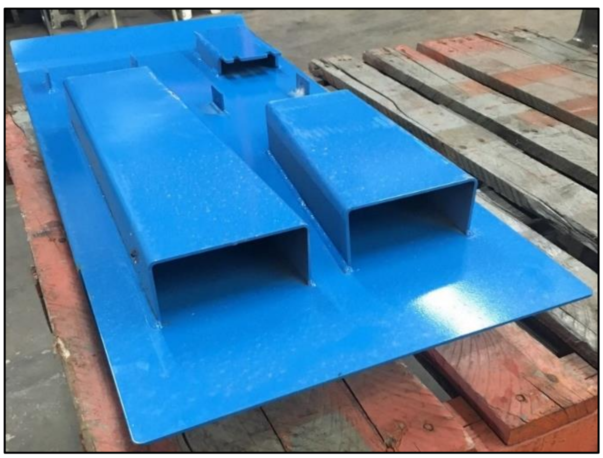
The highest increase in total soluble solids (40%) were observed in middle season, whereas most pigment accumulation in blueberries took place in early and middle season. A significant decrease in acidity (54%) and an increase in TSS:TA (74%) were found in middle and late season harvesting. The maximum gain in moisture content (89%), expansion in diameter (12%) and increase in weight (19%) were observed in middle season harvesting, whereas reduction in moisture (to a level of 84%), shrinkage of berries and loss of weight occurred in late season. Firmness decreased gradually from early to middle season (88%); then an increase in firmness in late season was the consequence of gumminess, produced by loss of moisture and contraction of diameter. Therefore, optimum time to harvest wild blueberries would be in the middle season to ensure better quality blueberries.

9. Effective Use of Variable Speed Blower Fan for improvement of Berry Quality

The management of wild blueberry fields is continuously improving and plant density/leaf foliage have increased. The result of improved management practices has led to an increased amount of debris being collected while harvesting. When operating the mechanical harvesters during periods of high moisture the debris is more difficult to remove as compared to dry conditions. Many commercial harvester units contain a single speed blower fan to remove debris before the fruit enters the storage bins. The wild blueberry processing facilities are suggesting that producers should lower the amount of debris that is being collected in the bins.

The study was designed to examine the effective use of variable speed blower fan on wild blueberry harvester for improving berry quality. A new dual fan plenum was designed and tested that allowed for uniform air distribution to help separate debris away from the wild blueberries. The two fans installed on the mechanical harvester were controlled using a handheld speed controller from the driver's seat of the tractor. A dielectric leaf wetness sensor was used to determine the moisture of the debris that is being handled on the harvester conveyors.

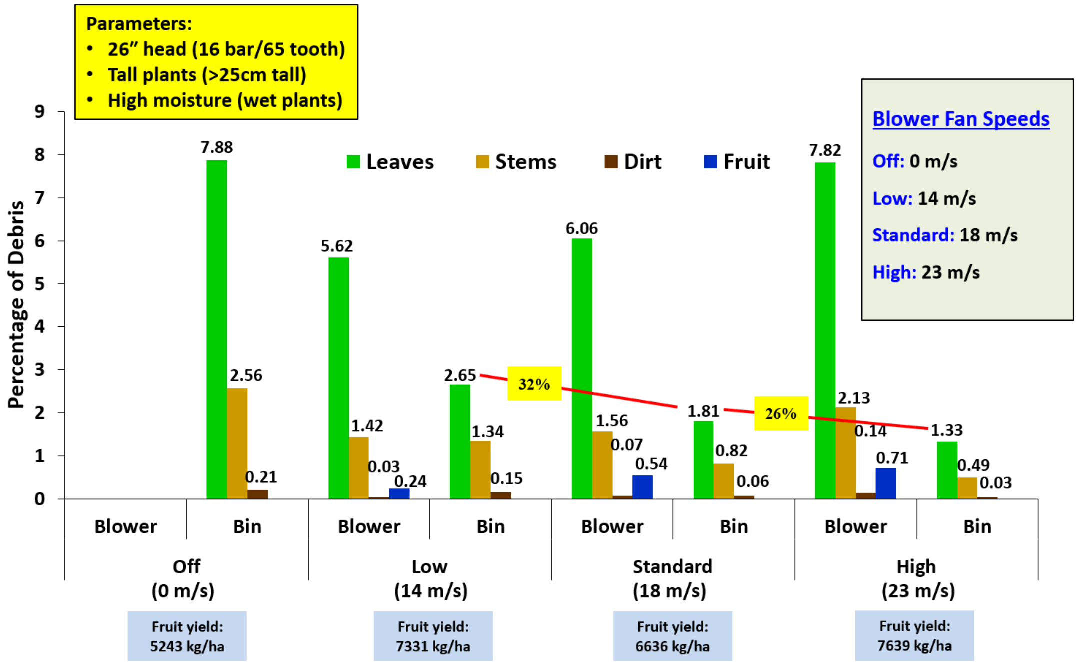
A commercial DBE mechanical harvester was tested with two style of picker bars (63 and 65 tooth configuration). Four different blower fan speeds (B_1=0 m/s, B_2=14 m/s, B_3=18 m/s & B_4=23 m/s) were tested for berry cleaning performance. The effectiveness of the blower fan speed for debris separation was tested at two different leaf wetness conditions (LW_1=high moisture & LW_2=low moisture) within selected wild blueberry fields.



New dual fan plenum & controller for fan speed adjustment.

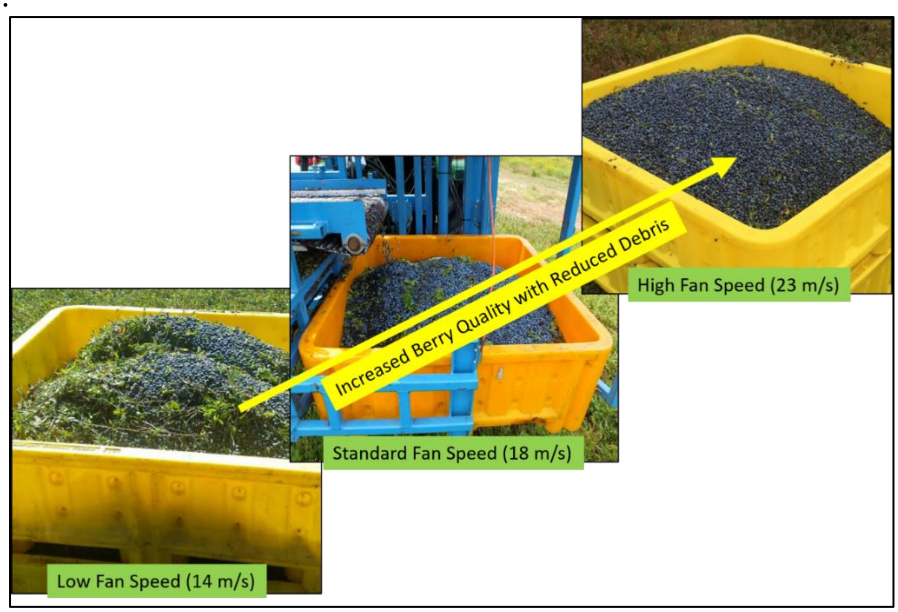
The picking heads in conjunction with different blower fan speeds and moisture conditions was tested at two levels of wild blueberry plant heights (PH_1 < 25cm & PH_2 > 25cm) within selected fields. The results of this experiment can be used to suggest an ideal combination of blower fan speeds for minimal debris during mechanical harvesting.

The harvester operating with a low fan speed (14 m/s) was able to remove 63.1% of the debris in high moisture conditions using the 26" head with and 65 tooth bars in tall plants (Fig 5). Under similar operating conditions, a fan speed of 18 m/s removed 74.1% debris while a fan speed of 23 m/s removed 84.5% debris. This data showed that the higher moisture conditions and taller plants led to an increased amount of debris in the harvested collection bin as compared to dry conditions or low plant height. The data suggests that there was not a significant difference between the amount of debris collected or separated with the 63 tooth head as compared to 65 tooth head.



Percentage of debris found under high moisture conditions (26" head, 65 tooth bar, tall plants)

Results from this study have shown a significant improvement with the debris separation using the developed variable speed blower fan system. Data suggests that operating the fan at a speed of 23 m/s resulted in the best debris cleaning performance with insignificant berry loss in both wet and dry conditions. A fan speed of 23 m/s leads to a 11% increase in debris separation using a 65 tooth head as compared to the standard operating speed of 18 m/s under high moisture field conditions without any significant loss in berry yield. Recommendations from this study have recently allowed new commercial systems to be developed with the new fan system incorporated into the design. The results proved to be an important step for the low bush blueberry industry to improve their harvested product to better compete with the highbush blueberry market on the global scale.



Increase in berry cleanliness with increase in blower fan speed.

Project Summary

The research project "Improving efficiency of commercial wild blueberry harvester using precision agriculture technologies" was completed in October 2016. This research would help to ensure the long term stability of industry and make growers more profitable over time. The intensive data collected during last four years have been gleaning, organizing and analyzing using innovative technologies. Proposed research would result in delivery of peer reviewed scientific publications and producer factsheets associated with improved harvesting techniques, environmental stewardship, food safety, and renewal and risk management. Seven articles have been published/publishing in peer-reviewed scientific journals and presented in industry, national and international conferences. In addition, it is anticipated that results from this research are being posted on the PA Website, and also be disseminated to growers and industry representatives at field days, twilight meetings, and oral and poster contributions at grower and scientific meetings. Broachers/factsheets are being published for producers.

The HQPs were trained to publish research results in peer-reviewed scientific journals and also present in regional, national and international conferences, growers' meetings, and farmers' field days. Two post-doctoral fellows, one PhD, two master students and several undergraduate students, two research assistants were part of this research program to develop and evaluate innovative harvesting technologies to increase harvestable berry yield. They have an opportunity to interact with researchers from multiple post-secondary institutions and various industrial partners including DBE, Oxford Frozen Foods Group (OFF), and Wild Blueberry Producers Associations. HQPs should feel the pain of farmer and poor consumer alike. They should wear dirty shoes while being cutting edge scientists. Both, research and extension will then flow from them, simultaneously! Producing 'degree holders' should not be the sole function of a university.

This collaboration between industry and research scientist was initiated to develop innovative and viable techniques that should enhance berry picking efficiency, assist with the stabilization of yields over time and increase farm profitability. While this project is submitted with the collaboration of wild blueberry industry to increase harvestable berry yield and quality, the DBE harvester is being used to harvest 80% of the total acreage of wild blueberry in the Atlantic Provinces. The combination of research and technology transfer activities situated within the project are in the process of resulting in the continued development of more efficient, sustainable, and environmentally friendly harvesting technologies, the continued training of graduate students, post-doc fellows, wild blueberry producers and industry personnel, and a more competitive wild blueberry industry.The results of this research project showed up to 6% increase in berry recovery using PA technologies, increasing farm profitability of NS farmers. Increased harvesting efficiency *(say 5% only) can* contribute $5.5 million to NS economy with no additional expenses and $31 million to Atlantic Provinces and Quebec every year.

This information obtained during last four years will directly support to develop an automated system (hardware and software) to adjust machine parameters automatically according to the variation in field and crop conditions to increase harvestable berry yield.