EFFECTIVE DEBRIS REMOVAL METHODS FOR MECHANICAL WILD BLUEBERRY HARVESTER

by

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DEDICATION

This MASc thesis dissertation is dedicated to my beloved husband, Travis, who has been a constant source of support and encouragement during my graduate studies. I am truly blessed to have the honor of being your wife. I would also like to dedicate this dissertation to my parents, who have always loved me unconditionally and taught me the meaning of hard work.

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ABSTRACT

Commercial management of wild blueberry fields is improving, and plant density/ leaf foliage have increased. Select weed and grass species have developed resistance to commonly applied herbicides and thrive in wild blueberry fields despite the continuous control efforts. As a result, increased amounts of debris have been collected during harvesting and berry processing facilities are suggesting that producers reduce the excess amounts to decrease shrink and increase fruit quality. The main objective of this study was to evaluate the existing debris removal system on the commercial mechanical wild blueberry harvester and make improvements for optimization while increasing harvesting efficiency and berry quality.

The existing single blower fan system was replaced with a new dual fan system increasing air flow and effective debris cleaning capabilities. An apparatus to measure terminal velocity of blueberries and common weed and grass species was developed and tested to measure optimum air velocities for effective debris removal. Wild blueberries were found to have a significantly higher terminal velocity (15.65 m s^{-1}) as compared to common debris samples ($\leq$ 5.64 m s^{-1}) tested in both dry and wet experimental conditions. The significantly lower surface area to mass ratio (61 mm^2 g^{-1}) of berries proved to aid the effective removal of harvested debris using air. Experimental testing of the cylindrical debris cleaning brush suggested the importance of proper maintenance and accurate adjustments within the field was essential to remove debris from the picker teeth while harvesting.

Evaluation in commercial wild blueberry fields found the new dual fan blower system with an increased air velocity of 18 to 23 m s^{-1} was optimum for removing more than 99% of unwanted debris from the harvested fruit before it drops in the storage bins. The debris cleaning brush was found to have the highest level of debris removal from picker teeth with a bristle length of 120 mm operating at a bristle tip speed of 13.88 m s^{-1}. Using these settings, harvesting field efficiency was increased by 41.95% as compared to using a brush with a bristle length of only 87 mm. Results of this study emphasize the importance of knowing and understanding the components of the mechanical wild blueberry harvester and have led to increased field efficiency, picking performance, berry quality and factors that lead to reduced shrink at the processing facilities.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ABBREVIATIONS

Adj. – Adjustment

ANOVA – Analysis of variance

cm – Centimeters

CV – Coefficient of variation

DAL AC – Dalhousie University Agricultural Campus

DBE – Doug Bragg Enterprises Limited

DGPS – Differential global positioning system

g – Gram

GLM – General linear model

ha – Hectare

kg – Kilogram

kW – Kilowatt

LS – Least squares

Ltd – Limited

LW – Leaf wetness

m – Meter

Max – Maximum

Min – Minimum

mm – Millimeters

n – Number of samples

N – Newton

P – Probability

PTO – Power take off

PVC – Polyvinyl chloride

reps – Repetitions

rpm – Revolutions per minute

s – Second

S.D. – Standard deviation

SP – Short plant

t – Teeth

TP – Tall plant

V – Volt

® – Registered

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CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

1.1.1 Wild Blueberry Crop

Wild blueberries (*Vaccinium angustifolium* Ait.) are native to Northeastern North America, and with over 93,000 ha under management produce approximately 117 million kg of berries valued at 491 million dollars per year (Yarborough, 2013). Wild blueberry fields develop due to pre-existing blueberry rhizomes that are naturally present in the soils of uncultivated land (Eaton, 1988). Many of the wild blueberry fields have been developed from deforested farmland after removal of trees and other existing vegetation such as weeds and grass allowing the wild blueberry plants to flourish and develop (Eaton, 1988). Since this land is not tilled or cultivated and usually unleveled where stumps were removed, they tend to be rough and bumpy (Jameel et al., 2016a; Zaman et al., 2008). It can take several years for the plant coverage to fill in and develop enough to make mechanical harvesting feasible and even well-developed fields tend to be rough and have many bare spots (Zaman et al., 2008). Wild blueberries grow on a two-year cycle, the first year being vegetative growth of the plant and the second year for pollination and production of blueberries (Fig. 1-1). Wild blueberry stem height can range from 50 to 300 mm and the berry diameter ranges from 4.8 to 12.7 mm (Farooque et al., 2014). Wild blueberries range from light to dark blue/black in color and are often soft in texture and favorable in taste (Hayden & Soule, 1969).

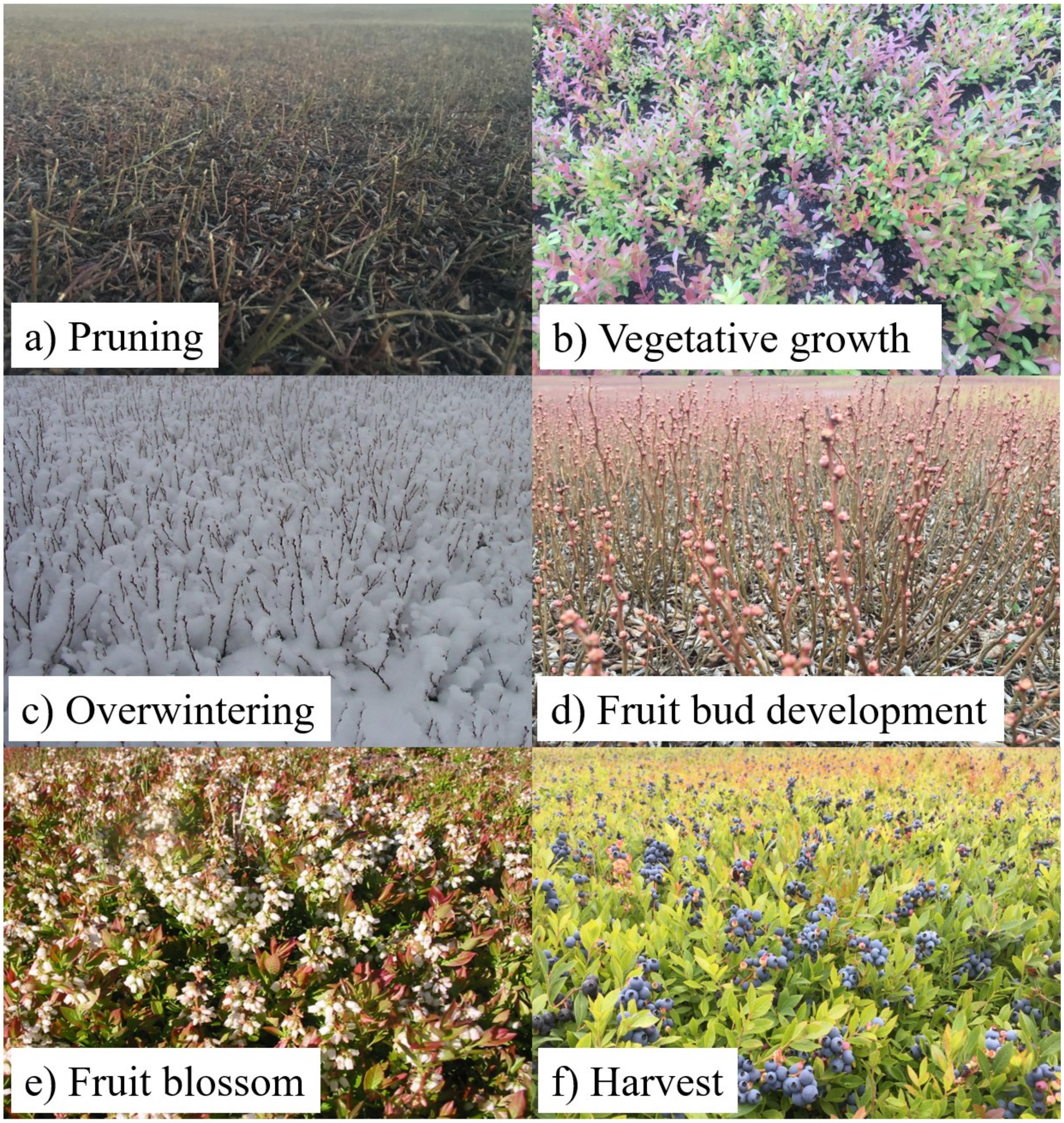

Figure 1-1: Wild blueberry crop growth stages over 2-year production cycle.

Ripening in the final stage of fruit develop involves a complex variety of characteristics and factors such as biochemical and physiological changes in the fruit tissue. These factors can be as simple as a change in color or more complex such as production of volatiles and degradation of organic acids (Blanpied, 1969; Grierson, 1986; Rhodes, 1980) (Fig. 1-2). Fruit can be categorized into two general groups (climacteric and nonclimacteric) in reference to their ripening patterns (Biale & Young, 1981). Climacteric fruit such as peach and apples will produce excess ethylene at the onset of ripening which in turn will increase respiration (Blanpied, 1969). Whereas, nonclimacteric fruit (blueberries and cherries) do not have the same increase in ethylene and will not continue to ripen post-harvest (Biale & Young, 1981; Özgen et al., 2002).

Figure 1-2: Wild blueberry stems with fruit at varying ripeness stages.

Mechanical harvesting of high bush blueberry was found to yield 90% marketable berries, 4% purple berries which are considered immature, 4% green berries and 2% defective berries while hand picking was found to yield 99% marketable berries and only 1% defective berries (Brown et al., 1996). Brown et al. (1996) determined after 10 days in cold storage only 22% of the mechanically harvested highbush blueberries were left unbruised, compared to 77% when handpicked. Brown et al. (1996) also studies the firmness of undamaged berries directly after harvest and measured firmness of approximately 1,080 N m^{-1}, whereas after prolonged time in cold storage reduces to 880 N m^{-1}. Similarly, a highbush blueberry, bruised during harvesting, will decrease in firmness significantly faster dropping to 440 N m^{-1} after prolonged cold storage (Brown et al., 1996).

1.1.2 Weeds in the Wild Blueberry Cropping System

Weeds in wild blueberry fields have consistently been a limiting factor on harvesting maximum yields (Jensen & Yarborough, 2004; Metzger & Ismail, 1976; Yarborough, 2006; Yarborough & Bhowmik, 1993). This is in part due to the weeds becoming lodged in the picking teeth of mechanical harvesters resulting in yield losses of 10 to 30% (Hoelper & Yarborough, 1985; Trevett & Durgin, 1972). Fields with minimally competitive weeds can have up to a 5% decrease on yields whereas fields with the more serious weed infestations can lead to a decreased yield of up to 80% (Gianessi & Sankula, 2003). Weeds can also cause damage to wild blueberries reducing berry quality and in extreme cases, result in product rejection at the processing facility (Esau et al., 2016). Wild blueberries cannot be easily planted and spread from existing stands by propagation of underground rhizomes. The lack of conventional management practices such as tillage that would damage rhizomes makes it more difficult to manage weeds throughout the field

(Cardina et al., 2002; Yenish et al., 1992) and impeds fruit yields (Kennedy et al., 2010). Wild blueberry fields commonly contain over 100 different weed and grass species (McCully et al., 1991) (Fig. 1-3) with the most common being herbaceous perennials (Jensen & Yarborough, 2004; Rehman, 2017).

Figure 1-3: Traditional wild blueberry field showing weed and grass variability during harvest.

Common weeds found in wild blueberry fields throughout Nova Scotia, New Brunswick and Prince Edward Island include: *Agrostis* (bentgrass), *Poa compressa* (Canadian bluegrass), *Apocynum cannabinum* (dogbane), *Chamaenerion* (fireweed), *Solidago spp.* (goldenrod), *Festuca filiformis* (hair fescue), *Tragopogon pratensis* (meadow salsify), *Rumex acetosella L.* (red sorrel), and *Panicum capillare L.* (witchgrass) (White & Boyd, 2016). Goldenrod being the most common has been found in 90% of wild blueberry fields and is considered to be the fifth most invasive species (Boyd & White, 2010; McCully et al., 1991) (Fig. 1-4).

Figure 1-4: Goldenrod growing in wild blueberry fields.

Traditionally weeds were removed from agricultural crops by manual hand picking (Klonsky, 2012). Hand weeding is a major expense as labor costs are continually increasing (Fennimore et al., 2014). Klonsky et al. (1994) found that organic onion cropping had 13% of its input cost as a direct result of hand weeding. Hand weeding is not only labor intensive but, was shown to only remove 65% to 85% of weeds due to human error (Vargas et al., 1996). An alternative to manual hand weeding is the use of herbicide to suppress weed growth (Jensen & Yarborough, 2004; McCully et al., 1991; Stern, 2009). Common pre-emergence herbicides for weed control in wild blueberry fields are hexazinone (Velpar®), terbacil (Sinbar®), Pronamide (Kerb™) and atrazine (AAtrex®) (Jensen, 1997; Jensen & Yarborough, 2004; Sikoriya, 2014). It has been suggested that common fescue species within Nova Scotia have developed a resistance to hexazinone and terbacil (Jensen & Kimball, 1985; Jensen & Yarborough, 2004; Sikoriya, 2014). Although herbicides are typically very effective at weed eradication, environmental and health regulations promoting organic farming could decrease herbicide application allowance (Stern, 2009). To help battle increasing herbicide cost and strict environmental policies, automated weed targeting technologies have been introduced for farm use (Chang et al., 2012; Owen, 2016; Schieffer & Dillon, 2015).

1.1.3 Wild Blueberry Harvesting

Traditionally, wild blueberries were harvested manually using a hand rake that was similar in design to the cranberry scoop (Yarborough, 1991). Hand raking requires a large labor force and losses vary (15% to 40%) depending on the workers (Kinsman, 1993). Initial research into developing a mechanical wild blueberry harvester began in the 1950's but a functional and viable harvester was not produced until the 1980's (Hall et al., 1983). The first wild blueberry harvester was adapted from a pre-existing mechanical cranberry picking machine and consisted of six combs that raked in the opposite direction of travel of the machine (Dale et al., 1994). Currently, the major manufacturer of commercial mechanical wild blueberry harvesters is Doug Bragg Enterprises Limited (DBE) located in Collingwood, Nova Scotia with over 1,500 harvesters operating in Northeastern North America. DBE improved the mechanical wild blueberry harvester by adding hydraulics with rotational head speed control (Malay, 2000). Recent advancements have been a semi-automated hydraulic bin handling system that reduces the need for manual back help while harvesting (Swinkels, 2015). Farooque et al. (2014) evaluated the effect of ground speed and header revolutions on the picking efficiency of a commercial DBE harvester and found the picking efficiency to be greater than 90%. Presently, the area of mechanically harvested wild blueberry is larger than 80% of the total wild blueberry fields in Canada. The remaining fields with extremely rough terrain are still hand raked (PMRA, 2005).

The modern wild blueberry harvester consists of a 660 mm cylindrical picking head with height and rotational speed controlled by the operator from the cabin of the tractor (Fig. 1-5). The head consists of a circular picking reel with 16 teeth bars, each with 65 equally spaced curved teeth. The picker teeth travel in the same rotational pattern as the tractor tires with speed controlled independently by the operator (Farooque et al., 2014). A 306.8 mm cylindrical debris cleaning brush (20411, Doug Bragg Enterprises, Collingwood, NS) with annealed nylon filamentary bristles is positioned on top of the picking head mechanism and continuously rotates the opposite direction as the picking reel to propel debris from the picker teeth during harvesting. The debris cleaning brush is controlled via a 0.19 l s^{-1} hydraulic motor (21988, Doug Bragg Enterprises, Collingwood, NS). The blueberries are gently picked off the vine and dropped onto a conveyor belt in the center of the picking reel that carries them to the side conveyor (Fig. 1-5). As the conveyed berries drop from the side conveyor to the rear conveyor a 12 V electric blower fan with 11-amp current draw, removes the leaves, stems, soil and other unwanted debris with an air flow rate of 0.14 m^3 s^{-1} (Farooque et al., 2014). The blueberries are then moved by the rear conveyer into storage bins that are hydraulically lowered onto the ground when filled to 136 kg. Loader tractors with forks are used to pick up the full blueberry bins and transport them to a truck and enclosed trailer that is used for hauling the fresh blueberries to the processing plants for sorting and cold storage.

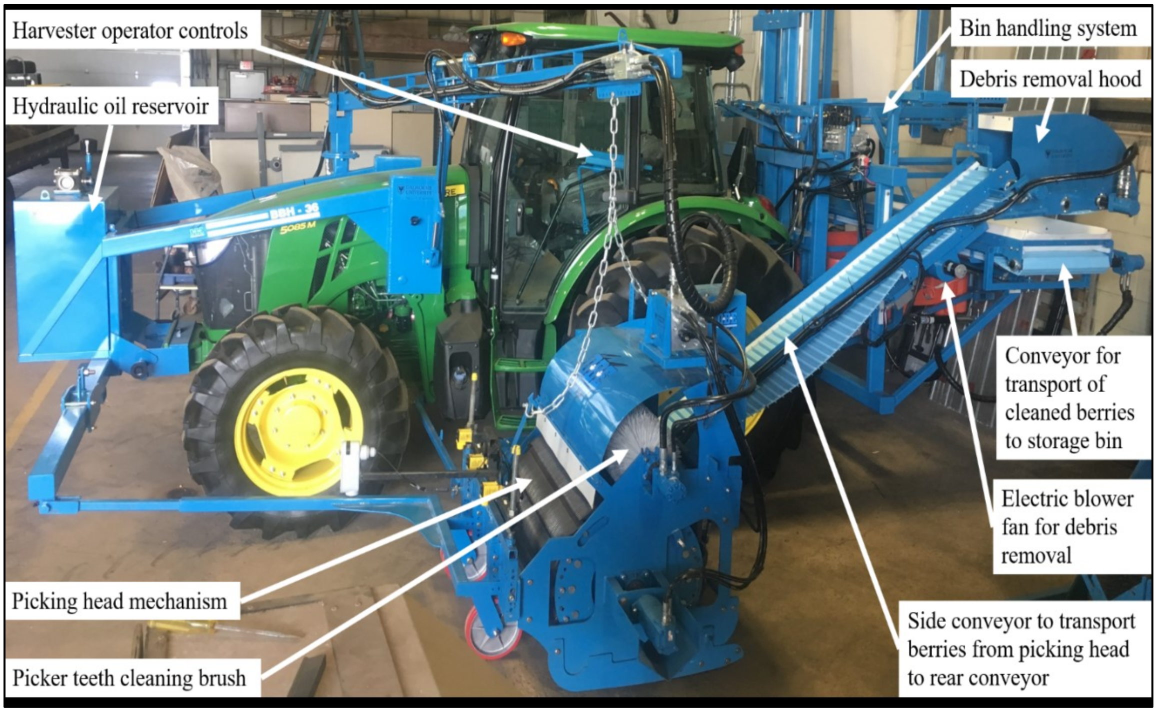

Figure 1-5: Image showing commercial wild blueberry mechanical harvester with components labelled.

Recent studies have improved the picking efficiency of the mechanical wild blueberry harvesters (Farooque et al., 2013; Farooque et al., 2014) however, research is still required to quantify and optimize the debris management system to further increase effectiveness.

1.2 OBJECTIVE AND GOALS

The overall objective is to effectively remove unwanted debris from harvested fruit during mechanical wild blueberry picking to increase berry quality and lower shrink for easier cleaning at the processing facilities. The detailed objectives of this study were to:

i) Investigate the terminal velocity of harvesting debris and field evaluate a multivariable speed blower fan system for effective debris separation during mechanical harvesting.

ii) Experimentally determine the optimum debris cleaning brush parameters for effective debris removal on commercial mechanical wild blueberry harvesters.

iii) Field evaluate different debris cleaning brush wear levels to determine optimal debris removal and berry recovery settings.

CHAPTER 2 EFFECTIVE USE OF A VARIABLE SPEED BLOWER FAN FOR DEBRIS REMOVAL ON MECHANICAL WILD BLUEBERRY HARVESTERS

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. Many commercial harvester units contain a single blower fan to remove debris before the fruit enters the storage bins. Processing facilities are suggesting that producers reduce the excess debris that is being collected in the bins.

A new dual fan plenum was designed and tested that allowed for improved air distribution to help separate debris from the wild blueberries. The two-fan system installed on the mechanical harvester was developed and controlled using a handheld blower speed controller from the driver's seat of the tractor. Adjusting the speed settings on the handheld controller allowed the change in fan speed for fine tuning the wind velocity. Wild blueberry fruit was found to have a significantly higher terminal velocity (15.65 m s^{-1}) as compared to debris and a significantly lower surface area to mass ratio (64 mm^2 g^{-1}).

Two experimental wild blueberry field sites were selected to analyze the effect of using a variable speed blower fan while operating in both low and high moisture field conditions. A commercial DBE mechanical harvester was tested with two styles of picker bars (63 and 65 tooth configuration). Four different blower fan speeds ($B_1 = 0$, $B_2 = 14$, $B_3 = 18$ and $B_4 = 23$ m s^{-1}) were tested for berry cleaning performance. The picking heads in conjunction with different blower fan speeds and moisture conditions was tested at two levels of wild blueberry plant heights ($PH_1 < 250$ and $PH_2 > 250$ mm) within selected fields. One hundred and twenty-eight data points were established to collect debris (leaves, stems, dirt) from the blower in each wild blueberry field. Results showed a fan speed of 18 m s^{-1} removed a significant amount of unwanted debris while harvesting without fruit losses.

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2.1 INTRODUCTION

In 1989, Bragg & Weatherbee (1989) designed a housing enclosing a centrifugal fan, with an outlet channel directed just below the extreme terminal end of the side conveyor. Thus, as the berries and debris fall downward from the outer end of the side conveyor, the blueberry leaves and other debris are carried away from the falling berries by virtue of the stream of air being emitted from the mouth of the fan plenum (Bragg & Weatherbee, 1989). Similarly, (Collins et al., 1994; Weatherbee & Weatherbee, 1999) both designed mechanical wild blueberry harvesters using a single blower fan system to remove unwanted debris in the field during harvest. Changes in wild blueberry crop conditions caused by improved management practices over the past decade has caused increased plant density and leaf foliage. This extra foliage has made it more difficult for the existing harvester blower fan to adequately remove debris (leaves, stems, soil, sticks, etc.) from the blueberries before they are placed in the loading boxes. The limitation with the existing 12 V blower fan system is the inability to properly separate the debris especially in high moisture and weedy field conditions because of inadequate blower fan air velocity (Farooque et al., 2014). The debris removal fan system was originally designed for traditional harvesting machines that fill small boxes with berries (10 kg) and were stacked and handled on a rear platform with the use of physical labor. The person running the back platform also assisted by manually removing excess debris from the harvested berries. Recent advancement of a semi-automated bin handling system eliminates the need for the manual labor for stacking boxes however, an upgraded blower fan system is required for superior debris removal (Bragg, 2016). The wild blueberry processing facilities have indicated the need to decrease the debris found in the bins to reduce processing time and increase the fruit quality (Wyllie, 2015). A logical solution is the addition of a second blower fan with control system regulating the fan air velocity based on the specific field conditions. For precise control this system could be operated in real-time and able to be continuously variable throughout the day based on the weather and crop conditions.

Many factors contribute to harvest loss through the actions of the blower fan process including leaf aerodynamic characteristics, fan and air leg design, fan speed and debris loading rate (Studer & Olmo, 1976). Mechanical grape harvesters use high volume blower fans to separate the grapes from leaves and other debris while harvesting and research found fruit loss more than 4% of the total fruit yield (Studer & Olmo, 1976). Several other types of nut, sugar cane, strawberry, grain, straw and cotton harvesters rely on fans for debris separation (Croft, 1995; Fowler, 2002; Gebrehiwot et al., 2010; Holden et al., 1995; Ledebuhr & Hansen, 1985; Ramacher, 1987; Shuknecht & Shuknecht, 1994; Stanley & Sousa, 1991; Uhl & Lamp, 1966; William et al., 1970) however, very little research has been done for optimized fruit and debris separation on the mechanical wild blueberry harvester.

The objective of this project is to develop an improved blower fan system to decrease the amount of debris in harvested blueberry bins and to improve the understanding of the relationship between moisture condition and the amount of debris in the harvested blueberry bins. Not only will this knowledge benefit wild blueberry producers but the findings could also be applied to future agricultural endeavors in other cropping systems such as grape and cranberries. The goal is a reliable, cost effective and efficient solution to lowering the excess debris that is causing concern at the wild blueberry processing facilities (Fig. 2-1).

Figure 2-1: Image showing harvested wild blueberry with excess debris causing nuisance to processing plants.

2.2 MATERIALS AND METHODS

2.2.1 Multivariable Air Flow Chamber

An apparatus to measure the terminal velocity of common types of debris found while harvesting wild blueberries was developed at the Dalhousie University Faculty of Agriculture (DAL-AC) Precision Agriculture Research Lab (Fig. 2-2). The apparatus was designed using two variable speed fans that were connected to a 150 mm polyvinyl chloride

(PVC) pipe. The vertical PVC pipe was plumbed into a clear section for easy viewing (Fig. 2-2). Inside the viewing area was an aluminum screen creating a surface to monitor debris and wild blueberries. A short distance (15 mm) above the screen, a hole (13 mm) was drilled to insert a hot-wire anemometer (Digi-Sense 20250-16, Cole-Parmer Canada Company, Montreal, QC) to record the wind velocity being exerted through the aluminum screen. The screen was located 150 mm below the open end of the clear piping. The specific objects of interest (debris and wild blueberry) were placed on the screen and the wind velocity was incrementally increased until the selected object levitated approximately 25 mm above the aluminum screen.

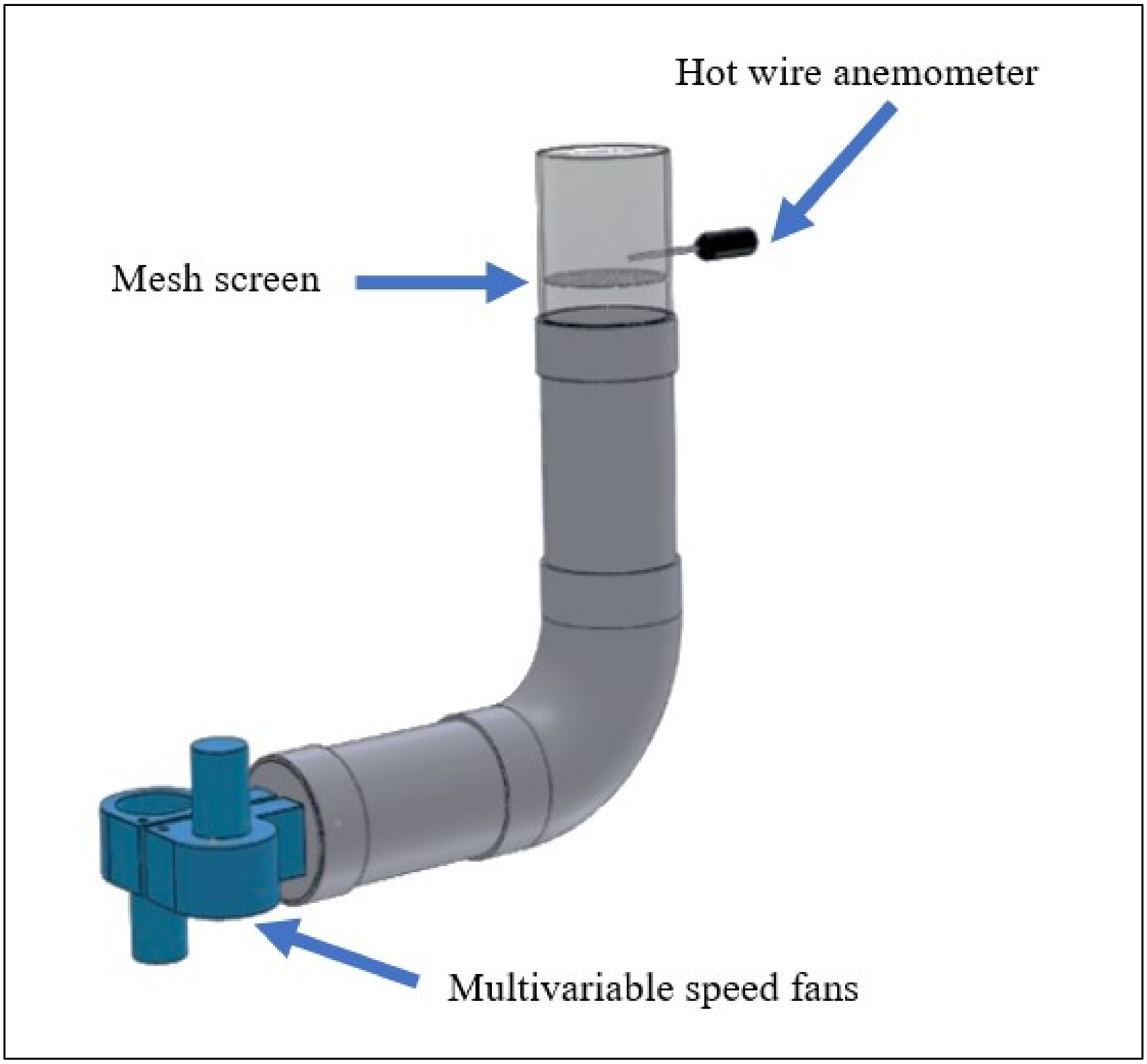


Figure 2-2: Multivariable air flow chamber for measuring terminal velocity of selected debris and berry samples.

2.2.2 Lab Evaluation of Multivariable Dual Fan Air Flow System

A traditional wild blueberry harvester is fitted with a fan plenum housing operating with a single 12 V blower fan and a fixed air flow rate (Fig 2-3a). A new dual fan plenum system was designed with two separate air flow channels (120 mm wide, 50 mm tall, 400 mm long) to increase the air flow for greater debris cleaning performance (Fig 2-3b). The new plenum was built using 3.175 mm thick sheet metal and designed to replace the old plenum mounted on the berry handling conveyor without the need to disassemble the harvester. A variable speed handheld fan controller positioned in the cab of the harvester was designed to allow the operator the ability adjust the rate of air flow (Fig 2-3c).

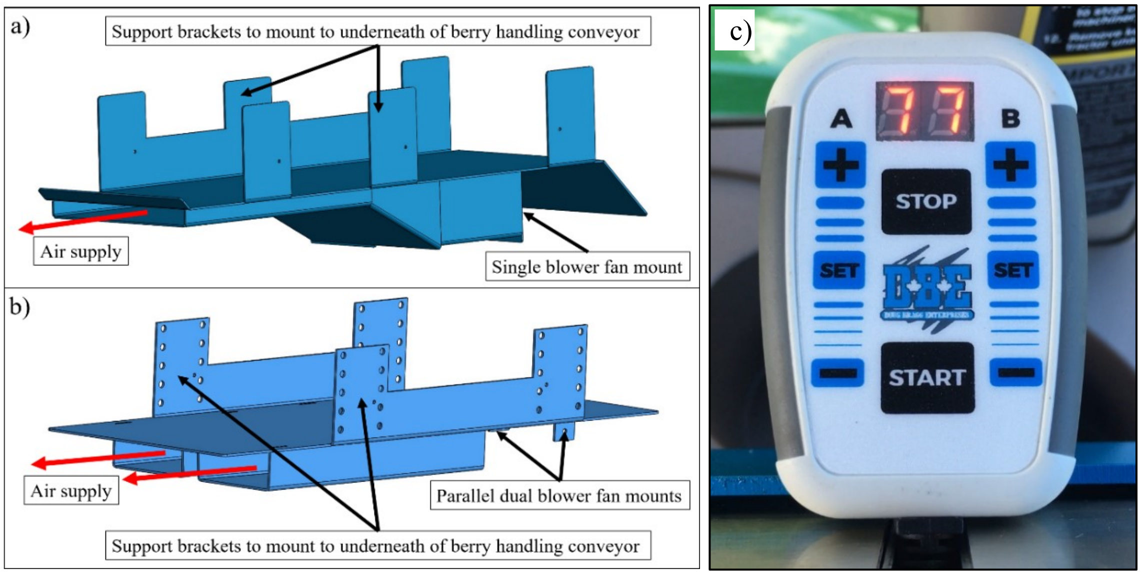


Figure 2-3: Diagram showing (a) traditional single blower fan plenum design as compared to (b) new dual blower fan plenum design with (c) variable speed handheld fan controller.

A hot-wire anemometer was positioned at five equally spaced (63.5 mm) locations where berries fall from the 254 mm wide side conveyor to the back conveyor to determine the air speed the berries encounter using each fan setting and replicated three times. Statistical analysis was performed using Minitab 17 (Minitab Inc., State College, Pa.) statistical software. Classical statistics was used to calculate minimum, maximum, mean and standard deviation. Multiple means comparison was performed using least squares (LS) means to determine which fan settings were significantly different.

2.2.3 Surface Area to Mass Ratio of Fruit and Debris Samples

A selection of common debris (*Vaccinium angustifolium* Ait. (wild blueberry) stems, red sorrel, *Hypericum perforatum* L. (St. John’s wort), goldenrod, witchgrass, hair fescue) and wild blueberry fruit samples were collected in August 2016 from a commercial wild blueberry field at the North River site (45.466416°N, -63.209014°W) in Colchester County, Nova Scotia just prior to harvest (Fig. 2-4). The North River field was in the crop year of the biennial crop production cycle. This field had been under commercial management over the past decade and received conventional fertilizer, weed, and disease management practices along with biennial pruning by mowing for the past several years. The soil at the North River site had pH ranging from 5.0 – 5.5 (Farooque et al., 2012). Each debris samples mass was recorded using an electronic balance (TP-1502, Denver Instruments Inc., Bohemia, N.Y.) and the cross-sectional area was determined using ImageJ2 image processing software (Schindelin et al., 2015). Wild blueberries were also manually harvested, the berries mass was recorded and analyzed for cross sectional area.

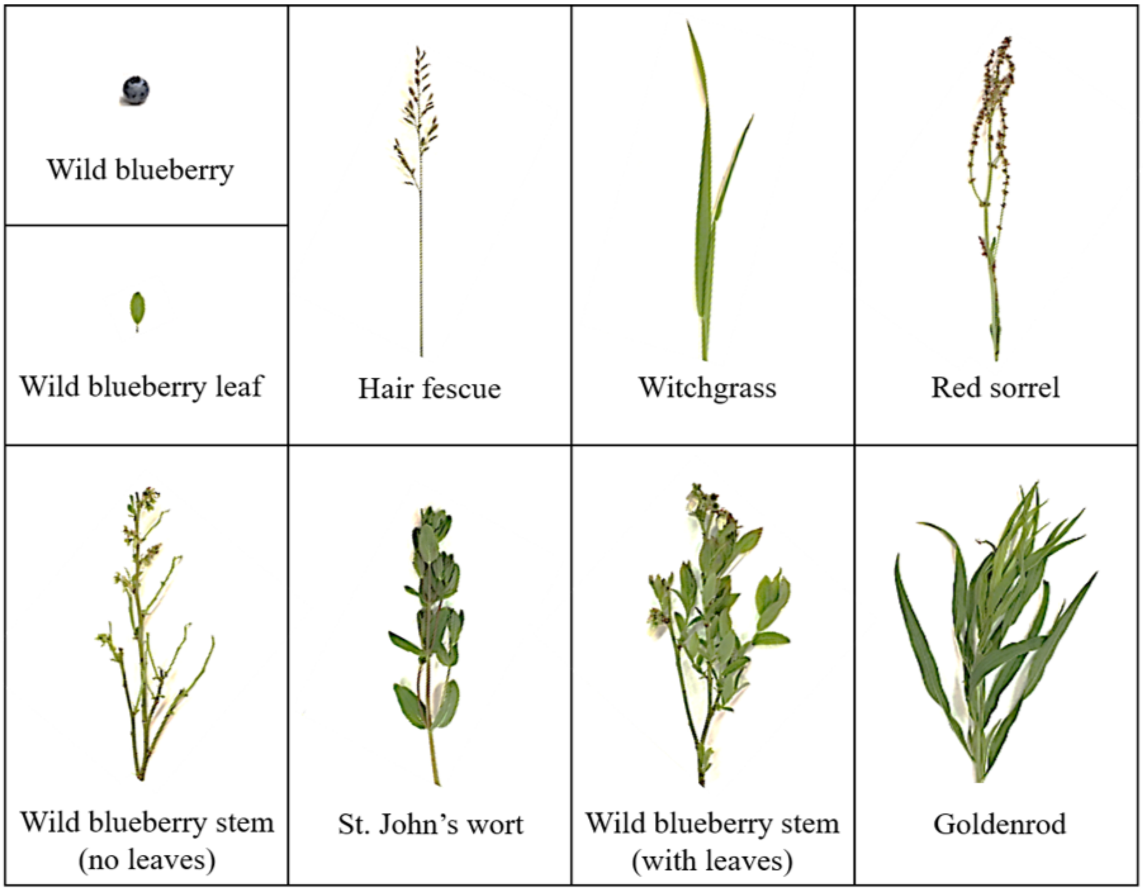


Figure 2-4: Wild blueberry and common debris types selected from North River field site used for terminal velocity calculations.

2.2.4 Terminal Velocity of Fruit and Debris Samples

Each of the collected debris and wild blueberry fruit samples from the field were individually placed on the aluminum screen with the blower fans off. The fan speed was incrementally increased until the object remained levitated for 30 s. At this point, the hot-wire anemometer was inserted into the airstream and used to record the terminal velocity of each of the objects. Three samples of each form of debris and wild blueberry were tested and the procedure was replicated three times in both low moisture (<77 g m^{-2} water) and high moisture (>127 g m^{-2} water) conditions. The moisture for each trial was determined using a leaf wetness sensor (Phytos 31 LWS, Decagon Devices, Pullman, WA) and datalogger (EM50, Decagon Devices, Pullman, WA). Statistical analysis was performed using Minitab 17 statistical software. Classical statistics was used to calculate minimum, maximum, mean and standard deviation. Multiple means comparison was performed using LS means to determine which sample masses were significantly different, cross-sectional area and terminal velocity under both low and high moisture conditions.

2.2.5 Field Evaluation of Multivariable Fan System

Two commercial wild blueberry fields were selected in Colchester Country, Nova Scotia for evaluation of the developed variable speed fan system. The selected fields were the Highland Village site (45.405875°N, -63.670548°W; 2.2 ha) and East Mines site (45.425611°N, -63.482099°W; 4.0 ha). Both fields were in their vegetative sprout year of the biennial crop production in 2015, and crop year in 2016. The fields had both been under commercial management over the past decade and received conventional fertilizer, weed, and disease management practices along with biennial pruning by mowing for the past several years.

A commercial single head DBE wild blueberry harvester operating with a single 12 V blower fan and a fixed velocity of 14 m s^{-1} was retrofitted with the new dual fan plenum system with a variable velocity of 0 to 23 m s^{-1} and mounted on a 62.5 kW John Deere 5093E tractor. Standard picker bars have 65 picker teeth each with a diameter of 7.92 mm and equally spaced at 13.41 mm. Modified picker bars with 63 picker teeth with a diameter of 7.92 mm and a slightly larger spacing of 13.72 mm were designed for research testing. The two different styles of mechanical harvester picker bars (PB_1 = 63 and PB_2 = 65 tooth) were used for field evaluation. Four different blower fan speeds (B_1 = 0, B_2 = 14, B_3 = 18 and B_4 = 23 m s^{-1}) 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 (>127 g m^{-2}) and LW_2 = low moisture (<77 g m^{-2})) within the selected wild blueberry fields. The picker bars in conjunction with different blower fan speeds and moisture conditions were tested at two levels of wild blueberry plant heights (SP < 250 and TP > 250 mm) within the selected fields. Factorial experimental design was used with two levels of leaf wetness and two levels of harvester picker bars with eight treatment combinations of plant height and blower fan speed ($SP \times B_1$; $SP \times B_2$; $SP \times B_3$; $SP \times B_4$; $TP \times B_1$; $TP \times B_2$, $TP \times B_3$ & $TP \times B_4$). Fruit samples and debris (leaves, stems, dirt) were collected from the blower and the collection bin within selected plots from each treatment combination. Following a similar technique to Farooque et al., (2014), the 32 treatment combinations were each replicated four times and randomly established throughout the field to achieve independence of error terms.

Plots the same width as the harvester head (0.91 m), and 30 m in length were made randomly using a measuring tape in the path of the operating harvester. Following a similar technique to Jameel et al., (2016b), five blueberry plant heights were recorded randomly using a ruler from each plot prior to harvest to determine the average height. The harvester operator raised the picking head just prior to each plot and allowed time to expel all the previously harvested fruit and the picking teeth were cleaned of debris before entering the experimental plot. Experimental plots were harvested at each fan setting while the yield and debris was collected from the bin and blower fan shroud (Fig. 2-5). The collected samples from each plot were separated (wild blueberry, leaves, stems and dirt) and the mass was recorded using an electronic balance (Denver Instruments Inc., Bohemia, N.Y.) to quantify the magnitude of debris included in the fruit for each of the treatment combinations in both fields. The individual masses (wild blueberry, leaves, stems and dirt) were divided by the total mass from each sample and converted to a percent of mass. Statistical analysis was performed using Minitab 17 statistical software. Analysis of variance (ANOVA) using the general linear model (GLM) procedure was performed to study the effect of the selected factors on fan debris removal performance. Multiple means comparison was performed using LS means to determine which specific means differ significantly from one another in each treatment.

Figure 2-5: Field data collection from mechanical wild blueberry harvester blower fan and bin.

2.3 RESULTS AND DISCUSSION

Mass of selected debris and berry samples in low moisture conditions ranged from <0.01 to 1.80 g (Table 2-1). The wild blueberry stem with leaves had the highest mass in both low and high moisture conditions (1.80 and 1.98 g) and the wild blueberry leaf had the lowest mass in both low and high moisture conditions (<0.01 and <0.01 g) (Table 1). The mass did not significantly increase for any fruit or debris sample after being soaked in water. Wild blueberry fruit had the same mass as red sorrel, wild blueberry stem without leaves and the St. John's wort in both low and high moisture conditions. Goldenrod had the highest surface area (4,276 mm^2) while the wild blueberry leaf, hair fescue and wild blueberry fruit had the lowest (30 mm^2). The wild blueberry surface area to mass ratio is much less than that of the debris samples. The low surface area to mass ratio of the wild blueberry will help the blower fan to easily remove the unwanted debris without fruit loss.

Table 2-1. Multiple means comparison using least-squares method of debris and blueberry sample mass (low/high moisture) and surface area collected from North River site.

Parameter measured	Low moisture mass (g)	High moisture mass (g)	Surface area (mm^2)	Surface area to mass ratio (mm^2 g^{-1})
Wild blueberry leaf	<0.01 E	<0.01 D	74 F	8,905
Hair fescue	0.07 DE	0.09 D	217 EF	3,100
Witchgrass	0.24 CDE	0.24 CD	693 DEF	2,888
Red sorrel	0.42 BCD	0.50 BC	917 DE	2,183
Wild blueberry fruit	0.49 BC	0.51 BC	30 F	61
Wild blueberry stem without leaves	0.71 B	0.80 B	1,077 D	1,517
St. John's wort	0.76 B	0.78 B	2,141 C	2,817
Goldenrod	1.59 A	1.84 A	4,276 A	2,689
Wild blueberry stem with leaves	1.80 A	1.98 A	3,083 B	1,713

Means with no letter shared are significantly different at p = 0.05.

Debris samples under both low and high moisture conditions showed a significant difference in terminal velocity during harvesting as compared to the wild blueberry fruit (Table 2-2). Wild blueberry fruit had a terminal velocity of 15.65 m s^{-1} while the wild blueberry stem without leaves had the next highest terminal velocity (4.28 m s^{-1}) under low moisture conditions. Wild blueberry fruit had a terminal velocity of 16.24 m s^{-1} while the blueberry stems without leaves had the next highest terminal velocity (5.64 m s^{-1}) under high moisture conditions. The results suggest the ability to increase the fan speed above the terminal velocity of the various debris types without danger of accidentally removing the harvested fruit through the blower fan. The large gap in terminal velocity of wild blueberry fruit and unwanted debris suggests that a properly adjusted blower fan mounted on the harvester can adequately separate the wild blueberry fruit from debris.

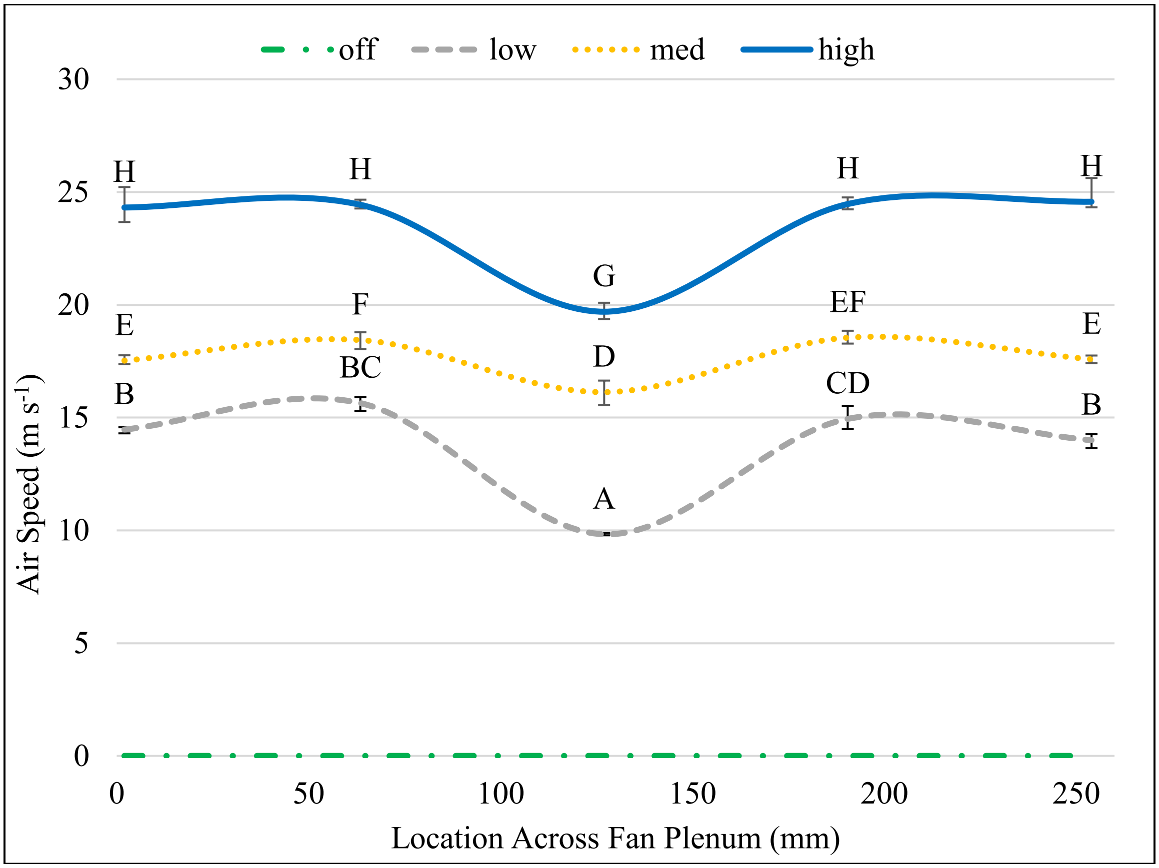
Table 2-2. Summary statistics and multiple means comparison using least-squares method to identify the terminal velocity of debris and wild blueberry fruit samples collected from North River site.

Parameter measured (n=6)	Low moisture conditions terminal velocity ($m\ s^{-1}$)				
	Min.	Max.	Mean	SE Mean	S.D.
Wild blueberry leaf	1.02	1.30	1.10 C	0.04	0.11
Hair fescue	1.24	2.01	1.65 C	0.13	0.32
Goldenrod	2.72	3.77	3.38 B	0.15	0.37
Witchgrass	2.99	3.87	3.53 B	0.13	0.31
Red sorrel	2.94	4.58	3.68 B	0.27	0.67
Wild blueberry stem with leaves	3.40	4.04	3.70 B	0.09	0.21
St. John’s wort	3.43	4.25	3.84 B	0.12	0.31
Wild blueberry stem without leaves	4.10	4.59	4.28 B	0.07	0.18
Wild blueberry fruit	14.13	17.42	15.65 A	0.54	1.33

Parameter measured (n=6)	High moisture conditions terminal velocity ($m\ s^{-1}$)				
	Min.	Max.	Mean	SE Mean	S.D.
Wild blueberry leaf	1.01	1.22	1.12 E	0.04	0.09
Hair fescue	2.21	3.51	2.84 D	0.19	0.46
Goldenrod	4.01	5.21	4.60 BC	0.22	0.54
Witchgrass	3.56	4.51	3.94 CD	0.14	0.36
Red sorrel	5.28	6.01	5.55 B	0.12	0.29
Wild blueberry stem with leaves	3.51	4.10	3.76 CD	0.08	0.19
St. John’s wort	3.89	4.21	4.03 CD	0.05	0.12
Wild blueberry stem without leaves	5.19	6.09	5.64 B	0.15	0.37
Wild blueberry fruit	14.50	18.84	16.24 A	0.70	1.71

Means with no letter shared are significantly different at $p = 0.05$.

The multivariable dual fan system created an airstream with the lowest velocity directly in the center of the conveyor at each fan speed setting (Fig. 2-6). The likely reasoning is because of the small gap between the two outflow plenums causing slight turbulence. The highest air velocity for each fan speed setting was found halfway between the edge and the center of the air stream. The low fan speed setting had ranged from 9.83 to 14.94 $m\ s^{-1}$. The medium fan speed setting had ranged from 16.13 to 18.54 $m\ s^{-1}$. The high fan speed setting had ranged from 19.69 to 24.57 $m\ s^{-1}$.



Means with no letter shared are significantly different at p = 0.05.

Figure 2-6: Mean comparison of each fan speed setting (off, low, med, high) at five positions measured across the width of the multivariable fan plenum during berry drop. Error bars at each measurement point show the minimum and maximum value recorded.

Experimental Field Evaluation

Field 1 was found to have a yield of 6,814 kg ha^{-1} as compared to 6,569 kg ha^{-1} in Field 2. Significant variations in fruit yield between fields and within fields is common as suggested by Farooque et al. (2014). GoPro Hero4 (GoPro, San Mateo, CA) video footage suggested that the increase in fan speed had a major reduction on the amount of debris that was removed from the harvested fruit (Fig. 2-7 and 2-8). It can be seen from figure 2-7 that the harvested fruit and debris landed in the center of the rear conveyor when the fans were off or at a low setting of 14 m s^{-1}. Increasing the fan speed higher than 14 m s^{-1} caused the wild blueberry fruit to be propelled slightly to the far edge of the rear conveyor (Fig. 2-7). This phenomenon is especially noted when using the high (23 m s^{-1}) fan speed that is greater than the terminal velocity of the wild blueberry fruit (15.65 m s^{-1}). Although visually no berries were lost, it is recommended to adjust the rear conveyor such that the berries land in the center of the conveyor while on flat ground at the fan speed being used. This reduces the risk of berry loss when travelling up or down inclines while harvesting.

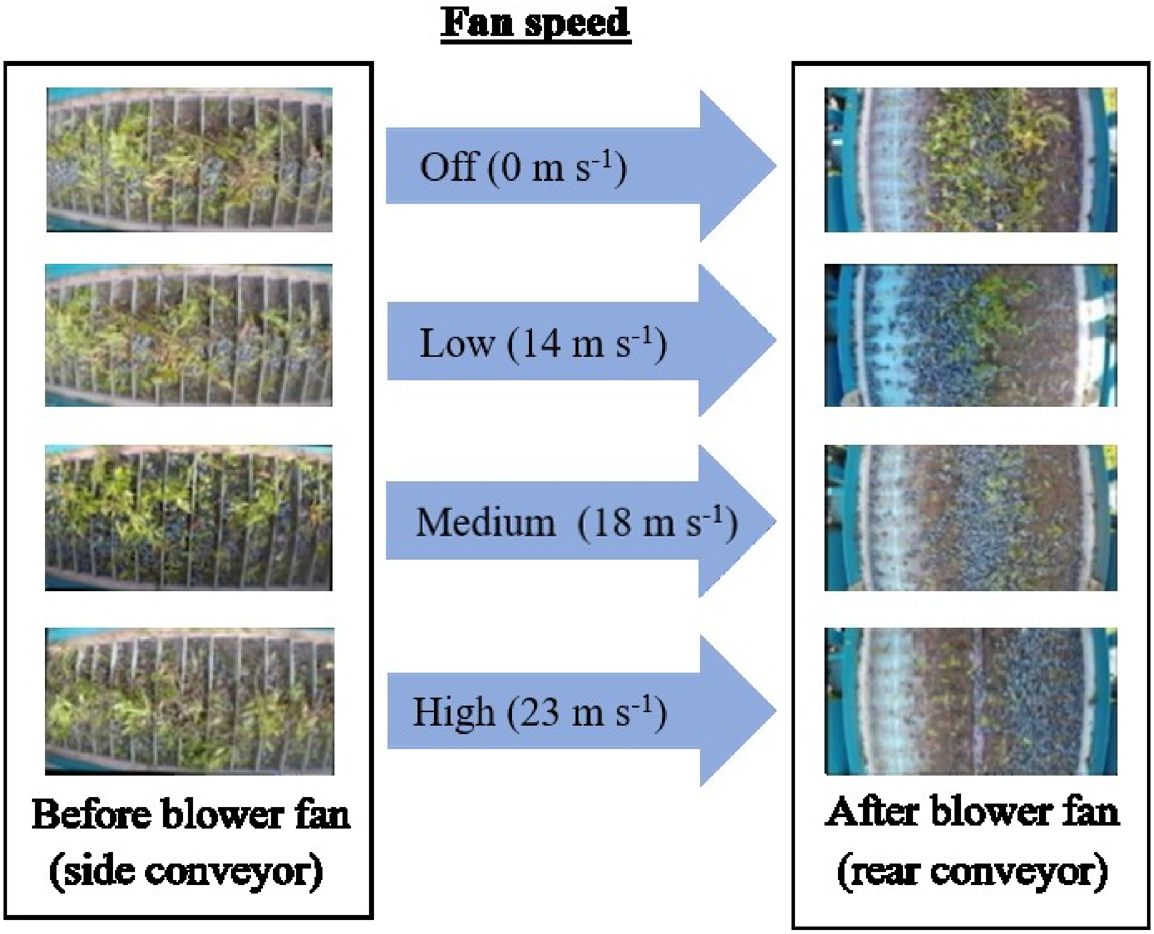


Figure 2-7: GoPro Hero4 camera footage showing debris separation (before and after) passing fan at different blower speed settings.

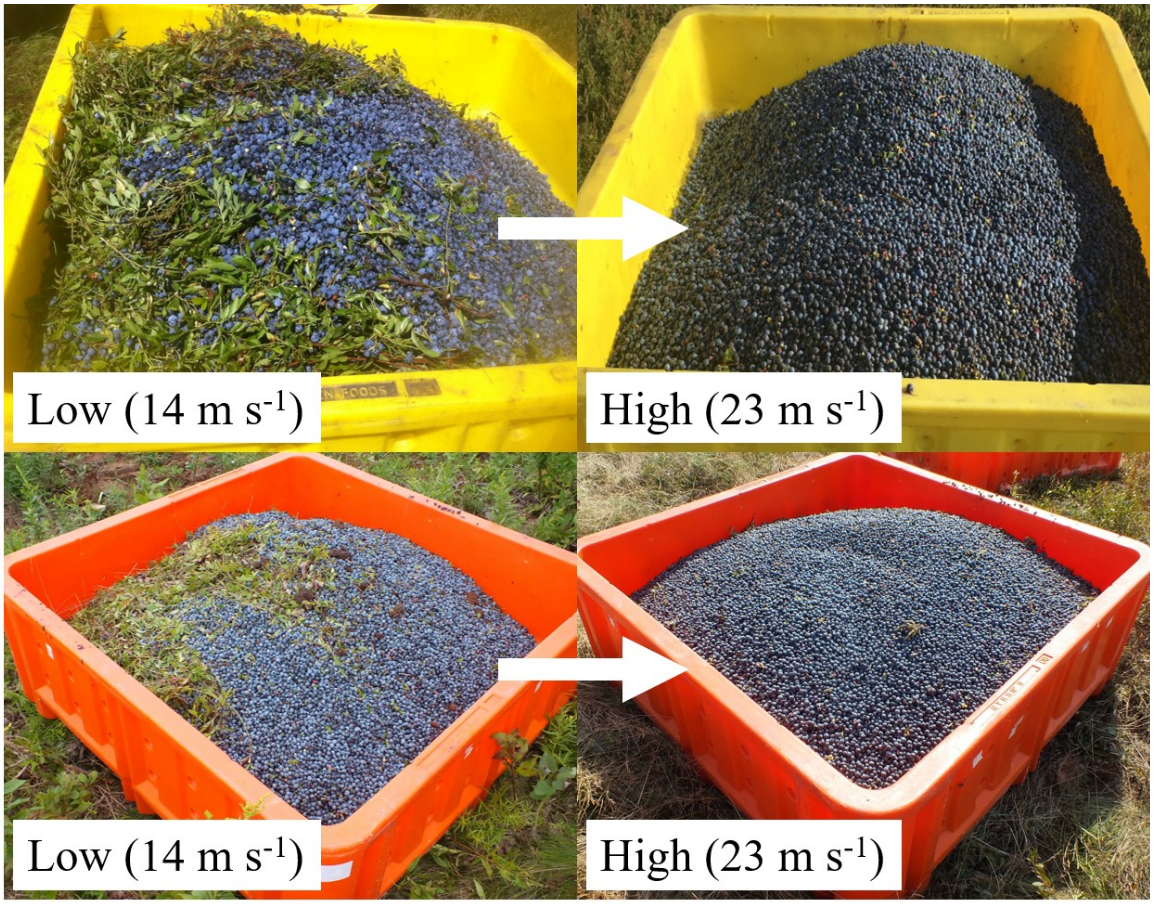
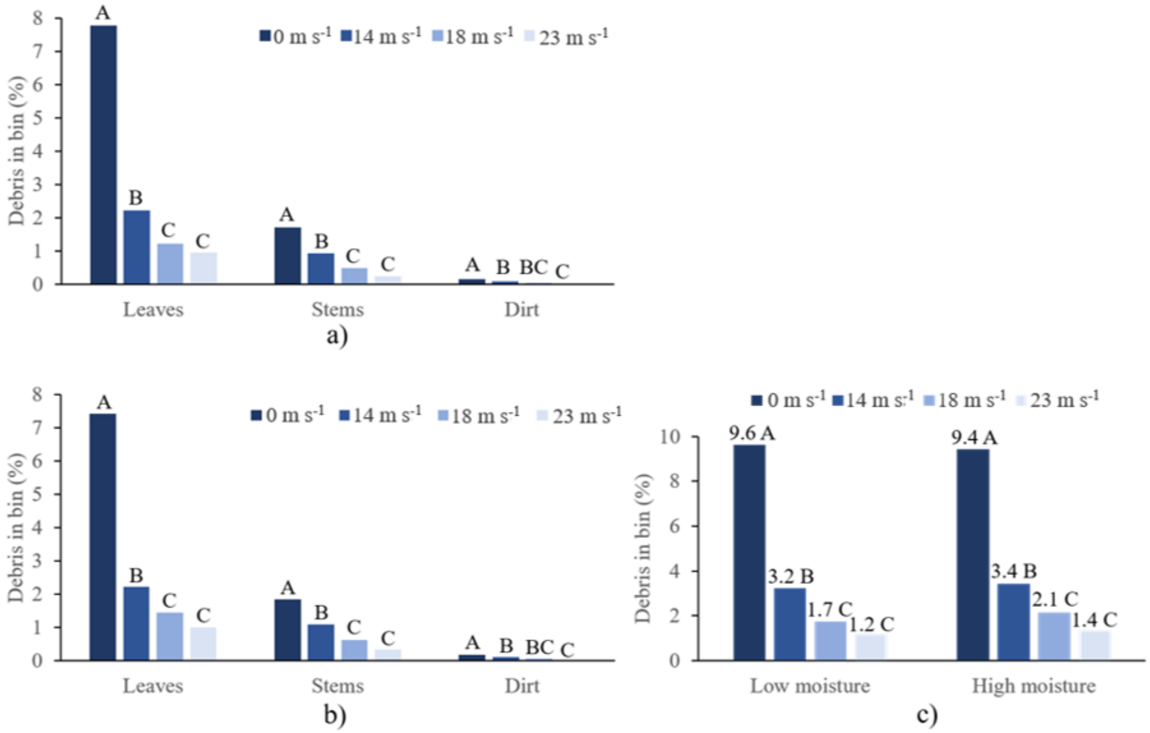


Figure 2-8: Images showing visual comparison of debris separation using low versus high fan speeds during harvesting.

Results of the means comparison indicated that the blower fan speed had a significant effect on the amount of leaves, stems and dirt that were removed during harvesting (Fig. 2-9). The highest percentage of debris (mass basis) came from wild blueberry leaves (7.77%) collected during low moisture harvest conditions and 7.41% during high moisture harvest conditions. Leaves were most effectively removed using the medium (18 m s^{-1}) and high (23 m s^{-1}) fan speed settings for both low and high moisture field conditions. Similarly, the wild blueberry stems were most effectively able to be significantly reduced from the harvested fruit bins by using the medium and high fan speed settings. Very little dirt was collected (0.18%) during harvesting in both low and high moisture field conditions and was easily able to be reduced by using even the lowest (14 m s^{-1}) fan speed setting (Fig. 2-9). A fan speed of 14 m s^{-1} performed significantly better than if no fan was used in both low and high moisture field conditions. Based on these results, fan speeds of 18 and 23 m s^{-1} performed equally during both low and high moisture field conditions to remove debris (98.8% and 98.6%) while harvesting.



a)

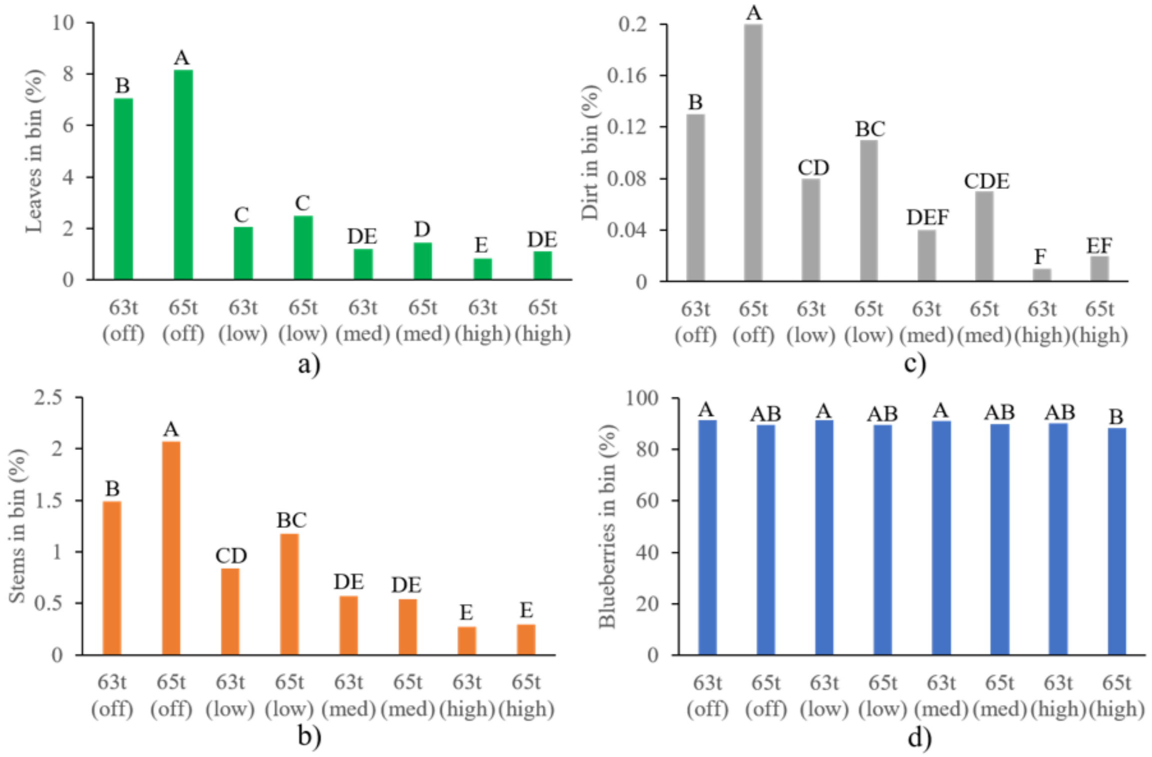
b)

c)

Means with no letter shared are significantly different at p = 0.05.

Figure 2-9: Mean comparison of debris separation with different blower fan speeds a) low moisture field conditions, b) high moisture field conditions, and c) comparison of both low and high moisture field conditions.

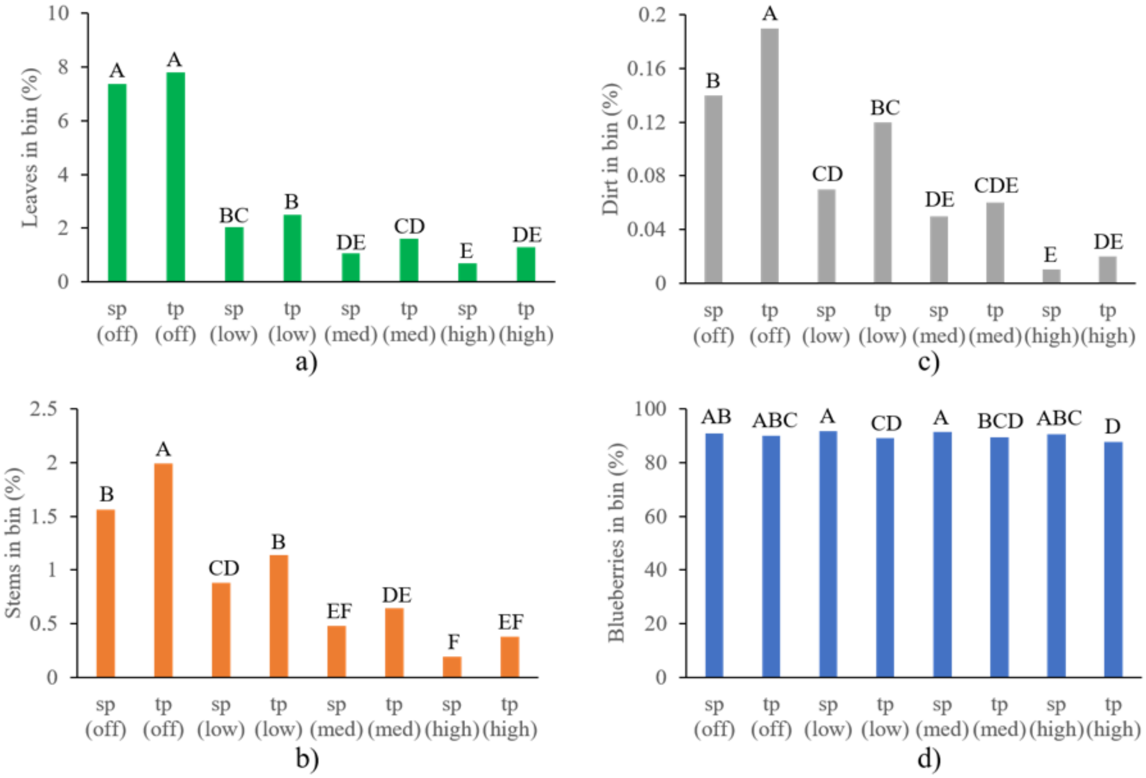
Results of the means comparison indicated that the 63 tooth picker bars significantly reduced the amount of harvested wild blueberry leaves, wild blueberry stems and dirt collected while harvesting (Fig. 2-10a, 2-10b, 2-10c). This is likely caused from the wider teeth spacing causing less plant pulling when the picker bars comb through the wild blueberry plant foliage. The picker bar tooth spacing did not have any significant effect on the harvested yield (Fig. 2-10d). The number of picker bars did not significantly affect the amount of debris in the harvested bin when the blower fan was used at any of the set speeds. A fan speed of 18 and 23 m s^{-1} significantly reduced the leaves in the harvested bin. Similarly, the fan speed of 18 and 23 m s^{-1} were significantly better than a fan speed of 14 m s^{-1} at removing wild blueberry stems from the harvested bin. There was no significant difference in the yield collected in the bin except for a slight reduction when using the 65-tooth bar and a fan speed of 23 m s^{-1}. This likely was the result of wild blueberry fruit getting lodged in the excess amount of debris being collected during harvesting and being blown away by the fan. Visual observation revealed that when wild blueberry fruit is resting on a large quantity of debris on the side conveyor the blower fan tends to remove the entire mass (including fruit) rather than being separated. However, when the wild blueberry fruit lay underneath the debris on the side conveyor the blower fan adequately removes the debris while the fruit safely drops on the rear conveyor.



Means with no letter shared are significantly different at p = 0.05.

Figure 2-10: Mean comparison of different blower fan speeds (off = 0, low = 14, med = 18 and high = 23 m s^{-1}) and number of picker bar teeth (63t = 63 and 65t = 65 tooth) for a) wild blueberry leaves (%), b) wild blueberry stems (%), c) dirt (%), and d) wild blueberry fruit (%) landing in harvested bins.

Results of the means comparison indicated that the wild blueberry plant height did not affect the amount of wild blueberry leaves that were collected during harvesting (Fig. 2-11a). Wild blueberry plants less than 250 mm tall resulted in a significant reduction in wild blueberry stems and dirt collected during harvesting as compared to plants taller than 250 mm (Fig. 2-11b, 2-11c). This is likely caused from increased plant pulling when the picker bars comb through the taller wild blueberry plant foliage. In the selected fields, the wild blueberry plant height did not have any significant effect on the harvested yield (Fig. 2-11d). The wild blueberry plant height did not significantly affect the amount of debris in the harvested bin when the blower fan was used except a slightly larger amount of wild blueberry stems when harvesting tall plants with a fan speed of 14 m s^{-1}. A fan speed of 18 and 23 m s^{-1} were significantly able to reduce the leaves in the harvested bin (Fig. 2-11a). Similarly, the fan speeds of 18 and 23 m s^{-1} were significantly better than a fan speed of 14 m s^{-1} at removing wild blueberry stems from the harvested bin (Fig. 2-11b). There was a significant reduction in the percent yield collected in the bin when harvesting tall plants and using a fan speed of 23 m s^{-1}. This result likely was the result of wild blueberry fruit getting lodged in the excess amount of debris (wild blueberry stems and dirt) being collected during harvesting and being blown away by the high fan air velocity.



Means with no letter shared are significantly different at p = 0.05.

Figure 2-11: Mean comparison of different blower fan speeds (off = 0, low = 14, med = 18 and high = 23 m s^{-1}) and wild blueberry plant heights (sp = < 250 and tp = > 250 mm) for a) wild blueberry leaves (%), b) wild blueberry stems (%), c) dirt (%), and d) wild blueberry fruit (%) landing in harvested bins.

2.4 CONCLUSIONS

Results of this study suggested that wild blueberry fruit has a significantly lower surface area to mass ratio (61 mm^2 g^{-1}) as compared to harvested debris allowing for an excellent opportunity for separation using forced air. Field experimentation suggested that debris removal was optimum when using a fan speed of 18 m s^{-1}. Caution must be used with a fan speed of 23 m s^{-1} because of potential yield loss. However, if the rear conveyor is adjusted properly the fruit loss is negligible. Harvesting in high moisture field conditions didn't have a significant effect on the collected debris as compared to low moisture conditions when using a blower fan speed of 18 or 23 m s^{-1}. Recommendations from this study have recently allowed commercial wild blueberry harvesters with a single fan plenum and a fixed velocity of 14 m s^{-1} to be retrofitted with the new dual fan plenum with an adjustable velocity of 0 to 23 m s^{-1}. The adoption of this improved system will be an important step for the wild blueberry industry to increase berry quality and suggests that other mechanisms such as the harvester debris cleaning brush be studied to determine optimum settings.

CHAPTER 3 EXPERIMENTAL DETERMINATION OF OPTIMUM CLEANING BRUSH PARAMETERS FOR EFFECTIVE DEBRIS REMOVAL ON COMMERCIAL MECHANICAL WILD BLUEBERRY HARVESTERS

Harvesting is one for the most important operations for farmers and special care to ensure maximum yield recovery and quality is vital for sustainability of the industry. Wild blueberry harvesting is especially important as farmers typically manage crops on a two-year production cycle applying time and expensive inputs for almost 24 months with anticipation of a successful and profitable harvest. Mechanical wild blueberry harvesters are unique to Northeastern North America with most being mounted and propelled using a farm tractor. An urgent push from berry processing facilities to improve berry quality and lower shrink has sparked effective debris removal during harvesting as an industry priority. Prior research has been done to improve berry picking efficiency but work to quantify and optimize the debris cleaning brush has been left untouched.

The cylindrical debris cleaning brush is positioned on top of the berry harvesting picking reel and continuously rotates to propel debris from the picker teeth. The brush's filamentary bristles (0.238 cm in diameter) are visually adjusted 0.32 cm into the picker teeth prior to harvest. The annealed nylon bristles wear over time and require constant operator adjustment to maintain proper picking performance. To bench mark debris cleaning brush adjustment parameters a survey was distributed to commercial harvester operators and the results were analyzed suggesting 69.2% were operating outside of the manufacturers recommended adjustment range. Misadjusted brushes have the potential to cause increased debris in the harvested fruit and may lead to reduced berry quality. Inaccurate visual adjustment settings and lack of knowledge regarding the importance of proper settings was the likely cause of wide range of debris cleaning brush adjustment settings. To overcome the visual inaccuracies, the mechanical harvester geometry was studied to develop a method of brush adjustment that was fast and accurate to ensure the bristle length was at the proper depth into the picker teeth.

Three commercially used debris cleaning brushes of varying condition were lab evaluated and compared to a new brush to quantify the bristle wear pattern. Results of ANOVA found a significant difference in the brush diameters however, number of bristles per brush were similar. Wet mass of each brush showed an increased trend as compared to the dry mass however, it was non-significant at $p = 0.05$ suggesting the annealed plastic doesn't absorb water likely extending its expected lifespan.

The bristle tip speed was analyzed in relation to common tractor engine speeds (1,200, 1,400 and 1,600 rpm) with results ranging from 6.58 to 13.88 m s^{-1}. The incremental increase in tractor engine speed significantly increased the bristle tip speed for each brush tested. The wide range of bristle tip speeds from common harvester parameters suggests the urgent need for optimization of the brush rotation to maintain adequate tip speed required for maximum berry quality and effective harvesting performance. Airflow generated in the debris deflection shroud using each brush was analyzed and compared with terminal velocities from chapter 2 with results suggesting only brush 1 is capable of wind velocities high enough to successfully propel the debris away from the picker teeth with bristle tip speeds ranging from 9.15 to 13.88 m s^{-1}. Lab testing concluded the need for a variable speed hydraulic drive motor for better control of the rotating brush speed based on variables such as brush bristle length, tractor engine speed, field moisture conditions and weed density while harvesting.

3.1 INTRODUCTION

Wild blueberries thrive in acidic soil, which is common of deforested land in Northeastern North America (Trevett, 1962). The deforested land is very uneven which creates diverse field conditions with bare spot areas that can take several years for the blueberry plants to spread populating the entire zone (Zaman et al., 2008; Zaman et al., 2009). Mechanical harvesters have been proven to pick most efficiently on smooth non-weedy ground (Kinsman, 1993; Soule & Gray, 1972). The existence of the variable weedy conditions in wild blueberry fields emphasizes the need for a grower's guide to effectively harvest in all differing field conditions.

Wild blueberries are grown on a two-year cycle, the first year being a vegetative year and the second year is the fruit producing year (Wood, 2004; Zaman et al., 2009). The berries will remain on the plant until approximately 90% of the crop reaches maturity (Farooque et al., 2013). Typically, the crop will be ready for harvest within the first two weeks of August and the harvest season will last for roughly one month. The wild blueberry crop will be harvested all at once, unlike other crops that partake in multiple harvesting events including strawberry and raspberry (Wood, 2004). This creates a significant time constraint to harvest all of the fields within peak season. Due to this time constraint many harvester operators will work their machine for long days without stopping to adjust the cleaning brush potentially lowering field efficiency.

Mechanical harvesting may damage blueberries by bruising the soft skin which leads to berry softening and increased risk of decay during processing (Dale et al., 1994; Farooque et al., 2013; Mehra et al., 2013b). An improperly adjusted brush can increase the risk of damaged berries during the harvesting operation when the brush is adjusted too far into the teeth the bristles have a greater chance of making contact with harvested berries. However, if the brush is not into the teeth far enough the bristle may not adequately clean the picker teeth thus allowing debris to accumulate causing berry damage. The wild blueberry industry lacks an operator’s guide to educate and assist with the proper debris cleaning brush settings during harvesting.

Rotating brushes used for debris removal have a diverse range of application, from street sweeping to agricultural weed ripping. Likely the most widely used application being the brushes used to remove plaque and food logged in peoples teeth (Bergenholtz et al., 1984). Previous attempts have been made to summarize some of the common brush applications and designs although none directly applying to debris removal on mechanical wild blueberry harvesters (Gaser, 1999; Peel, 2002). The following gives a brief overview of select commonly used applications of debris cleaning brushes with similar designs to that of the mechanical wild blueberry harvester brush.

Filamentary cylindrical brushes similar in design to the mechanical wild blueberry harvester are available for use for street sweeping from industrial brush manufacturers such as C.C.A.G. Crottie, Corso Italia, Italy (Fig. 3-1). Street sweeping vehicles rely heavily on debris cleaning brushes for the clearing of road ways and sidewalks (Vanegas-Useche et al., 2015).

Figure 3-1: Cylindrical brush designs for street cleaning (C.C.A.G. Crotti, 2018).

The first mechanical street sweeper was invented by Joseph Whitworth in 1843 (Chang et al., 2005; Pitt et al., 2004). Street sweepers have multiple brushes attached of varying style and material to adjust to different terrain and conditions (Fig. 3-2). The rotating circular side brushes are typically used for clearing gutters and up to edges of sidewalks or buildings while the main channel brush is mounted in the center to clear a wider flat section of the streets (Vanegas-Useche et al., 2015; Wang & Parker, 2014).

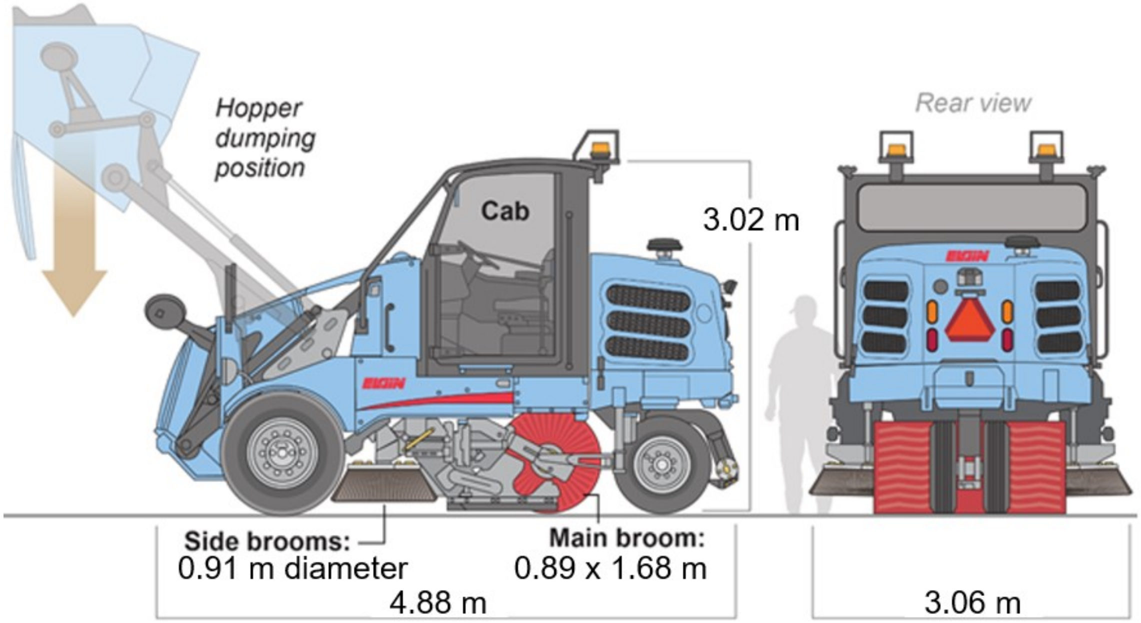


Figure 3-2: Multifunctional self-propelled street sweeper with front hopper (Vivanco & Bentle, 2016).

An alternative to a self-propelled street sweeper is using a sweeping brush attachment that can be fitted to agricultural and industrial tractors, all-terrain vehicles or other types of similar motorized equipment (Fig. 3-3). The brush attachments come in a variety of bristle types and are comparable to the ones used solely on the self-propelled street sweepers with diameters up to 250 cm while also having the advantage of being removed for alternative use. (Cat® North America, 2018).

Figure 3-3: Commercially available detachable hydraulically controlled brush attachment (Cat® North America, 2018).

The bristles on the street sweeping side brushes are usually made of steel and grouped together into clusters then placed in a circular pattern (Vanegas-Useche et al., 2007; Vanegas-Useche et al., 2015). Sweeping channel brush bristles are also made of steel and are designed to look and behave very similar to the debris brush on the wild blueberry harvesters. The bristles for channel brushes are individually wrapped around a center axis to form a cylindrical design allowing a flicking action from the bristle tips when rotated (Abdel-Wahab et al., 2011; Rosca & Butsch, 2016; Vanegas-Useche et al., 2011). Debris cleaning brushes are available in a wide range of filamentary material types depending on the application and performance requirement (Table 3-1). Early design of debris cleaning brushes for mechanical wild blueberry harvesters used metal bristles similar to the street sweeping bristles however, never commercially manufactured because of excessive wear caused to the picker teeth and potential metal fragments contaminating the harvested fruit (Bragg, 2017). Soft bristle materials including horsehair were found inefficient at removing the rigidly logged debris from the picker teeth (Bragg, 2017). Nylon bristles were later tested and found to be a superior choice for lifespan of both the bristles and the picker teeth, effective debris removal and minimizing chance of fruit contamination. Nylon also has a hard wear resistance and is resistant to most chemicals making it relatively easy to clean and maintain during harvesting (Table 3-1). Nylon and polypropylene are both rated at a similar toughness of 64 Nm m^{-1} but nylon has both a higher bending stiffness and tensile strength as compared to polypropylene (Curbell Plastics, 2017).

Table 3-1. Common brush bristle filamentary material types (Peel, 2002).

Bristle material type	Performance benefit
Polypropylene	Good chemical resistance and stability
Nylon	Hard wearing and resistant to most cleaning chemicals
Polyester	Resistant to dilute acids, oils, fats and heat
Steel wire	Available black, zinced or crimped
Flat steel	Hard wearing, hardened and tempered
Brass wire	Available crimped or smooth
Stainless steel	Available crimped or smooth
Nylon with impregnated silicon carbide or aluminum oxides	Hard wearing with abrasive cleaning/scouring action. Impregnated material to suit application
Vegetal fibers	Natural fibers, environmentally friendly
Horsehair	Very soft natural fiber

Rotating brushes have been used for the management of fouling in marine vessels and are of a similar design to the debris cleaning brush found on the mechanical harvester (Fig. 3-4). These brushes are used to remove fouling collected on ship hulls to reduce the spread of non-indigenous species and increase hydrodynamics and fuel efficiency (Hopkins et al., 2010; Tribou & Swain, 2015). Marine fouling brushes are reasonably small at only 35 to 40 cm in width with a bristle lengths of 35 to 50 cm and a bristle diameter of 0.1 to 0.5 cm (Hopkins et al., 2010; Tribou & Swain, 2015). The rotational speeds typically range from 250 to 700 rpm (Hearin et al., 2015; Hopkins et al., 2010; Tribou & Swain, 2015). Tribou & Swain's (2015) research found effective fouling removal using brushes operating at a tip speed of only 1 m s^{-1}. Holm's et al. (2003) found a brush rotational speed of 457 rpm was optimum for effective marine fouling removal. Hopkins et al. (2010) found brushes to be 89% effective at removing fouling from the ship's hull when operated using optimal settings.

Figure 3-4: Commercially used de-fouling brush designed for boat hulls (Yacht shop, 2018).

Channel brushes are also found on agricultural machinery for mechanical weeding (Fig. 3-5). The mechanism shown in Figure 3-5 is designed to be used for inter-row weeding by either uprooting or covering weeds with soil in organically grown crops. Although effective to reduce agrochemical usage, research has suggested a concern with large amounts of dust created during dry field conditions (Pullen & Cowell, 2007).

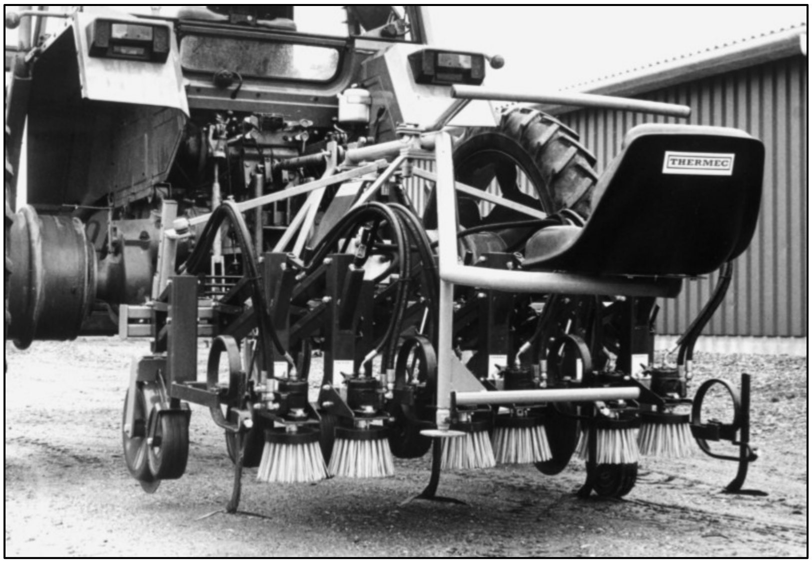


Figure 3-5: Agricultural rotary brush weeder (Melander, 1997).

In the 1980's brushes were developed for animal grooming and comfort especially in dairy for increased milk production of up to 1 kg per day as well as decreasing the rate of mastitis by 34% (Devries et al., 2007; Mandel & Nicol, 2017; Miller, 2010; Schukken & Young, 2009). Brushes improve cow comfort by stimulating blood circulation through scratching and rubbing (Mandel & Nicol, 2017). The electrically controlled brushes mounted in dairy housing facilities are typically made using nylon bristles and are mechanically rotated when pressure is applied from the animal (Georg & Totschek, 2001; Newby et al., 2013). Three common types of bristles designs on cow brushes are shown in Figure 3-6. Figure 3-6a is the most common type that has a uniform bristle length and material type. Select brushes can be designed with different bristle lengths and materials alternating across the width for a customized animal grooming. Figure 3-6b illustrates a brush with two different bristle lengths alternating throughout the width. Figure 3-6c uses bristles formed into an hour glass to allow the brush to form closer to the shape of the cows back (Newby et al., 2013). Advanced versions of the cow brush system also include a swinging mechanism to allow increased ease of use for the cattle (Mandel & Nicol, 2017; Schukken & Young, 2009).

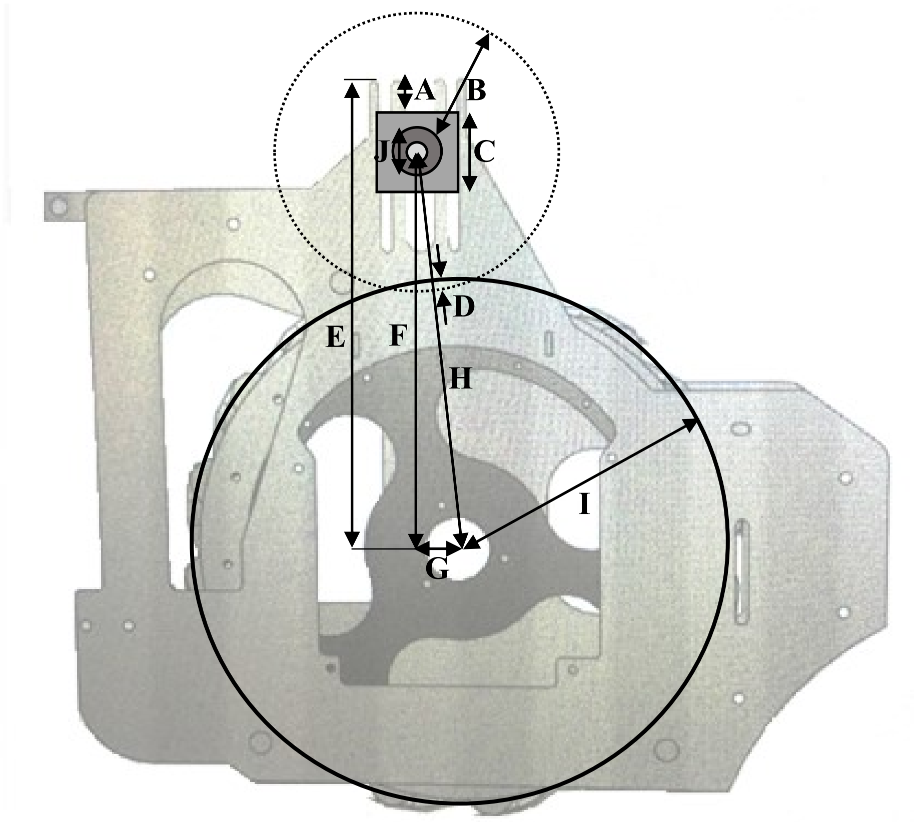
Figure 3-6: Common brush designs used for animal comfort (DeLaval, 2018; GEA, 2018; MS Schippers, 2018).

The wild blueberry industry has made substantial improvements in crop management practices over the last two decades including improved fertilizer use. In turn, the result has led to improved berry yield and taller blueberry plants (Farooque et al., 2013; Wood, 2004). However, it has also increased the weed and grass strengths, making it necessary to improve the debris management systems of the mechanical harvester. The aim of this work is to study the characteristic of varying sized cleaning debris cleaning brushes as well as their potential effects during operation and develop a grower guide to improve the harvester operator's ability to properly maintain the cleaning brush while harvesting.

3.2 MATERIALS AND METHODS

3.2.1 Wild Blueberry Harvester Picker Reel and Debris Cleaning Brush Geometrical Configuration

Mechanical wild blueberry harvester manufacturers recommend debris cleaning brushes to be adjusted such that 0.32 cm of the brush bristle extend into the picker bar teeth (Bragg, 2017). Brush re-adjustment is continually required because the plastic bristle tips wear after contact with debris and abrasion on the metal picking teeth. Operators are required to manually adjust the debris cleaning brush by loosening the four adjustment bolts at adjustment prongs on each end of the harvester head. Typically, operators use a small hammer and tap the bearing housing on either side until the desired bristle depth into the picker teeth is visually made. Visual observation is difficult and can easily lead to inaccurate brush adjustment settings. To help overcome the visual inaccuracies, the mechanical harvester geometry was studied to develop a method of brush adjustment that was fast and accurate to ensure the bristle length was at the proper depth into the picker teeth (Fig. 3-7).



Legend	
A	Top of adjustment prongs to top of bearing housing
B	Bristle length
C	Width of bearing housing
D	Depth of bristle into picker teeth
E	Center of picking reel to top of brush adjustment prongs
F	Vertical distance between picking reel and brush
G	Horizontal distance between picking reel and brush
H	Distance between picking reel and brush
I	Radius of picking reel
J	Diameter of brush shaft

Figure 3-7: Harvester geometry relating the picking reel and debris cleaning brush (side view).

Vernier calipers and a ruler were used to measure components and distances required to relate the bristle length and depth into the picking teeth to the position of the brush adjustment prongs. Computer aided design of the harvester head was supplied by the manufacturer to confirm the manual distance measurements (Bragg, 2017). A schematic diagram was constructed to visually illustrate the geometric measurements required to accurately determine brush position (Fig. 3-7). The distance between the rotating brush shaft and center of the picking reel can be found using formula 3-1:

$$H = \frac{J}{2} + B + I - D \qquad (3\text{-}1)$$

Where:

H =distance between center of picking reel and center of brush

J = diameter of brush shaft

B = bristle length

I = radius of picking reel

D = depth of bristle into picker teeth

The vertical distance between the rotating brush shaft and the center of picking reel can be found using formula 3-2 and 3-3:

$$F = E - A - \frac{C}{2} \qquad (3\text{-}2)$$

and

$$F = \sqrt{H^2 - G^2} \qquad (3\text{-}3)$$

Where:

F = vertical distance between center of picking reel and center of brush

H = distance between center of harvester head and center of brush

*G = horizontal distance between center of harvester head and center of brush (*6.47 cm)

E = center of head to top of brush adjustment prongs

A = distance from top of adjustment prongs to top of bearing housing

C = width of bearing housing

Substituting *F* from equation 3-2 into equation 3-3 and *H* from equation 3-1 into equation 3-3 we get:

$$E - A - \frac{C}{2} = \sqrt{(\frac{J}{2} + B + I - D)^2 - G^2} \qquad (3\text{-}4)$$

And solving for the distance from top of adjustment prongs to top of bearing housing in terms of the brush's bristle length we get:

$$A = E - \frac{C}{2} - \sqrt{(\frac{J}{2} + B + I - D)^2 - G^2} \qquad (3\text{-}5)$$

After inputting the measured distances in centimeters, equation 3-5 becomes:

$$A = 54.10 - \frac{9.48}{2} - \sqrt{(\frac{6.11}{2} + B + 33.02 - 0.32)^2 - 6.47^2} \qquad (3\text{-}6)$$

And simplifies to:

$$A = 49.37 - \sqrt{B^2 + 71.52 * B + 1236.75} \qquad (3\text{-}7)$$

Equation 3-7 can be used to determine the distance from the top of the brush adjustment prongs to the brush's bearing housing based on the measured bristle length of the brush to maintain the manufacturers recommended bristle depth into the picker teeth of 0.32 cm.

3.2.2 Commercial Harvester Debris Cleaning Brush Grower Evaluation

A brush adjustment data collection sheet was distributed to 13 harvester operators during August of 2017 to record bristle depths into the picker teeth. To ensure consistent and accurate results each operator was given a metric ruler and asked to record both the distance (*A*) from the top of the adjustment prong to the bearing housing for each side of the brush assembly and (*B*) the bristle length at both ends of the debris cleaning brush (Fig. 3-7). Operators recorded the bristle length and adjustment distance each time the brush was adjusted down and at the end of every working day. Results from the survey were collected from each operator at the end of the harvest season and entered into Excel. Data from each operator was averaged to display the mean bristle depth (into picker teeth) used during commercial harvesting. The minimum and maximum bristle depths were tabulated along with standard deviation. Furthermore, results from each operator were pooled together to display a single average to compare to the manufacturers recommended bristle depth into the teeth (0.32 cm). The results from this study will be used to justify the need for the adoption of a refined method to properly adjust the debris cleaning brush without relying on visual observation.

3.2.3 Debris Cleaning Brush Physical Characteristic Comparison

Three commercially used brushes were donated from local harvester operators to be included in the lab evaluation. In addition, a brand-new brush was supplied by DBE. Each brush was assessed by first marking three randomly selected bristles with red tape. The brush diameter was measured at the same bristle locations using a right-angle carpenter’s level attached to a metal ruler (Fig. 3-8a). A centimeter ruler was used to measure the bristle length at each marked bristle for each brush (Fig. 3-8b). The bristle diameter was taken at both the base and bristle tip using Vernier calipers (Fig. 3.9). When measuring the bristle base diameter of bristles in the center of the brush, the adjacent bristles were held back so as to get accurate readings. Each of the previously used brushes had bristles with a noticeable taper towards the end of the tip. The location of the taper was found by using Vernier calipers and finding the point in which the bristle diameter began to shrink (Fig. 3-10a). The distance from the bristle base to taper location was measured using a ruler and recorded at the three marked bristles on each of the four brushes.

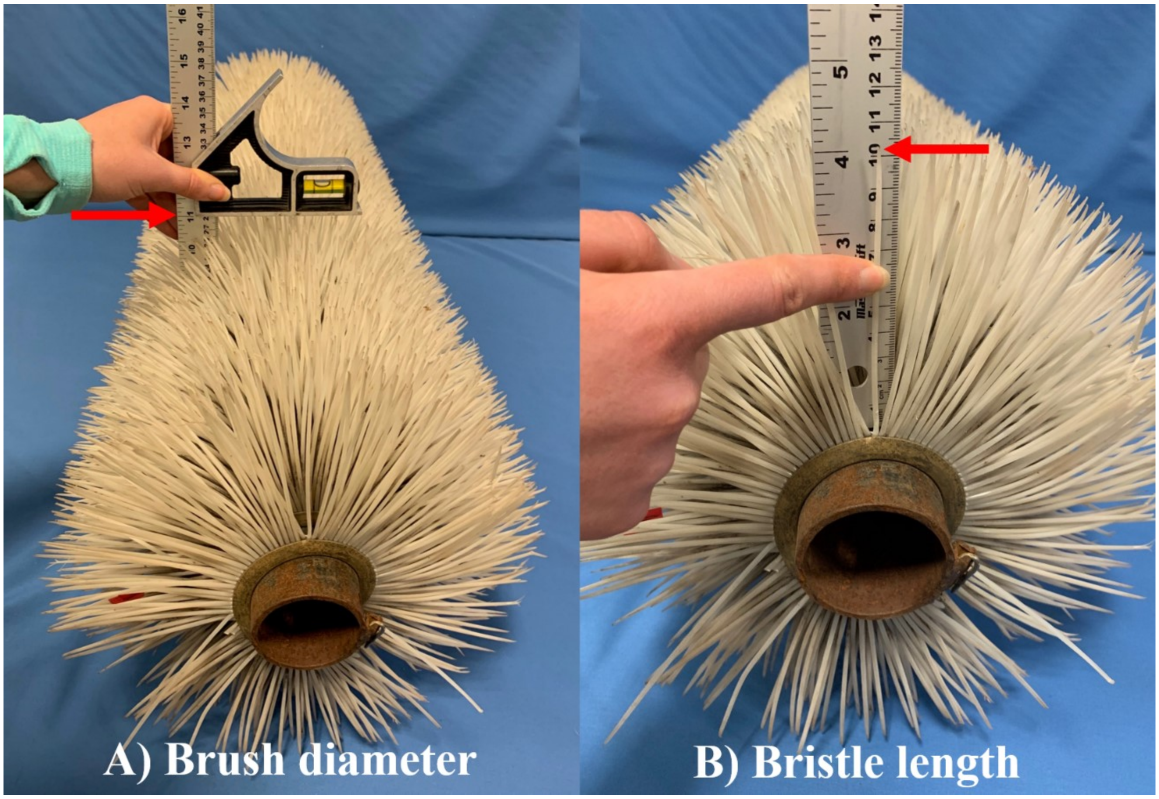


Figure 3-8: Measuring brush diameter and bristle length on a debris cleaning brush.

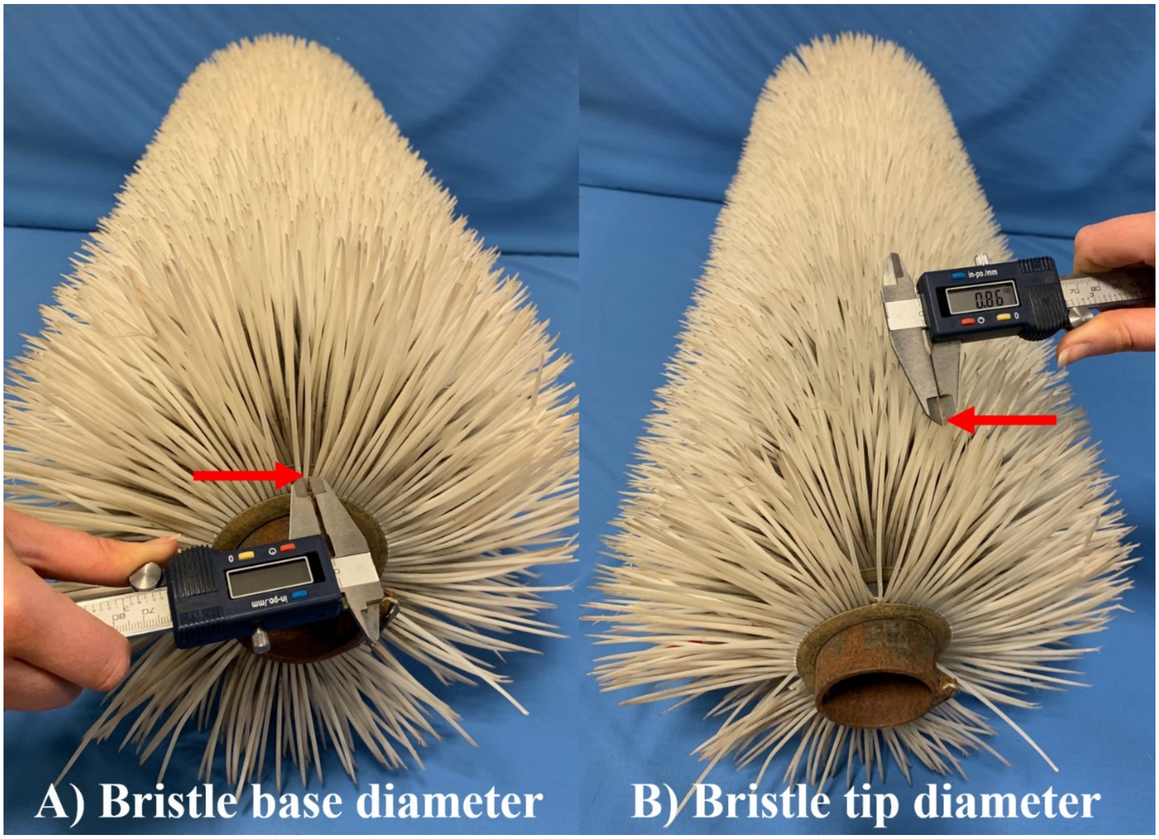


Figure 3-9: Measuring bristle base and tip diameter on a debris cleaning brush.

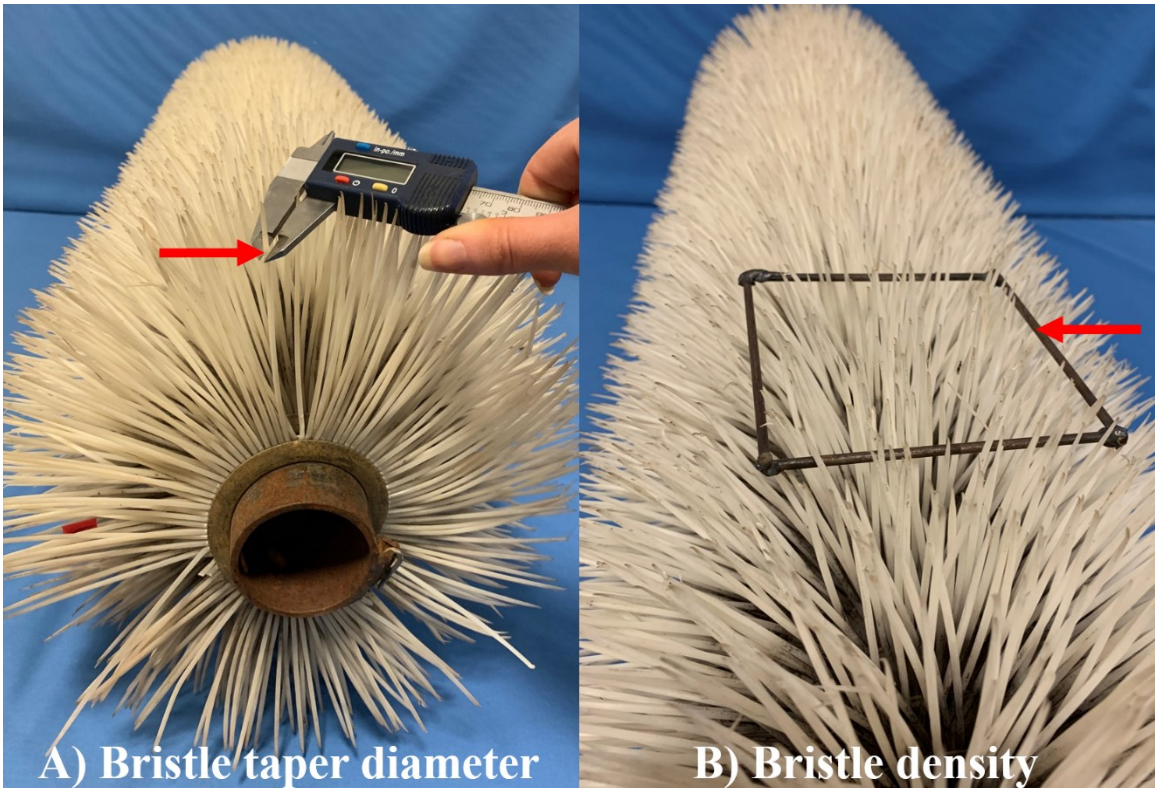


Figure 3-10: Measuring bristle taper diameter and bristle density on a debris cleaning brush.

Bristle density for each brush was determined using a 10.0 cm by 10.0 cm metal quadrat that was placed surrounding the marked bristles. The quadrat was placed on top of the bristles and gently pushed 2.0 cm down into the bristles (Fig. 3-10b). Bristles within the quadrate were counted manually. This procedure was repeated at the three marked bristle locations for each brush.

The dry mass of each brush was measured using an electronic scale (SBI 100, Salter Brecknell, Fairmont MN) after being left in a well-ventilated room for 7-days prior. Each brush was then submerged in a large storage tote filled with water. The brushes were left to soak in water for 24 hours before being removed and lightly shaken to remove excess surface water before recorded the mass using the electronic scale.

The above procedure for measuring brush diameter, bristle length, bristle diameter (base and tip), bristle taper location, bristle density, and dry and wet masses was repeated two additional times at each sampling location for each brush.

Statistical analysis was performed using Minitab 17 statistical software. Normal probability plot of residuals was used to check the normality of error terms using Anderson Darling test at a 5% level of significance. Residual versus fitted values plot was used to check the constant variance of error terms. Each treatment was completed in a random order to achieve independence of the error terms. Collected data was analyzed using classical statistics to determine the minimum, maximum, mean standard deviation and coefficient of variation. Analysis of variance using the GLM procedure was performed to study the brush characteristics. Multiple means comparison was performed using LS means to determine which specific means differ significantly from one another in each treatment.

3.2.4 Debris Cleaning Brush Airflow Analysis at Varying Rotational Speeds

A factorial experimental design was used with twelve treatment combinations of four cleaning brushes with varying bristle length (B_1 = 12.0 cm; B_2, = 11.5 cm; B_3 =10.6 cm; and B_4 =8.7 cm) and 3 tractor rpm speeds (rpm_1 = 1,200; rpm_2, = 1,400; and rpm_3 =1,600) with the following combinations ($rpm_1 \times B_1$; $rpm_1 \times B_2$; $rpm_1 \times B_3$; $rpm_1 \times B_4$; $rpm_2 \times B_1$; $rpm_2 \times B_2$; $rpm_2 \times B_3$ & $rpm_2 \times B_4$; $rpm_3 \times B_1$; $rpm_3 \times B_2$; $rpm_3 \times B_3$ and $rpm_3 \times B_4$), with four locations of measurements along the debris removal shroud. To map the air velocity profile of the debris cleaning brush system a series of sampling points in the debris shroud were studied while varying the tractor rpm for each brush tested in section 3.2.3. The debris shroud and discharge chute were divided into four rows to measure the air velocity produced by the rotation of the brush. Each row contained five sampling points equally spaced at 16.25 cm apart for individual air velocity measurement except the third row which due to the location of the hydraulic manifold only had three points of measurement (Fig. 3-11). The first row was located 12.0 cm above the cross pin along the front of the debris shroud (Fig. 3-11). Sampling row two was located 36.0 cm above the cross pin along the front of the debris shroud ahead of the brush (Fig. 3-11). Sampling row three was located at the top of the shroud 60.0 cm above the cross pin (Fig. 3-11). Sampling row four was located 3.0 cm from the back side of the debris shroud (Fig. 3-12). A 1.0 cm hole was drilled at each of the 18-sampling point in rows 1 through 4 to allow the hot-wire anemometer space to enter the air stream for consistent positioning during collection.

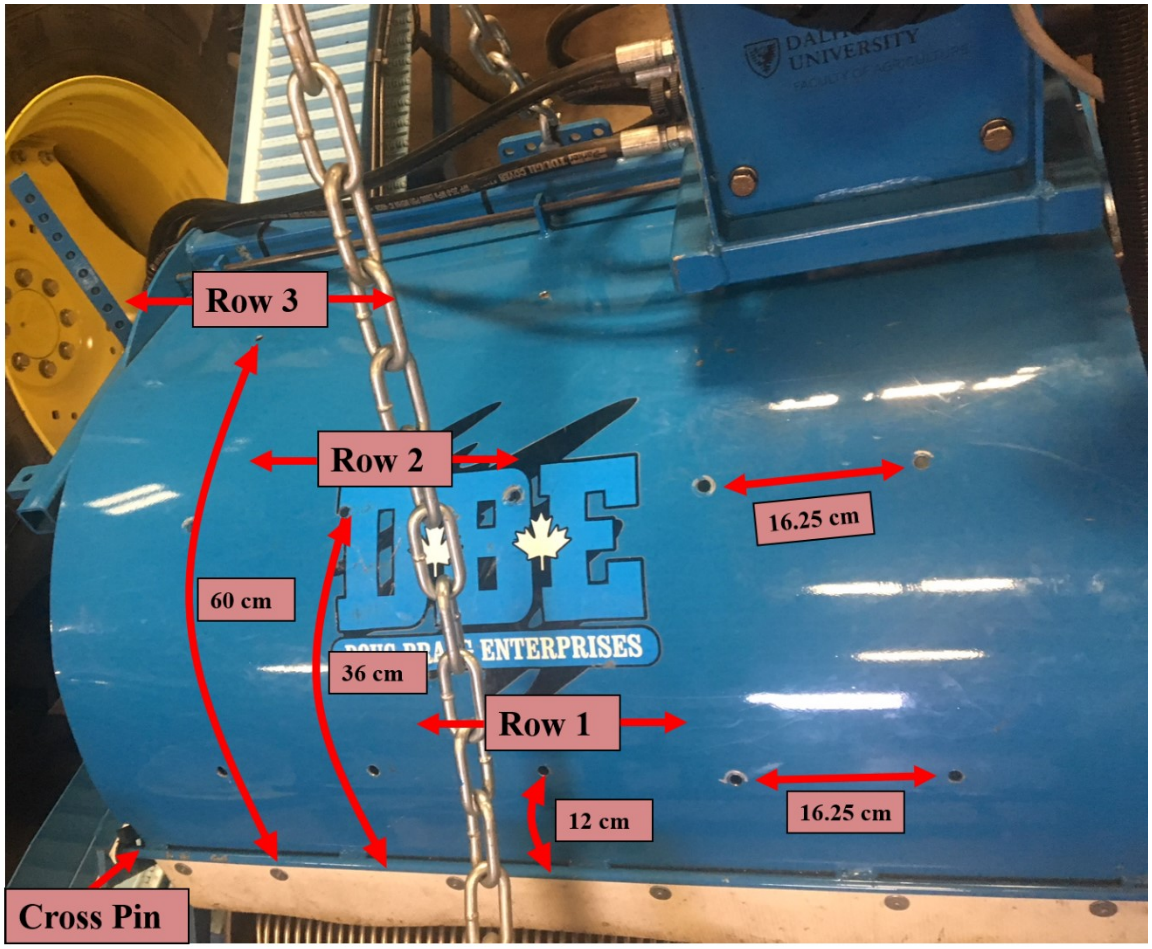


Figure 3-11: Top view of harvester picking head showing air velocity measurement locations (rows 1 – 3).

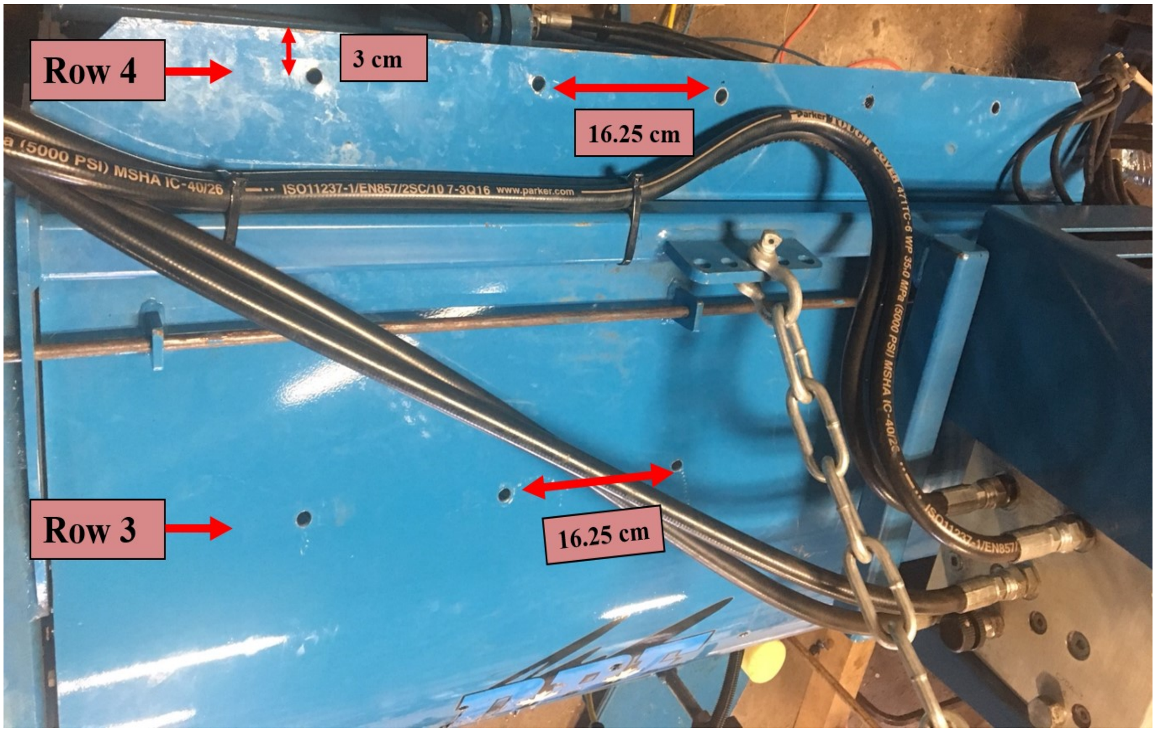


Figure 3-12: Top view of harvester picking head showing air velocity measurement locations (rows 3 – 4).

The four brushes previous studied were installed on a mechanical wild blueberry harvester mounted to a 63.4 kW John Deere 5085M tractor to determine any air flow differences resulting from varying brush characteristics. The harvester picking reel, debris cleaning brush and all berry handling conveyors were turned on and the tractor engine speed was fine-tuned and allowed to stabilize to exactly 1,200 rpm. The hot-wire anemometer was inserted 2.5 cm into each of the 18 sampling points in rows 1 through 4 and used to record the air velocity in a randomly selected order. Electrical tape was used to cover the drilled holes at the sampling points not be tested to ensure the airflow was not inadvertently affected. A digital contact tachometer (HHT13, Omega Canada, Laval, QC) was used to measure the brush's rotating shaft speed during collection of each data set to be used for calculating the bristle tip speed. This procedure was repeated for each of the four brushes and at three tractor engine speeds (1,200; 1,400; and 1,600 rpm) and replicated three times. Statistical analysis was performed using Minitab 17 statistical software. Normal probability plot of residuals was used to check the normality of error terms using Anderson Darling test at a 5% level of significance. Residual versus fitted values plot was used to check the constant variance of error terms. Each treatment was completed in a random order to achieve independence of the error terms. Collected data was analyzed using classical statistics to determine the minimum, maximum, mean standard deviation and coefficient of variation. Analysis of variance using the GLM procedure was performed to study the effect of the selected tractor rpm on air velocity created by the cleaning brush. Multiple means comparison was performed using LS means to determine which specific means differ significantly from one another in each treatment.

The tip velocity of each brush was calculated at each tractor engine speed by calculating the distance travelled by the outer brush circumference based on the rotating shaft speed (rpm) that was measured during experimentation with the help of equation 3-8:

$$Tip\ velocity\ (m\ s^{-1}) = \frac{Brush\ diameter\ (m) * \pi * Brush\ speed\ (rpm)}{60} \qquad (3\text{-}8)$$

Statistical analysis was performed using Minitab 17 statistical software. Normal probability plot of residuals was used to check the normality of error terms using Anderson Darling test at a 5% level of significance. Residual versus fitted values plot was used to check the constant variance of error terms. Each treatment was completed in a random order to achieve independence of the error terms. Collected data was analyzed using classical statistics to determine the minimum, maximum, mean standard deviation and coefficient of variation. Analysis of variance using the GLM procedure was performed to study the effect of the selected tractor rpm on tip velocity of the cleaning brushes bristles.

Multiple means comparison was performed using LS means to determine which specific means differ significantly from one another in each treatment.

3.3 RESULTS AND DISCUSSION

Results from the commercial harvester operators survey suggested variation in adjustment settings ranging from a maximum of 1.97 cm into the teeth (1.65 cm deeper than recommended) to a minimum value of -1.12 cm (1.44 cm shallower than recommended) (Fig. 3-13). On average the bristle depth into the teeth ranged from a maximum of 1.61 cm into the teeth (1.29 cm deeper than recommended) to -1.0 cm (1.32 cm shallower than recommended). Only 30.8% of operators had recorded values within the suggested operating range set by the manufacturer. The survey suggested that the majority of operators (53.8%) were running their debris cleaning brushes too shallow into the picker teeth causing increased brush lifespan with the potential trade-off of decreased berry quality and picking performance with increased debris buildup. After pooling all collected operator data together the bristle depth into the teeth was 0.03 cm (0.29 cm shallower than recommended). The standard deviation ranged from 0.10 to 0.33 cm (Fig. 3-13). The inconsistent variation in bristle depth suggests that the conventional visual observation method of adjusting the harvester brush is unreliable and results in bristle depths not matching the accepted manufacturer's recommendation. A bristle depth too deep into the teeth could potentially cause damage to the harvested fruit, excessive wear and lead to fluctuations in hydraulic flow resulting in varying rotational head speeds. A bristle depth too shallow into the teeth causes excessive debris buildup in the picker teeth causing decreased harvesting performance and reducing fruit quality. Results from this study suggested the urgent requirement for development of an easy to follow debris cleaning brush guide for fast and accurate adjustment of bristle depth into the picker teeth.

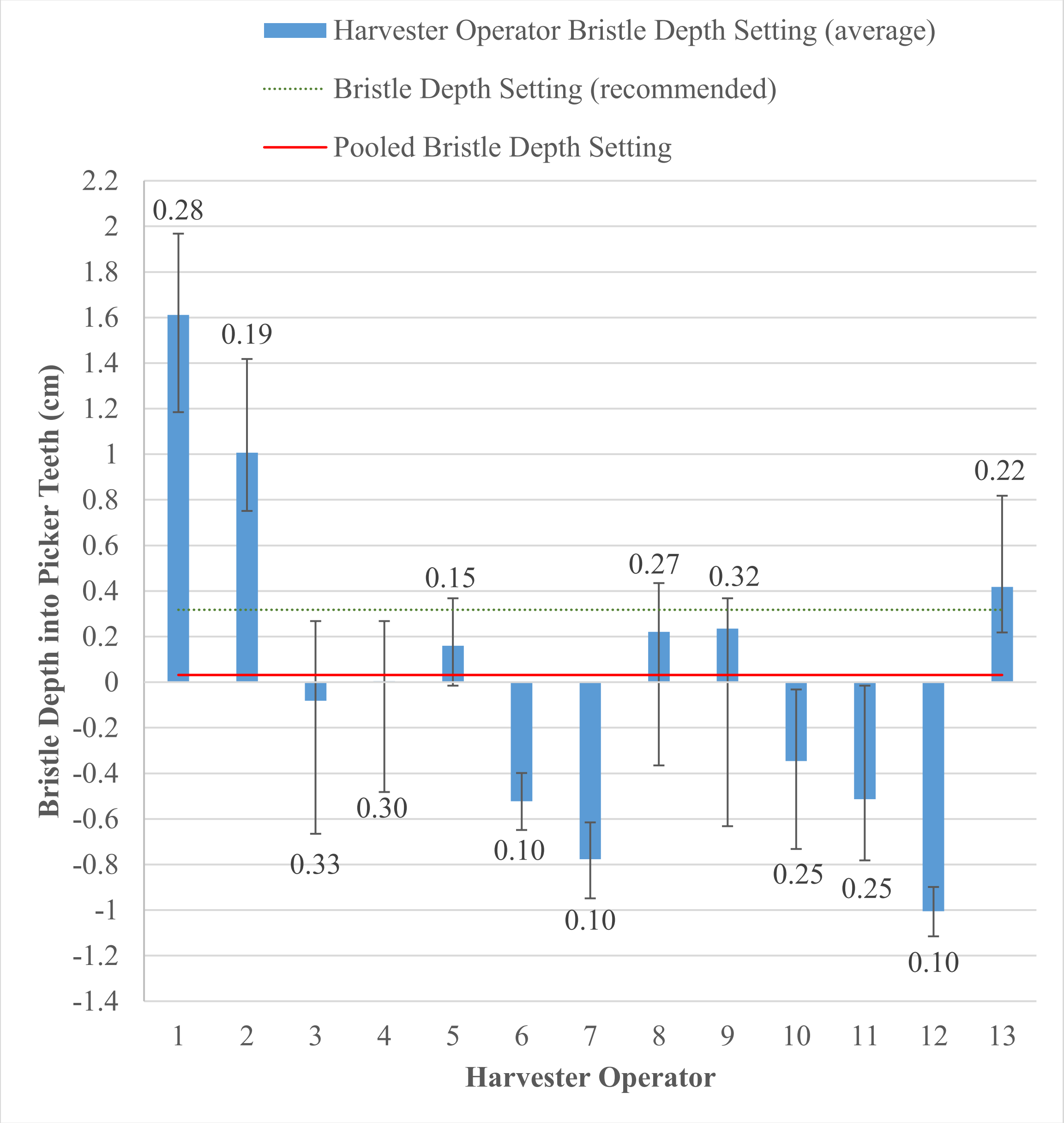
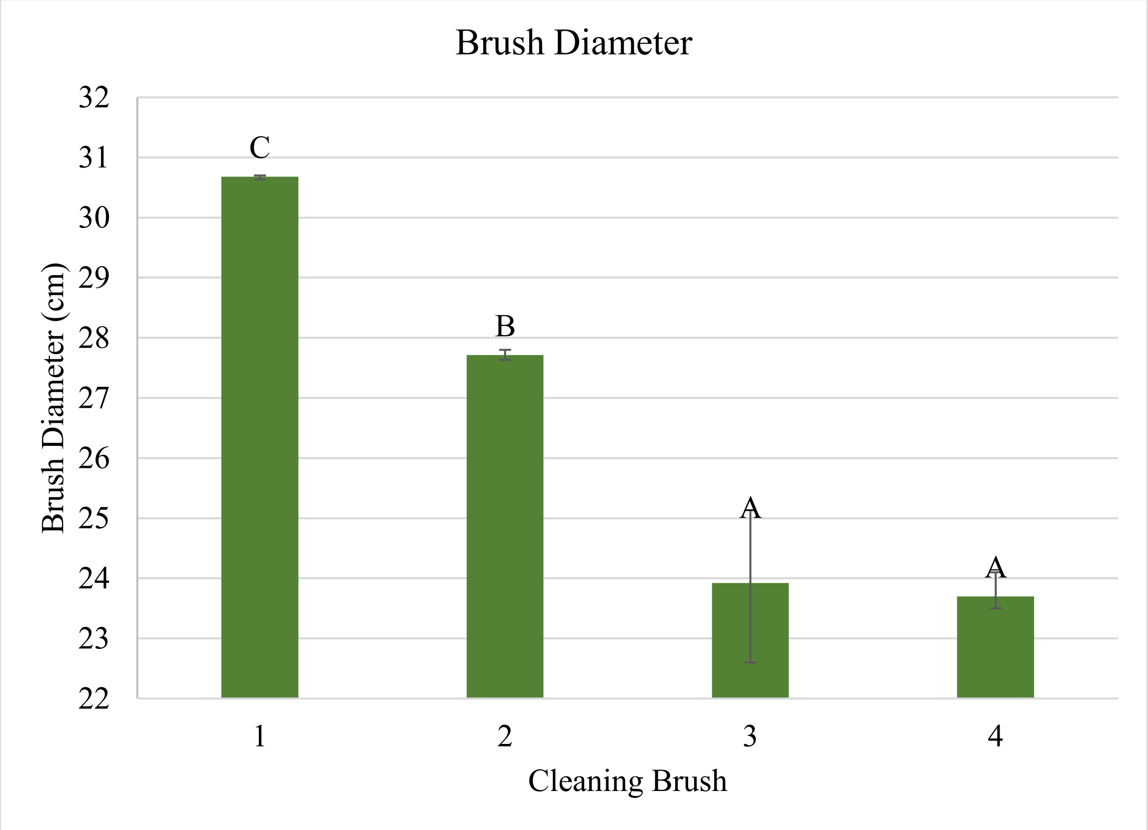


Figure 3-13: Harvester debris cleaning brush bristle depth into picker teeth from 13 commercial operators. Error bars represent the maximum and minimum bristle depth from each operator throughout the season. Standard deviation is numerically displaced for each set of data.

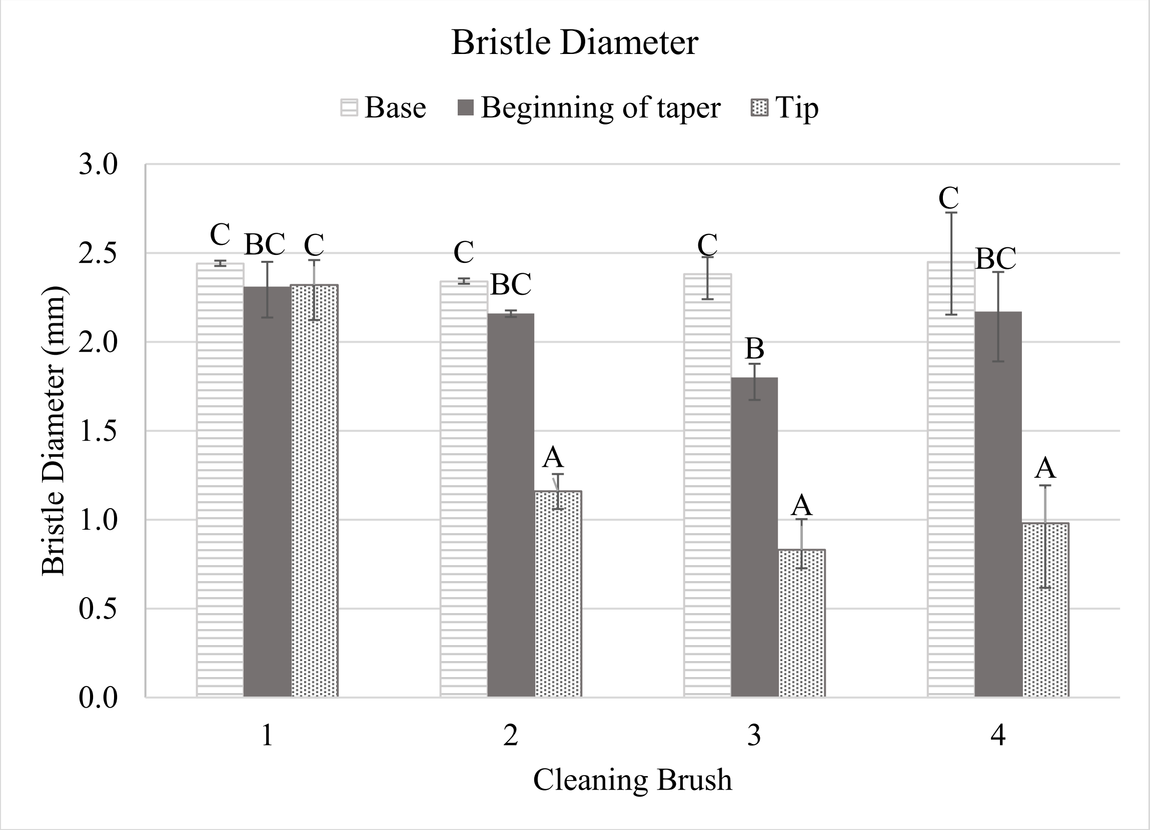
The diameter of brushes lab tested ranged from 30.68 to 23.70 cm (Fig. 3-14). Brush 3 had the largest variation in brush diameter (S.D. = 1.27) most likely because it had several hours of wear and visual observation suggested that misalignment of the brush caused a cone shaped wear pattern. Similarly, brush 4 had a larger variation of diameter measurements (S.D. = 0.35) as compared to brush 1 (S.D. = 0.04) and 2 (S.D. = 0.08). Results of the mean comparison indicated the brand-new brush (brush 1) had a significantly larger diameter (30.68 cm) as compared to each of the used brushes tested (Fig. 3-14). This indicates that the bristles are damaged during harvesting causing a component the operator must monitor and adjust to maintain the proper bristle depth into the picker teeth for effective debris removal.



Means with no letter shared are significantly different at p = 0.05.

Figure 3-14: Mean comparison of debris cleaning brush diameters (1 = new with bristle length of 11.28 cm, 2 = used with bristle length of 10.11 cm, 3 = used with bristle length of 8.42 cm, 4 = used with bristle length of 7.46 cm. Error bars represent the minimum and maximum diameters from the repeated sampling points on each brush.

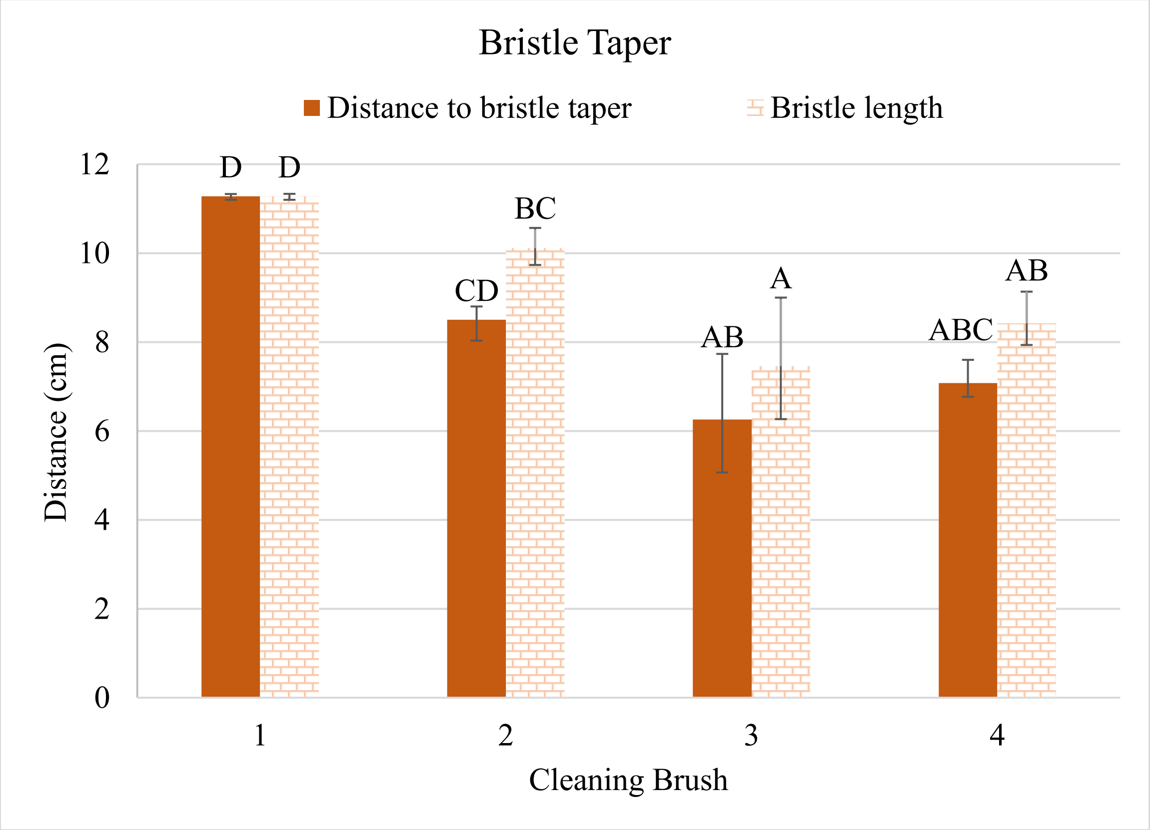
Results of the means comparison indicated a non-significant difference between the bristle diameters at the base of each brush ranging from 2.38 to 2.45 mm (Fig. 3-15). Brush 2, 3 and 4 each had a significantly lower bristle diameter at the tip as compared to the base suggesting that the bristles don't break clean off but rather slowly wear thin towards the bristle tips. Measurements along the length of the bristles of brush 1 indicate the diameter is uniform (~2.38 mm) before being mounted and used on the harvester.



Means with no letter shared are significantly different at p = 0.05.

Figure 3-15: Mean comparison of debris cleaning brush bristle diameters. Error bars represent the minimum and maximum bristle diameters from the repeated sampling points on each brush.

The bristle length of brushes tested ranged from 7.46 to 11.28 cm (Fig. 3-16). Brush 3 had the largest variation in bristle length (S.D. = 1.401). Results of the mean comparison indicated the brand-new brush (brush 1) had the longest bristle length and as a result of not being used the bristle diameter didn't taper along its length (Fig. 3-16). Results from lab analysis of the used brushes showed tapers that ranged from 1.20 to 1.61 cm measuring from the bristle tip to the start of the tapered portion of the bristle. These results suggest that brush 2, 3 and 4 were misadjusted too far into the picker teeth while mounted on the harvester causing excessive wear. If the brushes had been adjusted to manufacturers specification it would have been expected to see tapered sections on the bristles close to 0.32 cm in length to match the recommended depth into the picker teeth. As a result, it strengthens the industry need to build a debris cleaning brush guide for fast and accurate adjustment of bristle depth into the picker teeth.



Means with no letter shared are significantly different at $p = 0.05$.

Figure 3-16: Mean comparison of debris cleaning brush distance to bristle taper and bristle length. Error bars represent the minimum and maximum distances from the repeated sampling points on each brush.

The number of bristles per brush ranged from 8,322 to 10,050 (Fig. 3-17). Results suggested that there was no significant difference in the total number of bristles on debris cleaning brushes even after being used for several hours in the field. These favorable results confirm that the bristles diminish in length but are strongly held in tact remaining in contact at the base. Slight variation in the number of bristles is likely caused during the manufacturing process or potentially during harvesting.

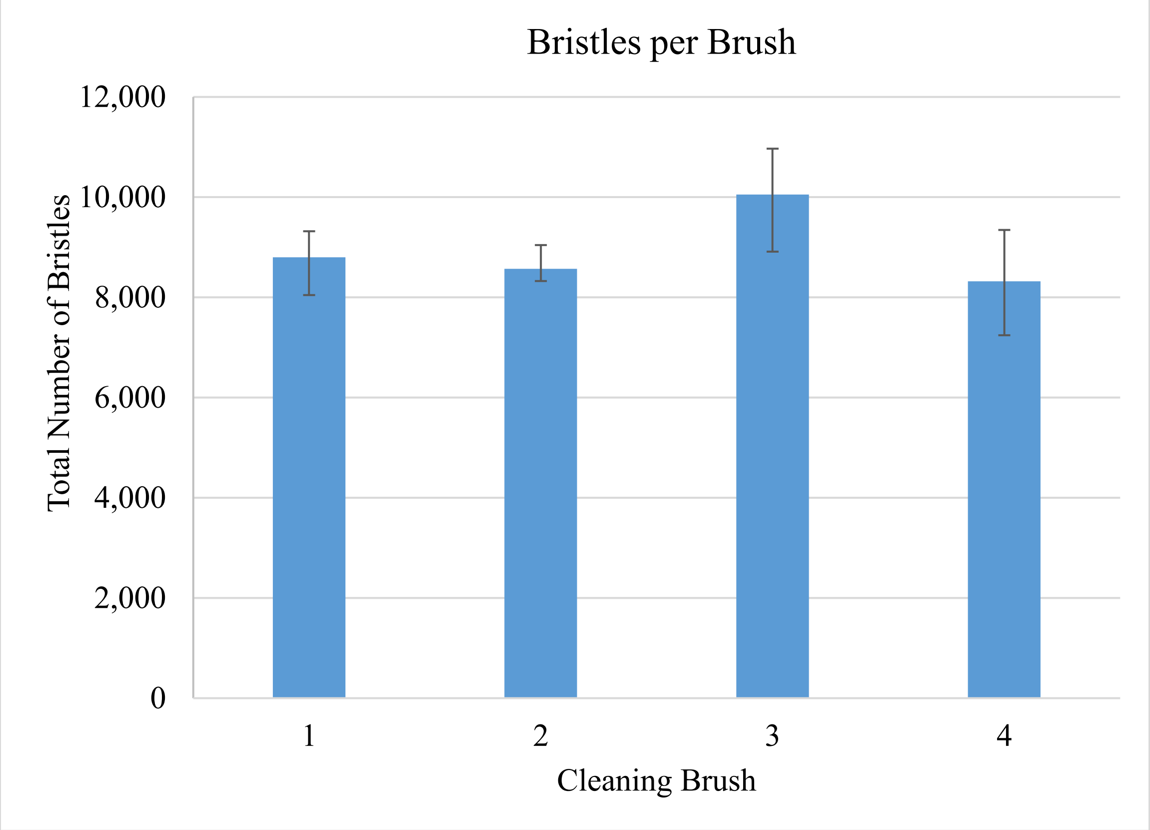


Figure 3-17: Bar chart showing comparison of total number of bristles per debris cleaning brush. Error bars represent the minimum and maximum number of bristles from the repeated sampling points on each brush.

Dry mass of the brushes ranged from 20.69 to 24.85 kg (Fig. 3-18). Mean comparison indicated brush 1 had the highest dry mass (S.D. = 0.16). Brushes 3 and 4 had the lowest dry mass most likely as a result of the excessive bristle wear from harvesting with S.D. ranging from 0.11 to 0.26 respectively. Wet masses of each brush showed an increased trend as compared to the dry mass however, it was non-significant at $p = 0.05$.

These results suggest the annealed plastic doesn't absorb water likely extending its expected lifetime.

Means with no letter shared are significantly different at p = 0.05.

Figure 3-18: Mean comparison of debris cleaning brush dry and wet masses. Error bars represent the minimum and maximum masses from the repeated sampling measurements on each brush.

The minimum bristle tip speed ranged from 6.62 m s^{-1} to 6.99 m s^{-1} measured with brush 4 operating at a tractor engine speed of 1,200 rpm. (Table 3-2). The maximum bristle tip speed ranged from 13.64 m s^{-1} to 14.04 m s^{-1} using brush 1 at a tractor engine speed of 1,600 rpm (Table 3-2). As expected, the bristle tip speed increased with the increased rotational shaft speed. Results further suggest that the longer bristle length of brush 1 created the highest bristle tip speed. The coefficient of variation (CV) approximates heterogeneity and according to Wilding (1985), parameters are most variable if CV > 35, moderately variable if CV ranges from 15% to 35% and least variable if CV < 15%.

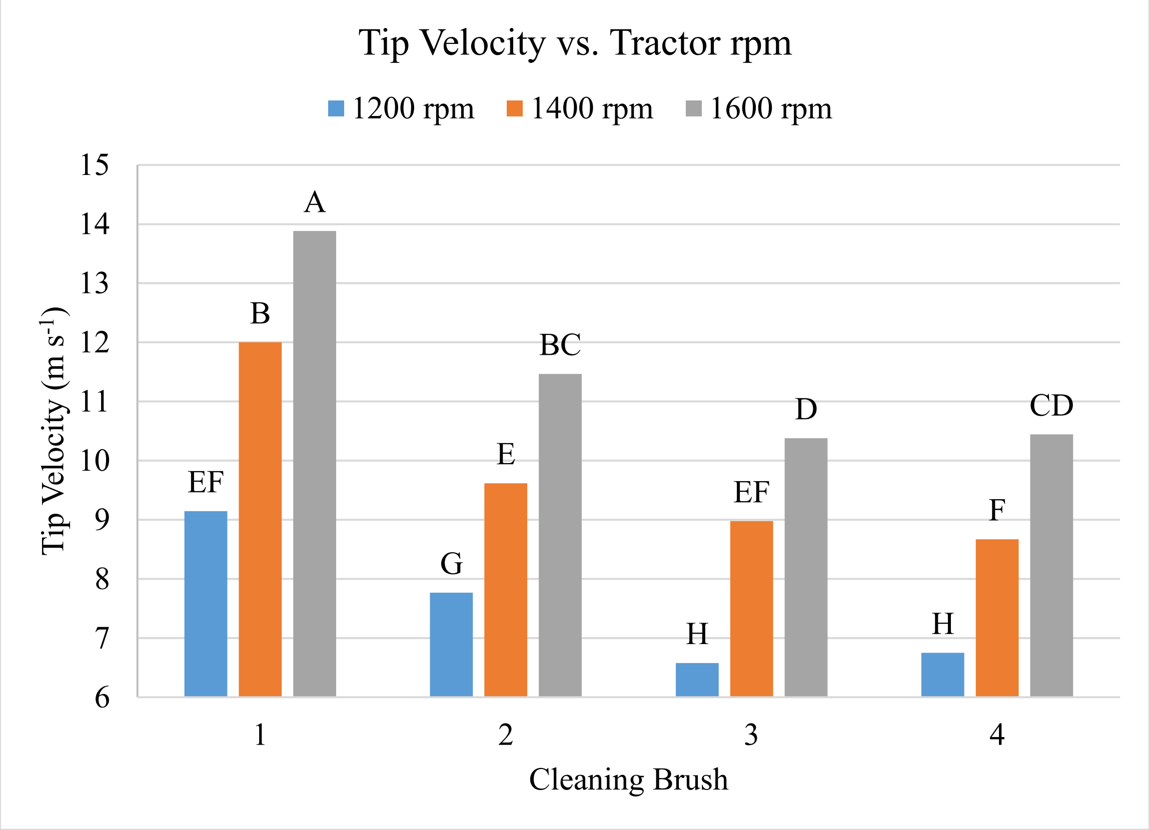
Descriptive statistics revealed that bristle tip speed was not highly variable within range of tractor rpm's tested with CV $\leq$ 3.59%.

Table 3-2. Summary statistics showing bristle tip velocity at varying tractor speeds (1,200; 1,400; and 1,600 rpm) for each experimental brush tested.

Brush	Tractor rpm	Reps	Tip velocity (m s^{-1})				
			Min	Max	Mean	S.D.	C.V.
1	1,200	3	8.97	9.40	9.15	0.23	2.46
	1,400	3	11.55	12.41	12.00	0.43	3.59
	1,600	3	13.64	14.06	13.88	0.22	1.57
2	1,200	3	7.60	8.08	7.77	0.27	3.50
	1,400	3	9.42	9.75	9.62	0.18	1.83
	1,600	3	11.39	11.58	11.47	0.10	0.87
3	1,200	3	6.49	6.70	6.58	0.11	1.64
	1,400	3	8.89	9.11	8.98	0.12	1.31
	1,600	3	10.13	10.51	10.38	0.22	2.09
4	1,200	3	6.62	6.99	6.75	0.21	3.08
	1,400	3	8.45	8.80	8.67	0.19	2.21
	1,600	3	10.32	10.69	10.44	0.21	2.05

Multiple means comparison of bristle tip velocity versus tractor engine speed suggested that brush 1 created a significantly higher tip velocity as compared to all other treatment combinations when operated at an engine speed of 1,600 rpm. The incremental increase in tractor engine speed significantly increased the bristle tip speed for each brush tested. Brush 1 operated at an tractor engine speed of 1,400 rpm was found to have the same tip velocity as brush 2 operating at 1,600 rpm. Brush 1 operating at 1,200 rpm was found to have the same tip velocity as brush 2, 3 and 4 when operated at 1,400 rpm. Brush 2 had a significantly higher bristle tip speed when operated at a tractor engine speed of 1,600 as compared to both brush 3 and 4. No significant difference was found in bristle tip speed when operating brush 2 or 3 at a tractor engine speed of 1,400 rpm. Both brush 3 and 4 were found to have the significantly lowest bristle tip speed as compared to all other treatment combinations. The wide range of bristle tip speeds (6.58 m s^{-1} to 13.88 m s^{-1})

from common harvester parameters suggests the urgent need for optimization of the brush speed to maintain adequate tip speed required for maximum berry quality and effective harvesting performance (Fig. 3-19).



Means with no letter shared are significantly different at p = 0.05.

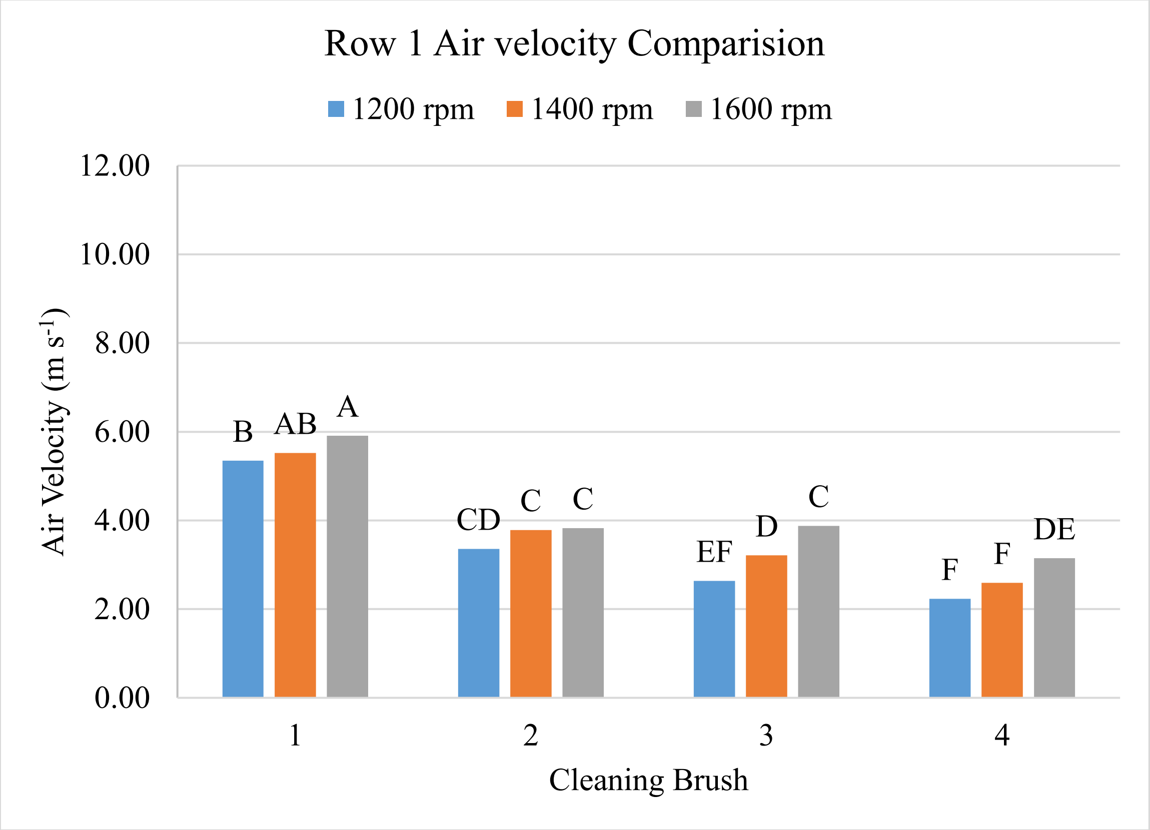
Figure 3-19: Bristle tip speed comparison at varying tractor rpm.

The minimum air velocity ranged from 1.84 m s^{-1} to 7.09 m s^{-1} measured at position 4 of the debris shroud (Table 3-3). The maximum air velocity varied from 2.07 m s^{-1} to 7.33 m s^{-1} with the highest speed measured using brush 1 at a tractor engine speed of 1,600 rpm (Table 3-3). As expected, the air velocity created by the rotation of the brush within the debris shroud increased with each incremental increase of the tractor speed. Results further suggest that the longer bristle length of brush 1 created the highest air speed within the debris shroud. Descriptive statistics revealed that air velocity developed at row 4 of the debris shroud was not highly variable within range of tractor rpm's tested with CV ≤ 11.92%. Dry wild blueberry stems without leaves having the highest required terminal velocity (4.28 m s^{-1}) of all weed and debris samples (Table 2-2) suggesting brush 1 is the only brush capable of wind velocities large enough to successfully propel the debris away from the picker teeth using any tractor engine speed operating at a bristle tip speed ranging from 9.15 to 13.88 m s^{-1} (Table 3-3). However, the tractor engine speed would need to be at least 1,400 rpm during wet field conditions to remove wild blueberry stems without leaves (5.64 m s^{-1}) using brush 1 with a minimum bristle tip speed of 12 m s^{-1}. Results suggest when using brush 2, 3 or 4 the insufficient wind speed created by the rotating brush may cause select debris removed from the picker teeth to drop onto the rear cross member of the harvester picker reel. The results from rows 1 through 3 were all very similar to row 4 suggesting that over time debris buildup using brushes 2, 3 or 4 may cause inefficient harvester operation and will be explored in detail with field testing in Chapter 4.

Table 3-3. Air velocity within the debris hood at position 4 using four different brushes at three different engine speeds (1,200; 1,400; and 1,600 rpm).

Brush	Tractor rpm	Reps	Air velocity (m s^{-1})				
			Min	Max	Mean	S.D.	C.V.
1	1,200	3	4.33	4.45	4.40	0.06	1.39
	1,400	3	5.83	6.12	5.98	0.15	2.43
	1,600	3	7.09	7.33	7.21	0.12	1.67
2	1,200	3	1.87	2.37	2.15	0.26	11.92
	1,400	3	2.62	2.68	2.65	0.03	1.15
	1,600	3	3.26	3.40	3.35	0.08	2.26
3	1,200	3	1.84	2.07	1.94	0.12	6.16
	1,400	3	2.42	2.46	2.45	0.02	0.94
	1,600	3	2.64	2.95	2.81	0.16	5.62
4	1,200	3	2.01	2.11	2.06	0.05	2.43
	1,400	3	2.49	2.55	2.52	0.03	1.21
	1,600	3	2.96	3.05	3.00	0.05	1.53

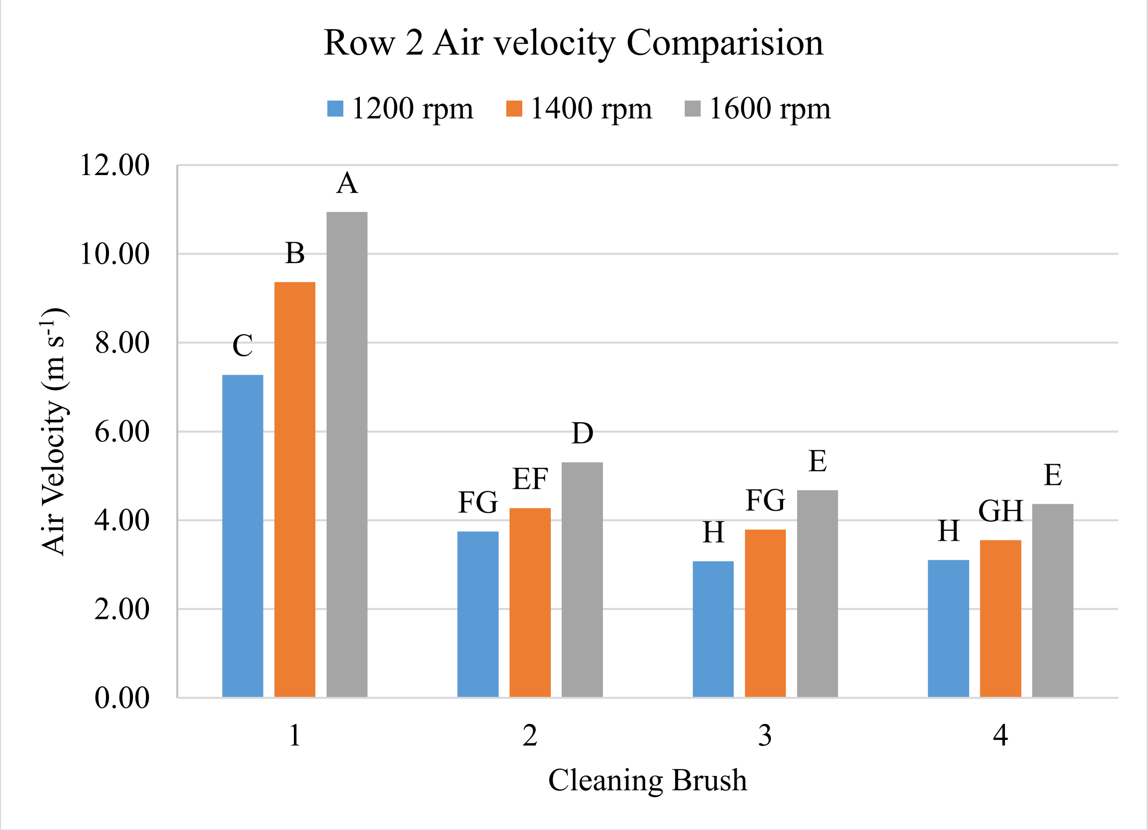
Multiple means comparison of air velocity measured at row 1 of the debris shroud suggests that brush 1 can be operated with a tractor engine speed of 1,400 or 1,600 without any signification difference between air velocities created by the brush (Fig. 3-20). Brush 1 was found to generate significantly higher air velocities as compared to brush 2, 3 or 4 (Fig. 3-20). A significant drop in air velocity was found when operating at a tractor engine speed of 1,200 rpm as compared to 1,600 rpm when using brush 1 (Fig. 3-20). This is likely caused from the higher tractor engine speed increasing power take off (PTO) rpm's that powers the hydraulic pump generating increased hydraulic flow feeding more oil to the hydraulic motor that rotates the debris cleaning brush causing it to turn faster. However, brush 2 was found to have no significant difference between air velocities when operating at the three tractor engine speeds. However, brush 3 and 4 both had a significantly higher air velocity when operating the tractor at 1,600 rpm as compared to 1,200 rpm. At 1,600 rpm brush 2 and 3 created similar air velocities but brush 4 had a significantly lower air velocity (Fig. 3-20). Both brush 3 and 4 were found to generate the lowest air velocity at 1,200 rpm and weren't significantly different from brush 4 operating at 1,400 rpm.



Means with no letter shared are significantly different at p = 0.05.

Figure 3-20: Air velocity produced by the brush in row 1.

Multiple means comparison of air velocity measured at row 2 of the debris shroud suggests that brush 1 generated a significantly higher air velocity when operated at 1,600 rpm as compared to 1,200 and 1,400 rpm. Brush 1 operating at 1,200 rpm still created a larger air velocity in the debris shroud as compared to brush 2, 3 and 4 operating at 1,600 rpm (Fig. 3-21). The air velocity at row 2 was significantly higher with each incremental increase in tractor engine speed for both brush 1 and brush 3. Brush 2 generated a significantly higher air velocity at a tractor engine speed of 1,600 rpm as compared to both brush 3 and 4. Brush 2 operated at a tractor engine speed of 1,400 rpm performed equally as well as brush 4 when operated at 1,600 rpm and brush 3 when operated at either 1,400 or 1,600 rpm. Debris cleaning brush 3 was found to generate the slowest air velocity in the debris shroud when operated at an engine speed of 1,200 rpm and was similar to brush 4 when operated at 1,200 or 1,400 rpm.

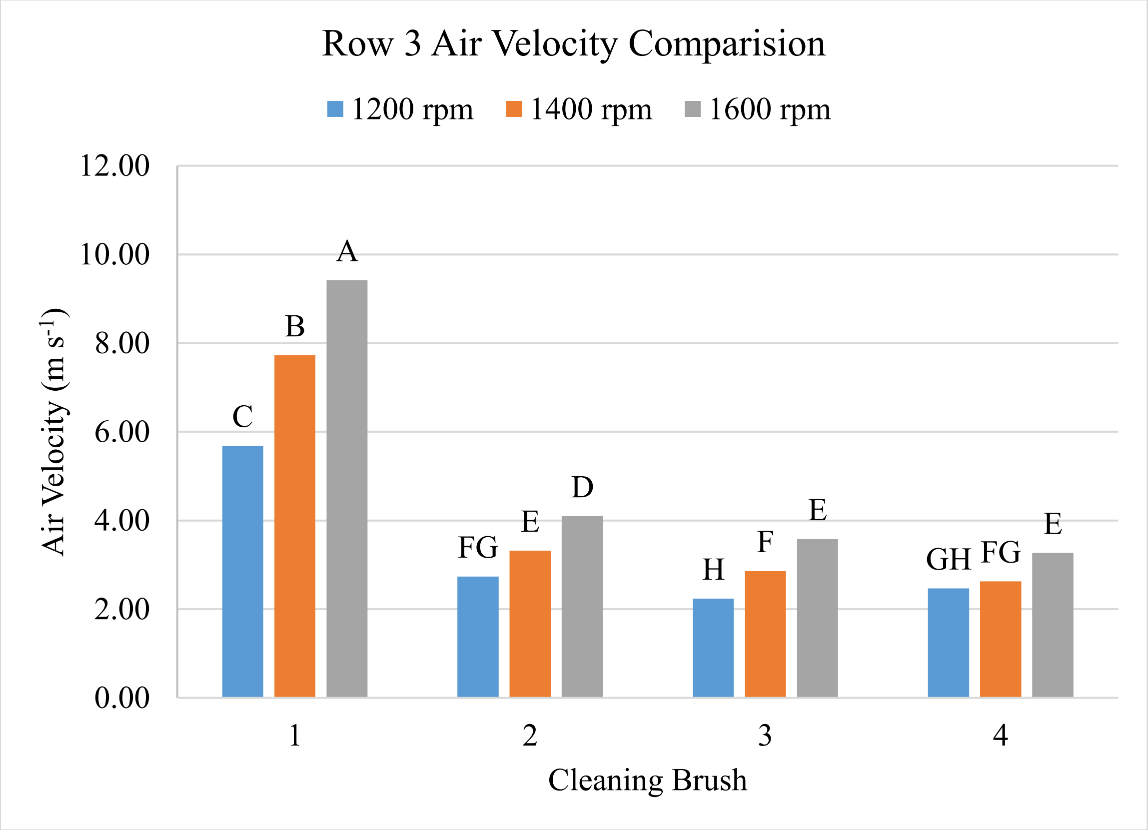


Means with no letter shared are significantly different at p = 0.05.

Figure 3-21: Air velocity produced by the brush in row 2.

Multiple means comparison of air velocity measured at row 3 of the debris shroud suggests that brush 1 generated a significantly higher air velocity when operated at 1,600 rpm as compared to 1,200 and 1,400 rpm. Brush 1 operating at 1,200 rpm still created a larger air velocity in the debris shroud as compared to brush 2, 3 and 4 operating at 1,600 rpm (Fig. 3-22). The air velocity at row 3 was significantly higher with each incremental increase in tractor engine speed for each brush type except brush 4 which performed equally when operated at both 1,200 and 1,400 rpm. Brush 2 generated a significantly higher air velocity at a tractor engine speed of 1,600 rpm as compared to both brush 3 and

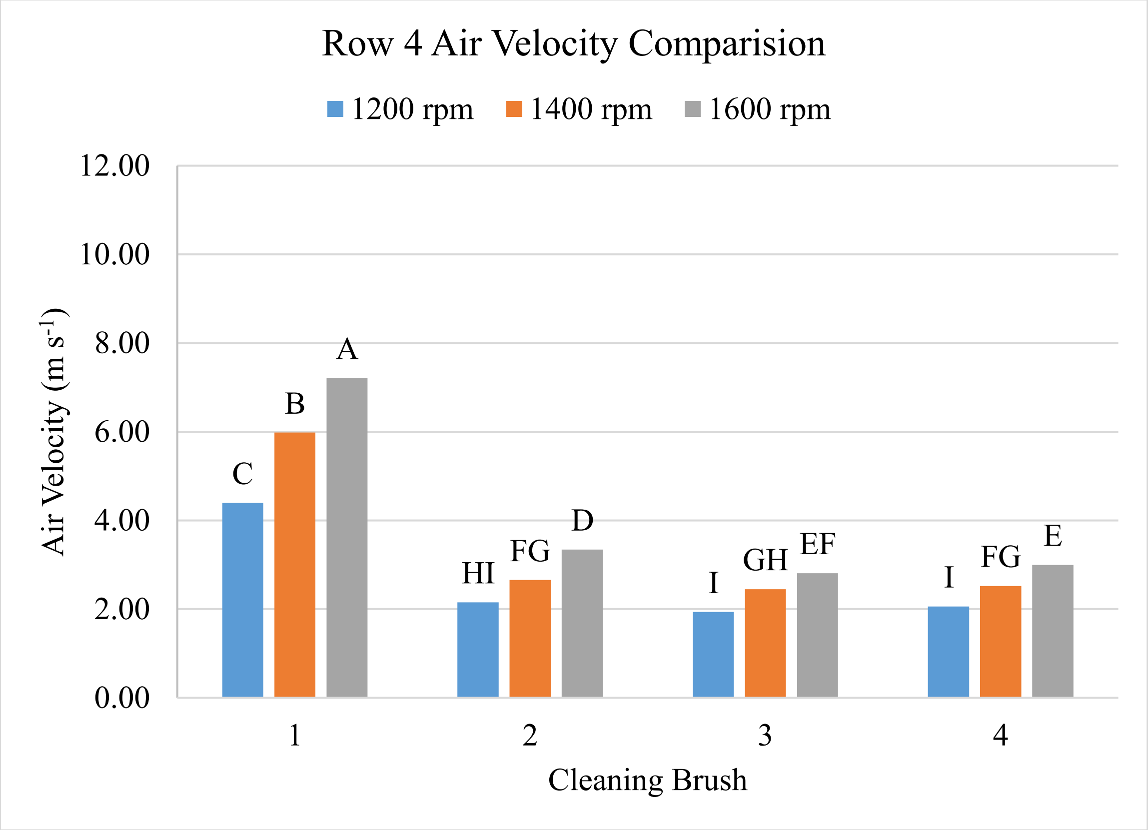
4. Brush 2 operated at a tractor engine speed of 1,400 rpm performed equally as well as both brush 3 and 4 when they were operated at 1,600 rpm. Debris cleaning brush 3 was found to generate the lowest air velocity in the debris shroud when operated at 1,200 rpm and was similar to brush 4 operating at 1,200 rpm.



Means with no letter shared are significantly different at p = 0.05.

Figure 3-22: Air velocity produced by the brush in row 3.

Multiple means comparison of air velocity measured at row 4 of the debris shroud suggests that brush 1 generated a significantly higher air velocity when operated at 1,600 rpm as compared to 1,200 and 1,400 rpm. Brush 1 operating at 1,200 rpm still created a larger air velocity in the debris shroud as compared to brush 2, 3 and 4 operating at 1,600 rpm (Fig. 3-23). The reason for the increased air velocity using brush 1 was likely due to the new brush not having tapered bristle tips causing the desired increased wind generation for improved debris removal. Brushes with tapered bristle tips have less rotational surface area lowering the effective amount of energy being transmitted to the air within the debris shroud. The air velocity at row 4 was significantly higher with each incremental increase in tractor engine speed for each brush type. Brush 2 generated a significantly higher air velocity at a tractor engine speed of 1,600 rpm as compared to both brush 3 and 4. Brush 2 operated at a tractor engine speed of 1,400 rpm performed equally as well as brush 4 at a tractor engine speed of 1400 rpm and similar to brush 3 when it was operated at 1,600 rpm. Debris cleaning brush 2, 3 and 4 were all found to generate the lowest air velocity in the debris shroud when operated at an engine speed of 1,200 rpm. Results from this study suggest the need for a variable speed hydraulic drive motor for more uniform control of the rotating brush speed based on variables such as brush bristle length, tractor engine speed, field moisture conditions and weed density while harvesting. Optimizing the brush speed automatically while harvesting would result in increased berry quality with lower debris, increased picking time from reduced time required for maintenance to the picker teeth and increased brush wear levels saving additional time and money on maintenance cost.



Means with no letter shared are significantly different at p = 0.05.

Figure 3-23: Air velocity produced by the brush in row 4.

3.4 CONCLUSIONS

The goal of this chapter was to evaluate and compare multiple previously used debris cleaning brushes and compare them to a brand new never used harvesting debris cleaning brush. Additionally, a harvester operator's survey to bench mark commercial operating parameters determined a large variation in bristle depth's into the picker teeth as compared to the manufacturers' suggested bristle depth of 0.32 cm. Only 30.8% of operators had recorded values within the suggested operating range set by the manufacturer. The survey suggested that the majority of operators (53.8%) were running their debris cleaning brushes too shallow into the picker teeth causing increased brush lifespan with the potential trade-off of decreased berry quality and picking performance with increased debris buildup. The inconsistent variation in bristle depth also suggests that the conventional visual observation method of adjusting the harvester brush is unreliable and resulted in bristle depths not matching the accepted manufacturer's recommendation. A bristle depth too deep into the teeth could potentially cause damage to the harvested fruit, excessive wear and lead to fluctuations in hydraulic flow resulting in varying rotational head speeds. A bristle depth too shallow into the teeth causes excessive debris buildup in the picker teeth causing decreased harvesting performance and reducing fruit quality. Results from this study suggested the urgent requirement for development of an easy to follow debris cleaning brush guide for fast and accurate adjustment of bristle depth into the picker teeth.

Lab evaluation of brushes with different wear levels found both bristle length and taper to be a significant factor in the amount of air flow generated within the debris shroud. The bristle density was found to be consistent for both new and used brushes signifying they are well designed against bristles being ripped or broken off while harvesting. A non-significant difference was found between the mass of a dry debris cleaning brush as compared to a brush that had the mass recorded immediately after being removed from a bath of water suggesting the annealed plastic doesn't absorb water likely extending its expected lifetime. Based on the results of ANOVA, it can be concluded that bristle tip speed increases with the increased rotational shaft speed. The hydraulic motor driving the debris cleaning brush was found to significantly increase the rotational shaft speed with the incremental increase of the tractor engine rpm. Results further suggest that the longer bristle length of brush 1 created the highest bristle tip speed as well as the highest air flow velocity in the debris shroud. Terminal velocity results from Chapter 2 suggests brush 1 is the only brush capable of wind velocities large enough to successfully propel the debris away from the picker teeth using tractor engine speeds ranging from 1,200 to 1,600 rpm and operating at a bristle tip speed ranging from 9.15 to 13.88 m s^{-1}. However, the tractor engine speed would need to be at least 1,400 rpm during wet field conditions to remove wild blueberry stems without leaves (5.64 m s^{-1}) using brush 1 with a minimum bristle tip speed of 12 m s^{-1}. Lab testing concluded the need for a variable speed hydraulic drive motor for more uniform control of the rotating brush speed based on variables such as brush bristle length, tractor engine speed, field moisture conditions and weed density while harvesting. Optimizing the brush speed automatically while harvesting would result in increased berry quality with lower debris, increased picking time from reduced time required for maintenance to the picker teeth and increased brush wear levels saving additional time and money on maintenance cost. Details about the field test evaluation of different debris cleaning brushes are discussed in Chapter 4.

CHAPTER 4 FIELD EVALUATION OF DIFFERENT CLEANING BRUSH WEAR LEVELS TO DETERMINE OPTIMAL DEBRIS REMOVAL AND BERRY RECOVERY SETTINGS

Wild blueberries are an important horticultural crop native to northeastern North America. Management of wild blueberry fields has improved over the past decade causing increased plant density and leaf foliage. The majority of wild blueberry fields are picked mechanically using tractor mounted harvesters with 16 rotating rakes that gently comb through the plants. The extra foliage has made it more difficult for the cleaning brush to remove unwanted debris (leaf, stems, weeds, etc.) from the picker bars while harvesting. Currently, there is no protocol for adjustment of the brush into the picking teeth for maximum debris cleaning performance while minimizing wear. Research is required to determine the cleaning brush's acceptable wear limit to allow harvester operators to make better management decisions.

Two wild blueberry fields were selected in central Nova Scotia to benchmark the performance of different wear levels of debris cleaning brushes. A factorial experimental design was used with four brushes of varying wear conditions (bristle length 87 to 120 mm in length. Brush wear condition was tested in combination with both low moisture and high moisture conditions in weedy and non-weedy field conditions along 10 m long test strips and each treatment was replicated in quadruplicate. Results found that brush bristle length was a significant factor for operational performance of the mechanical wild blueberry harvester. The use of a brush with a bristle length of 120 mm significantly reduces the amount of debris remaining in the picker teeth during harvesting as compared to bristle lengths of 87 and 106 mm.

Results from 200 m long plots revealed that the use of cleaning brush with a bristle length of 87 mm significantly increased the harvesting time by 41.95, 31.88 and 21.00%

as compared to using a brush with a bristle length of 120, 115 and 106 mm, respectively. Furthermore, using both a brush with bristle length of 106 and 87 mm required the operator to manually exit the cab of the tractor to dislodge built-up debris from the rear cross member of the harvester picking reel. A cleaning brush with 120 mm was the only treatment combination that didn't require the harvester to stop to maintain optimum picking performance during the 200 m trial. The results are supported from terminal velocity of common weed species findings suggesting when wind speeds drop below terminal velocity the weeds fall short and begin to pile on the rear cross member of the harvester head. The results from field experimentation were used along with the geometry of mechanical harvester to develop an optimum brush performance protocol and adjustment guide that operators can use throughout the harvesting season. This study has the ability to help operators make better decisions to replace the cleaning brush at the most economical time to increase field efficiency and berry quality.

4.1 INTRODUCTION

Wild blueberries (Vaccinium angustifolium Ait.) thrive in the acidic soils of northeastern North America, to which they are native too. A crop that was historically a wild occurring commodity, has since been commercialized. Wild blueberries are an important crop to the northeastern North American economic landscape, with over 93,000 ha under management leading to approximately 117 million kg of berries, which are worth 491 million dollars per year (Yarborough, 2013). Wild blueberries grow on a two-year cycle, with the first year being vegetative growth and the second year producing fruit yield (Zaman et al., 2008). Stem heights of wild blueberry range from 50 to 300 mm and blueberry fruit ranges from 4.8 mm to 12.7 mm in diameter (Hayden & Soule, 1969). The management practices surrounding this crop have significantly increased over the past decade leading to an increase in the yield and vegetation produced by this crop, with record high yield production in 2016 (Yarborough, 2013). During harvesting this additional vegetation causes issues in berry quality and slows cleaning and grading times once the berries arrive at the processing plant (Eaton, 1988). Progressive growers with fields with gentle to severe topography have found value in land leveling to allow for increased spraying effectiveness and greater equipment speeds and ease of harvest (Fig. 4-1).

Figure 4-1: Land leveling of wild blueberry ground using excavator with custom rake.

The wild blueberry processing facilities have indicated the need to decrease debris in the bins to reduce processing time and increase fruit quality (Wood, 2018). To address this industry concern, further evaluation of the debris management systems on wild blueberry harvesters is required. The hypothesis proposed in this study is that a protocol for proper cleaning brush adjustments and effective lifespan will increase field efficiency during the harvesting process.

Traditional manual hand raking of wild blueberries has yield losses that vary depending on the workers, but range from 15% to 40% (Kinsman, 1993). Hand raking of wild blueberries requires huge labor forces and has since been replaced by mechanical harvesters (Hall et al., 1983). Mechanical harvesting is significantly faster than hand raking but can cause damages to the berries and losses to the yield (Soule & Gray, 1972). These damages can consist of bruising and cracking of the berries (Soule & Gray, 1972). Damage to the wild blueberry fruit lessens the quality and increases the risk of decay during the storage process (Dale et al., 1994; Mehra et al., 2013a). The major manufacturer of commercial mechanical wild blueberry harvesters is DBE, located in Collingwood, Nova Scotia. DBE blueberry harvesters obtain a 88% to 92% picking efficiency (Farooque et al., 2014).

The modern single head wild blueberry harvester consists of a picking head mechanism with its height and speed hydraulically controlled by the operator from the cabin of the tractor (Fig. 4-2). The head consists of a circular picking reel with 16 teeth bars, each with 65 curved teeth spaced equally apart (Farooque et al., 2014). The picker teeth of the head travel in the opposite direction of the direction of the tractor to which it is attached (Farooque et al., 2012). A cleaning brush with 120 mm long nylon bristles is fixed above the picker teeth and used for debris removal during the harvesting process (Fig. 4-3).

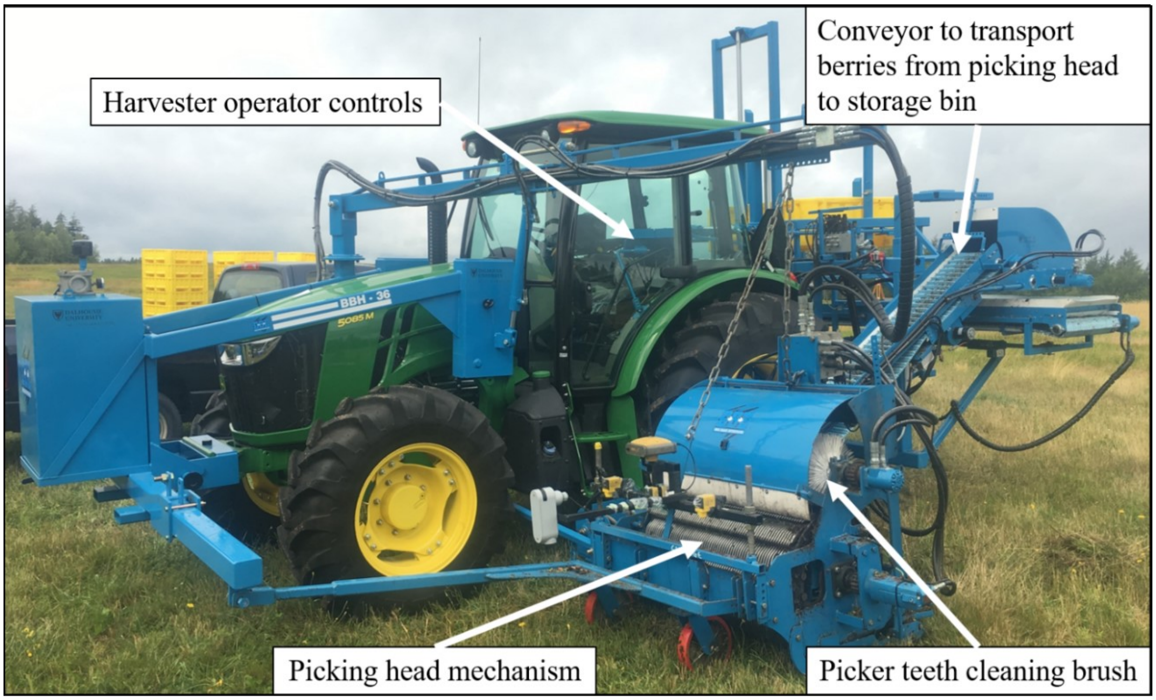


Figure 4-2: Doug Bragg Enterprises Limited wild blueberry mechanical harvester.

The blueberries are picked with the rotating reel travelling at 19 rpm then dropped onto a conveyer belt with a blower fan system that removes the remaining debris (stems, leaves and soil). The blueberries are then transported by the conveyer into bins (1.2 by 1.2 m and 0.3 m deep) loaded on the tractor that carry 136 kg of fruit (Fig. 4-2). The limitation is the inability to properly remove debris lodged in the picker teeth in wet and weedy field conditions because of wore or miss-adjusted cleaning brushes (Farooque et al., 2014).

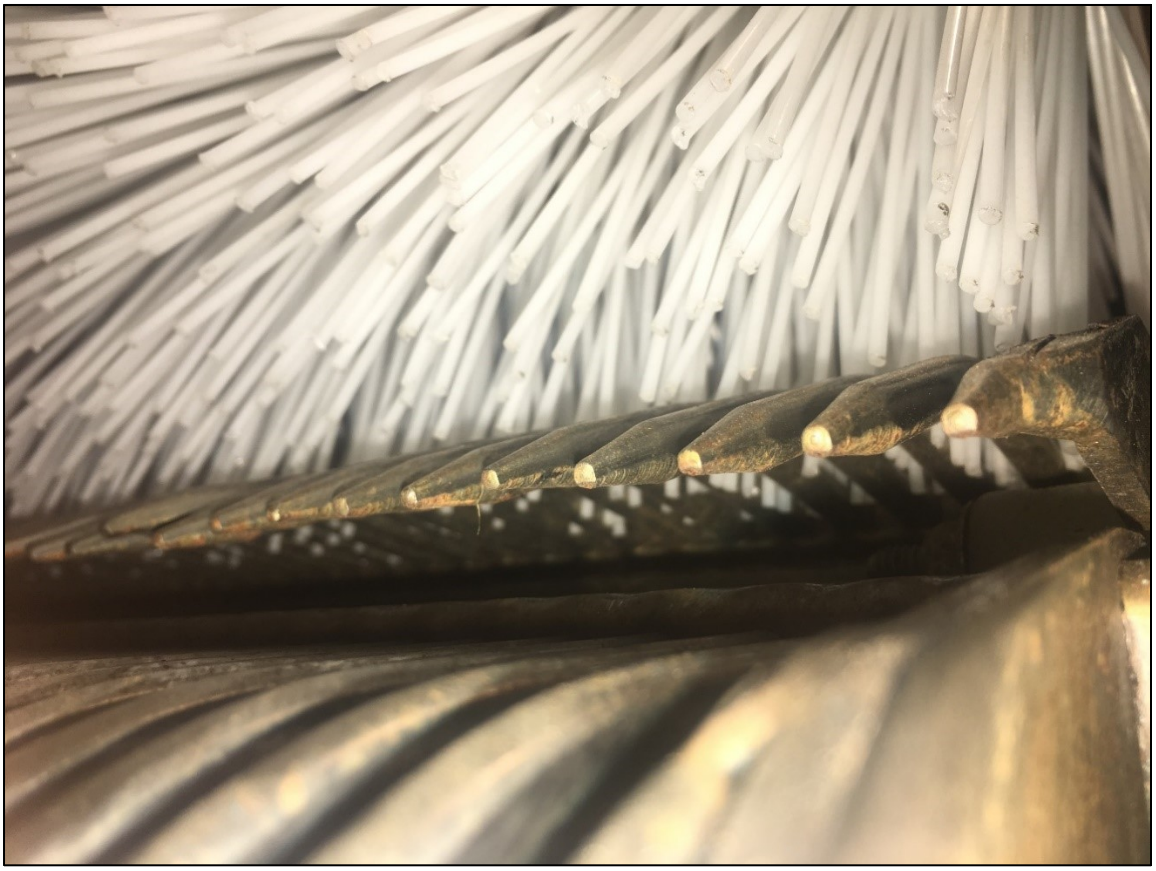


Figure 4-3: Wild blueberry mechanical harvester brush adjusted to remove debris from the picker teeth while harvesting.

The objective of this study was to field evaluate different wear levels of the cleaning brush on a mechanical wild blueberry harvester to determine the optimal debris removal setting and develop a recommended replacement protocol to optimize effective harvesting.

4.2 MATERIAL AND METHODS

4.2.1 Field Evaluation of Debris Cleaning Brush

4.2.1.1 Field Experiment 1 (Highland Village site)

A commercial wild blueberry field was selected in Highland Village, Nova Scotia (45.4059886°N, -63.6706440°W; 3.51 ha) for testing purposes during this experiment (Fig. 4-4). The selected field was in cropping year during experimentation in August 2017. The field received conventional fertilizer, weed, and disease management practices along with biennial pruning by mowing for the past decade.

Figure 4-4: Highland Village field site.

4.2.4.2 Field Experiment 2 (East Mines site)

A commercial wild blueberry field was selected in East Mines, Nova Scotia (45.427182°N, -63.481906°W; 3.76 ha) for testing purposes during this experiment (Fig. 4-5). The selected field was in cropping year during experimentation in August 2017. The field received conventional fertilizer, weed, and disease management practices along with biennial pruning by mowing for the past decade. A commercial DBE harvester with 16 bars each with 65 equally spaced picker teeth was mounted on a 63.4 kW John Deere

5085M tractor and used for debris cleaning brush benchmark testing.

Figure 4-5: East Mines field site.

A Factorial experimental design was used with four different brush wear conditions; B_1= 120 mm, B_2 = 115 mm, B_3 = 106 mm, B_4 = 87 mm (Fig. 4-6). Brush wear condition was tested in combination with two leaf wetness conditions high moisture (LW_1) and low moisture (LW_2) field conditions. Eight combinations of; (B_1 x LW_1; B_1 x LW_2; B_2 x LW_1; B_2 x LW_2; B_3 x LW_1; B_3 x LW_2; B_4 x LW_1 & B_4 x LW_2) were tested in both weedy non-weedy field conditions. Each combination was replicated in quadruplicate.

Figure 4-6: Debris cleaning brushes with different wear levels used for field experimentation.

Ten-meter long plots the same width as the harvester head (0.91 m) were arranged randomly throughout the field using a measuring tape and marker flags. Wild blueberry stem density and stem height was measured in three randomly selected sample areas inside the plot using 150 by 150 mm quadrates prior to harvest (Fig. 4-7).

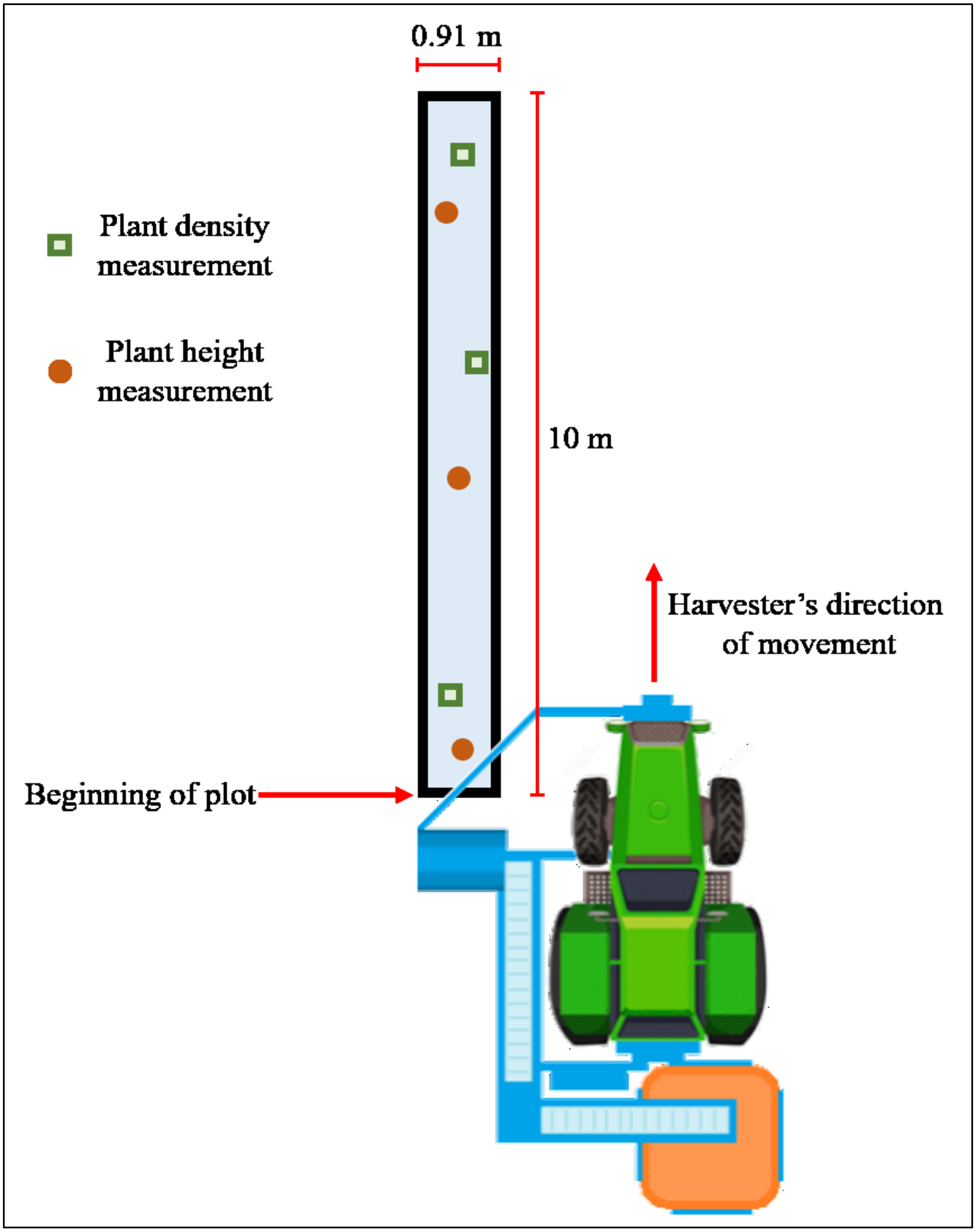


Figure 4-7: Pre-harvest plot measurements.

The harvester operator raised the picking head just prior to entering each plot and removed all debris from the picker teeth by rotating the reel in reverse. Any remaining debris lodged in the picker teeth was manually removed prior to plot harvest. The tractor engine speed was set to 1,500 rpm and the harvester was operated at a speed of 0.39 m s^{-1} and while in motion, debris removed from the picker teeth and flung behind the harvester by the cleaning brush was manually collected using a large collection bin (Fig. 4-8a). Debris expelled through the blower fan debris hood was collected while harvesting each plot using a large storage tote (Fig. 4-8b). At the end of each harvested plot the operator stopped the picking reel and any remaining debris left in the teeth was manually collected and transferred to a clear bag for further analysis (Fig. 4-8c). The harvested yield was also collected from each plot (Fig. 4-8d). The mass of the debris and yield samples from each plot was measured using an electronic scale (TP-1502, Denver Instruments Inc., Bohemia, N.Y.).

Figure 4-8: Collection of a) debris removed from the picker teeth and flung behind the harvester by the cleaning brush, b) harvested debris expelled through the blower fan hood, c) remaining debris left in the picker teeth and d) harvested yield collection from each 10 m long experimental plot.

The East Mines site was also used for time trial testing. A ProMark3 mobile mapper DGPS (Thales Navigation, Santa Clara, Ca.) was used to mark 200 m long test plots the same width as the harvester picking width (0.91 m) (Fig. 4-9). The harvester was tested with four brushes with bristle lengths; B_1= 120 mm, B_2 = 115 mm, B_3 = 106 mm, B_4 = 87 mm. Each brush was tested in triplicate changing the brush at the beginning of each new test plot to ensure randomization of the experiment.

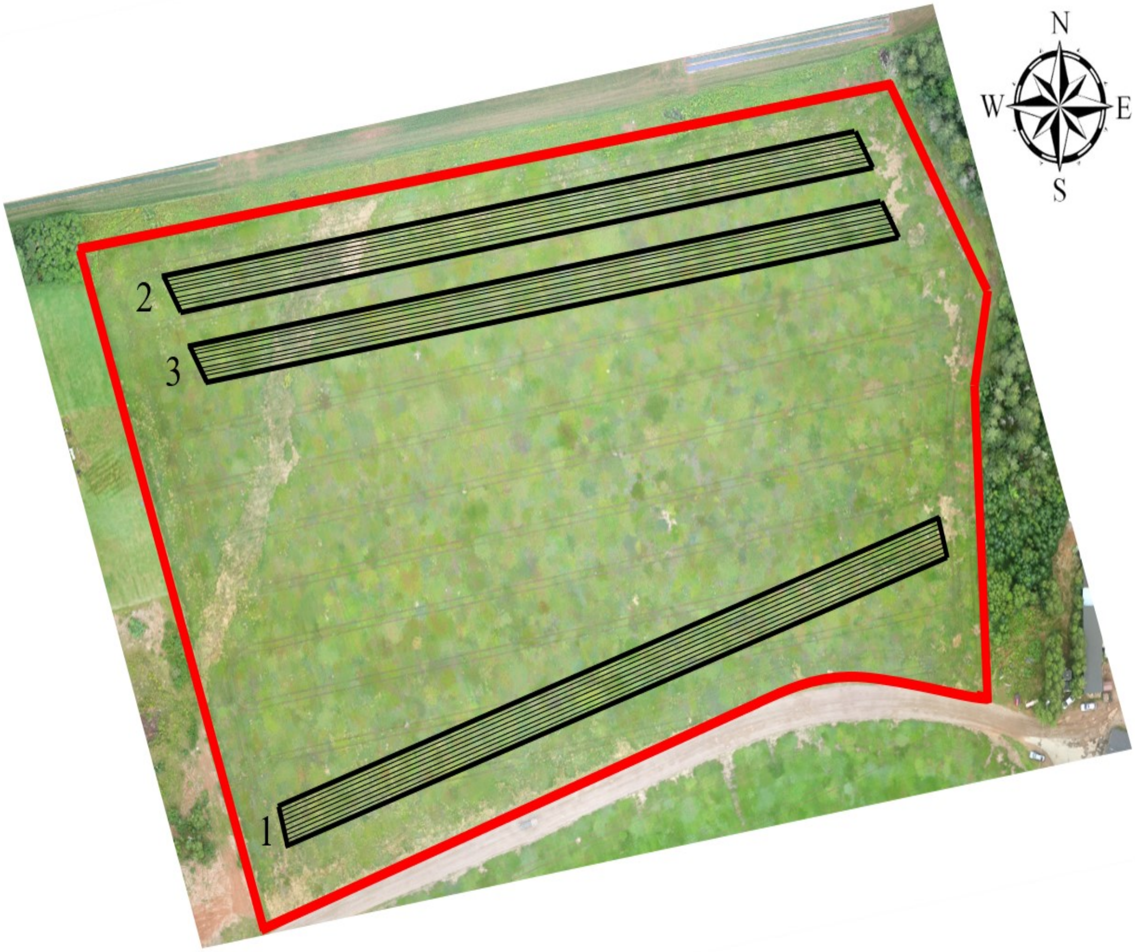


Figure 4-9: East Mines field site showing plot locations.

A timer was used to record the start of the plot harvest when the head was first lowered into the plants. The harvester operator raised the picking head just prior to entering each plot and removed all debris from the picker teeth by rotating the reel in reverse. Any remaining debris lodged in the picker teeth was manually removed prior to plot harvest. The tractor engine speed was set to 1,500 rpm and the harvester was operated at a speed of 0.39 m s^{-1}. The harvester proceeded through the test plot unless the picker teeth were clogged by debris. Teeth clogging required the operator to stop the forward motion of the harvester and raise the head to reverse the hydraulic motor allowing the brush to dislodge the debris from the teeth. If the brush successfully cleaned the picker teeth the harvester picking reel was lowered back into the plants and the plot harvest continued. However, if the brush was unable to successfully remove the debris, the operator was required to stop the picking reel rotation and exit the cab to manually remove the debris from the teeth. The total time to harvest the 200 m plot and all the individual stop times were recorded. Yield was collected in commercial totes during harvest of each plot and the mass was individually measured using an electronic floor scale (M1, Western Scale Co. Ltd., Port Coquitlam, B.C.).

The statistical analysis of collected field data was analyzed using Minitab 17 statistical software. Normal probability plot of residuals was used to check the normality of error terms using Anderson Darling test at a 5% level of significance. Residual versus fitted values plot was used to check the constant variance of error terms. Each treatment was completed in a random order to achieve independence of the error terms. Collected data was analyzed using classical statistics to determine the minimum, maximum, mean standard deviation and coefficient of variation. A factorial ANOVA using GLM procedure was completed and multiple means comparison performed using LS means to determine where the means differ.

4.2.2 Development of a Grower Brush Adjustment Guide and Optimum Replacement Protocol

Results from the grower survey in Chapter 3 suggested the need for the development of an easy to follow debris cleaning brush guide for fast and accurate adjustment of bristle depth into the picker teeth. Visual observation proved to provide inconsistent bristle depths into the picker teeth. Results from section 3.3 suggested the need to further field test varying bristle lengths to determine debris cleaning efficiency and performance to suggest to operators when their brush has exceeded its maximum lifespan. The guide was developed using the geometry of and relationship between the circular picking reel in relation to the rotating debris cleaning brush with varying bristle length depending on wear level. The protocol was developed using the bristle length of the brush and a conversion equation between bristle length and vertical adjustment distance into the teeth. An easy measuring location between the bearing housing and the top of the adjustment prong on either side of the harvester head was used for the conversion equation. The process was divided into a simple five step process for operators to measure and properly adjust their debris cleaning brush in the field and also understand the wear levels that lead to reduced debris cleaning performance suggesting replacement.

4.3 RESULTS AND DISCUSSION

The plant height at the Highland Village site varied from 154.17 to 234.20 mm (Table 4-1). Density ranged from 7.42 to 14.33 plants per 150 mm^2 quadrat at the Highland Village site (Table 4-2). Plant stem diameter ranged from 1.59 to 2.12 mm at the Highland Village site (Table 4-3). Slope ranged from 1.38 to 4.48 degrees in the Highland Village site (Table 4-1). The coefficient of variation (CV) is an approximation of field heterogeneity and according to Wilding (1985), parameters are most variable if $CV > 35$, moderately variable if CV ranges from 15% to 35% and least variable if $CV < 15\%$. Descriptive statistics revealed that plant height, plant density and stem diameter were not highly variable within the Highland Village field with $CV \leq 32.43\%$, $CV \leq 32.13\%$, $CV \leq 22.31\%$, respectively. However, CV of slope readings were high ($CV > 35$) at most plot locations in the Highland Village site suggesting the field was not land leveled and contained slopes ranging from 1.38 to 4.48 degrees (Table 4-4).

Table 4-1. Highland Village site pre-harvest plant height measurements.

				Plant Height (mm)				
Brush	**Leaf Wetness**	**Weeds**	**Reps**	**Min**	**Max**	**Mean**	**S.D.**	**C.V (%)**
1	Low	No	4	165.00	250.00	205.40	37.90	18.45
		Yes	4	161.70	210.00	196.20	23.30	11.88
	High	No	4	190.00	223.33	211.67	14.78	6.98
		Yes	4	166.67	210.00	187.50	17.72	9.45
2	Low	No	4	110.00	160.00	139.20	21.70	15.59
		Yes	4	146.70	253.30	185.80	46.70	25.13
	High	No	4	146.70	233.30	191.70	35.40	18.47
		Yes	4	150.00	230.00	190.80	40.00	20.96
3	Low	No	4	136.67	180.00	154.17	18.53	12.02
		Yes	4	123.30	220.00	175.00	41.50	23.71
	High	No	4	173.33	216.67	199.17	19.12	9.60
		Yes	4	180.00	286.70	234.20	44.60	19.04
4	Low	No	4	133.30	180.00	165.80	21.80	13.15
		Yes	4	133.30	183.30	161.70	21.20	13.11
	High	No	4	153.30	253.30	205.00	46.30	22.59
		Yes	4	123.30	256.70	185.00	60.00	32.43

Table 4-2. Highland Village site pre-harvest plant density measurements.

Brush	Leaf Wetness	Weeds	Reps	Plant Density per 150 mm² quadrat				
				Min	Max	Mean	S.D.	C.V (%)
1	Low	No	4	11.33	14.67	13 A	1.74	13.41
		Yes	4	10.33	16.33	13 A	2.61	20.08
	High	No	4	11.00	14.00	12.083 AB	1.32	10.89
		Yes	4	7.67	15.33	11.08 AB	3.56	32.13
2	Low	No	4	6.00	10.00	7.417 B	1.77	23.89
		Yes	4	5.67	8.67	7.583 B	1.32	17.35
	High	No	4	11.00	16.67	14.33 A	2.57	17.93
		Yes	4	10.67	16.33	14.08 A	2.47	17.54
3	Low	No	4	12.67	14.33	13.333 A	0.72	5.40
		Yes	4	9.33	13.00	11.417 AB	1.62	14.18
	High	No	4	12.67	15.00	13.833 A	1.04	7.49
		Yes	4	9.33	12.33	10.5 AB	1.29	12.30
4	Low	No	4	6.00	9.00	7.833 B	1.35	17.20
		Yes	4	8.67	11.67	9.917 AB	1.37	13.82
	High	No	4	11.00	16.33	13.42 A	2.39	17.81
		Yes	4	11.00	16.00	13.83 A	2.12	15.33

Table 4-3. Highland Village site pre-harvest stem diameter measurements.

				Stem Diameter (mm)				
Brush	**Leaf Wetness**	**Weeds**	**Reps**	**Min**	**Max**	**Mean**	**S.D.**	**C.V (%)**
1	Low	No	4	1.66	2.41	1.88	0.36	18.85
		Yes	4	1.29	1.94	1.72	0.29	16.94
	High	No	4	1.69	2.34	2.03	0.27	13.45
		Yes	4	1.69	2.03	1.86	0.18	9.88
2	Low	No	4	1.53	1.79	1.66	0.13	7.87
		Yes	4	1.56	1.99	1.73	0.19	10.75
	High	No	4	1.69	2.31	1.95	0.26	13.41
		Yes	4	1.54	2.55	2.05	0.46	22.31
3	Low	No	4	1.49	1.98	1.74	0.22	12.74
		Yes	4	1.51	2.05	1.75	0.24	13.88
	High	No	4	1.84	2.07	1.94	0.10	5.04
		Yes	4	1.89	2.23	2.12	0.16	7.55
4	Low	No	4	1.41	1.71	1.59	0.13	8.33
		Yes	4	1.50	1.74	1.62	0.10	6.36
	High	No	4	1.78	2.06	1.98	0.13	6.67
		Yes	4	1.58	2.21	1.89	0.27	14.43

Table 4-4. Highland Village site pre-harvest plot slope measurements.

Brush	Leaf Wetness	Weeds	Reps	Plot Slope (degrees) Min	Max	Mean	S.D.	C.V (%)
1	Low	No	4	1.67	4.30	2.94	1.19	40.58
		Yes	4	2.13	4.13	3.50	0.92	26.31
	High	No	4	0.63	2.97	1.71	0.96	56.38
		Yes	4	1.07	2.80	1.58	0.82	51.48
2	Low	No	4	1.93	5.47	4.25	1.58	37.13
		Yes	4	2.97	5.70	4.48	1.37	30.59
	High	No	4	1.73	2.70	2.13	0.44	20.71
		Yes	4	0.43	3.40	1.69	1.27	74.94
3	Low	No	4	1.37	6.93	3.72	2.57	69.09
		Yes	4	1.27	3.03	1.80	0.83	46.11
	High	No	4	0.77	5.73	2.75	2.43	88.36
		Yes	4	1.17	2.07	1.78	0.42	23.28
4	Low	No	4	0.80	2.17	1.38	0.60	43.27
		Yes	4	0.73	2.07	1.38	0.62	44.73
	High	No	4	1.90	2.90	2.23	0.46	20.72
		Yes	4	1.67	2.40	1.99	0.32	15.96

The plant height at the East Mines site varied from 160.00 to 208.30 mm (Table 4-5). Density ranged from 9.83 to 14.67 plants per 150 mm^2 quadrat at the East Mines site location (Table 4-6). Plant stem diameter ranged 1.79 to 2.12 mm at the East Mines site (Table 4-7). Slope ranged from 1.30 to 2.58 degrees in the East Mines site (Table 4-8). Plant height and plant density were also not highly variable at the East Mines site with CV $\leq$ 21.96%, CV $\leq$ 27.81%, respectively. The stem diameter and slope were not variable at the East Mines site with CV $\leq$ 2.28%, CV $\leq$ 11.71%, respectively. The likely reason the slope was not variable at the East Mines site was because it had been recently land leveled using an excavator to smooth uneven topography allowing for less field variations.

Table 4-5. East Mines site pre-harvest plant height measurements.

				Plant Height (mm)				
Brush	**Moisture**	**Leaf Wetness**	**Reps**	**Min**	**Max**	**Mean**	**S.D.**	**C.V (%)**
1	Low	No	4	143.33	166.67	160.00	11.22	7.01
		Yes	4	136.70	210.00	173.30	34.10	19.68
	High	No	4	140.00	193.30	169.20	25.10	14.83
		Yes	4	140.00	196.70	173.30	23.90	13.79
2	Low	No	4	166.70	250.00	205.80	42.00	20.41
		Yes	4	180.00	210.00	188.33	14.53	7.72
	High	No	4	150.00	190.00	169.20	22.20	13.12
		Yes	4	180.00	206.67	190.83	13.16	6.90
3	Low	No	4	186.70	243.30	204.20	26.90	13.17
		Yes	4	176.70	236.70	204.20	27.50	13.47
	High	No	4	173.33	193.33	182.50	8.33	4.56
		Yes	4	166.70	263.30	200.80	44.10	21.96
4	Low	No	4	190.00	246.70	208.30	25.90	12.43
		Yes	4	150.00	210.00	187.50	26.00	13.87
	High	No	4	173.33	206.67	194.17	14.50	7.47
		Yes	4	186.67	213.33	195.00	12.62	6.47

Table 4-6. East Mines site pre-harvest plant density measurements.

Brush	Leaf Wetness	Weeds	Reps	Plant Density per 150 mm^2 quadrat Min	Max	Mean	S.D.	C.V (%)
1	Low	No	4	12.33	17.00	14.67 A	2.07	14.11
		Yes	4	11.00	15.33	12.917 AB	1.79	13.87
	High	No	4	10.33	13.67	11.833 AB	1.40	11.84
		Yes	4	10.67	14.67	12.083 AB	1.77	14.67
2	Low	No	4	11.33	14.67	13.25 AB	1.40	10.55
		Yes	4	11.67	13.00	12.583 AB	0.63	5.01
	High	No	4	11.67	14.67	13 AB	1.31	10.04
		Yes	4	10.00	13.33	11.667 AB	1.47	12.57
3	Low	No	4	12.00	15.33	13.833 AB	1.48	10.68
		Yes	4	8.67	16.00	12.08 AB	3.36	27.81
	High	No	4	13.33	16.67	14.583 A	1.45	9.94
		Yes	4	9.67	14.67	12.17 AB	2.05	16.84
4	Low	No	4	9.67	12.67	11.25 AB	1.23	10.92
		Yes	4	10.67	14.00	12.75 AB	1.45	11.37
	High	No	4	8.00	12.00	9.833 B	1.67	16.95
		Yes	4	10.67	12.67	12 AB	0.94	7.86

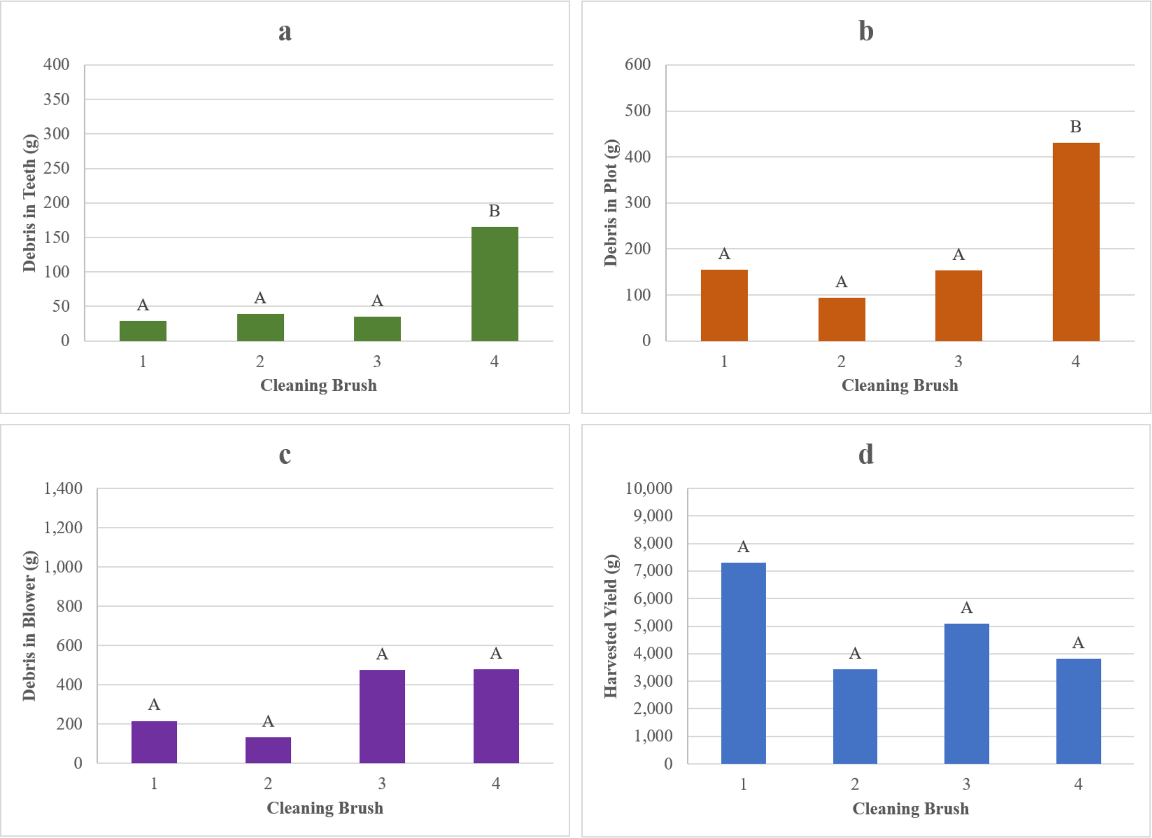
Table 4-7. East Mines site pre-harvest stem diameter measurements.

Brush	Leaf Wetness	Weeds	Reps	Stem Diameter (mm)				
				Min	Max	Mean	S.D.	C.V (%)
1	Low	No	4	1.61	2.21	1.85	0.28	1.90
		Yes	4	1.55	1.85	1.73	0.13	0.99
	High	No	4	1.59	2.12	1.82	0.24	1.99
		Yes	4	1.64	1.88	1.79	0.10	0.85
2	Low	No	4	1.87	2.21	1.98	0.16	1.21
		Yes	4	1.71	2.14	1.92	0.18	1.45
	High	No	4	1.84	1.97	1.91	0.07	0.51
		Yes	4	1.86	2.42	2.08	0.25	2.11
3	Low	No	4	1.66	1.92	1.81	0.12	0.83
		Yes	4	1.43	2.01	1.83	0.28	2.28
	High	No	4	1.90	2.20	2.05	0.17	1.17
		Yes	4	1.64	1.95	1.81	0.14	1.15
4	Low	No	4	1.85	2.08	1.96	0.11	1.00
		Yes	4	2.03	2.23	2.12	0.09	0.71
	High	No	4	1.77	2.25	2.05	0.21	2.11
		Yes	4	1.62	1.93	1.84	0.15	1.23

Table 4-8. East Mines site pre-harvest plot slope measurements.

Brush	Leaf Wetness	Weeds	Reps	Plot Slope (degrees) Min	Max	Mean	S.D.	C.V (%)
1	Low	No	4	1.83	2.63	2.21	0.39	2.63
		Yes	4	1.27	3.67	2.37	0.99	7.69
	High	No	4	0.90	1.93	1.30	0.46	3.88
		Yes	4	0.87	2.70	1.71	0.98	8.11
2	Low	No	4	0.13	3.83	2.01	1.55	11.71
		Yes	4	0.70	2.00	1.62	0.62	4.89
	High	No	4	1.10	2.43	1.71	0.59	4.50
		Yes	4	0.37	2.33	1.63	0.90	7.69
3	Low	No	4	1.77	4.10	2.58	1.09	7.91
		Yes	4	1.27	2.00	1.64	0.35	2.88
	High	No	4	1.07	2.83	1.74	0.76	5.22
		Yes	4	0.73	2.87	1.63	1.01	8.32
4	Low	No	4	1.03	4.87	2.41	1.77	15.74
		Yes	4	0.87	2.17	1.68	0.56	4.42
	High	No	4	0.83	2.87	1.63	0.97	9.90
		Yes	4	1.57	3.63	2.14	1.00	8.32

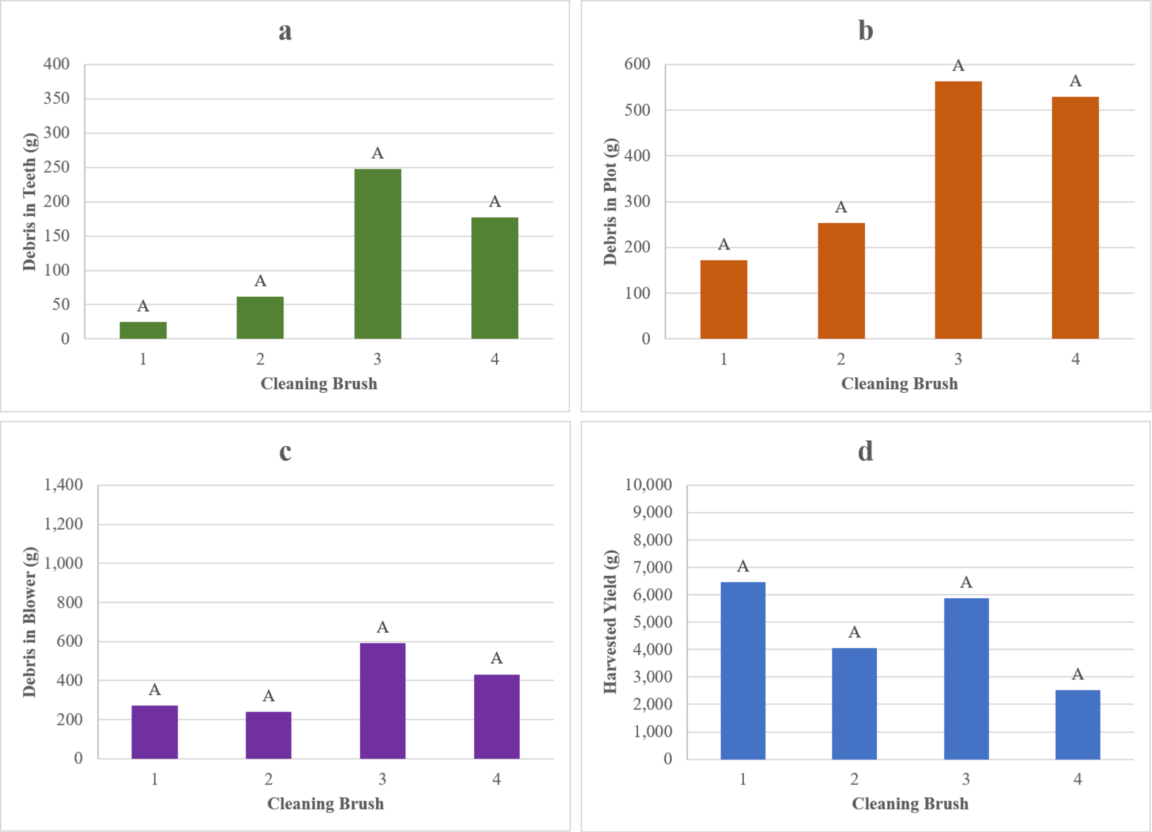
Results of the means comparison of the 10 m tracks indicated that the longer bristle length had a significant effect on removing leaves, stems and dirt that were lodged in the teeth as well as thrown behind the harvester during picking in dry and weed free plots at the Highland Village site (Fig. 4-10a). A possible reason why brush 4 had the largest amount of debris in the plots (431 g) could be because as more debris gets lodged in the teeth and not effectively removed it led to additional debris getting intertwined and ripped from the ground (Fig. 4-10b). Brushes 1, 2 and 3 were effectively able to remove the same amount of debris from the picker teeth in weed free, low moisture plots within the Highland Village site each having only 29.25, 39.00, 34.75 g, respectively, remaining in the picker teeth. No significant difference was found in the amount of the debris that was collected from the blower in the weed free, low moisture plots at the Highland Village site (Fig. 4-10c). Similarly, no significant difference was found in the harvested yield samples in dry and weed free field conditions at the Highland Village site (Fig. 4-10d). A possible reason for this outcome is because wild blueberry yields are highly variable as suggested by Farooque et al. (2013).



Means with no letter shared are significantly different at p = 0.05.

Figure 4-10: Highland Village site in low leaf wetness, non-weedy field conditions.

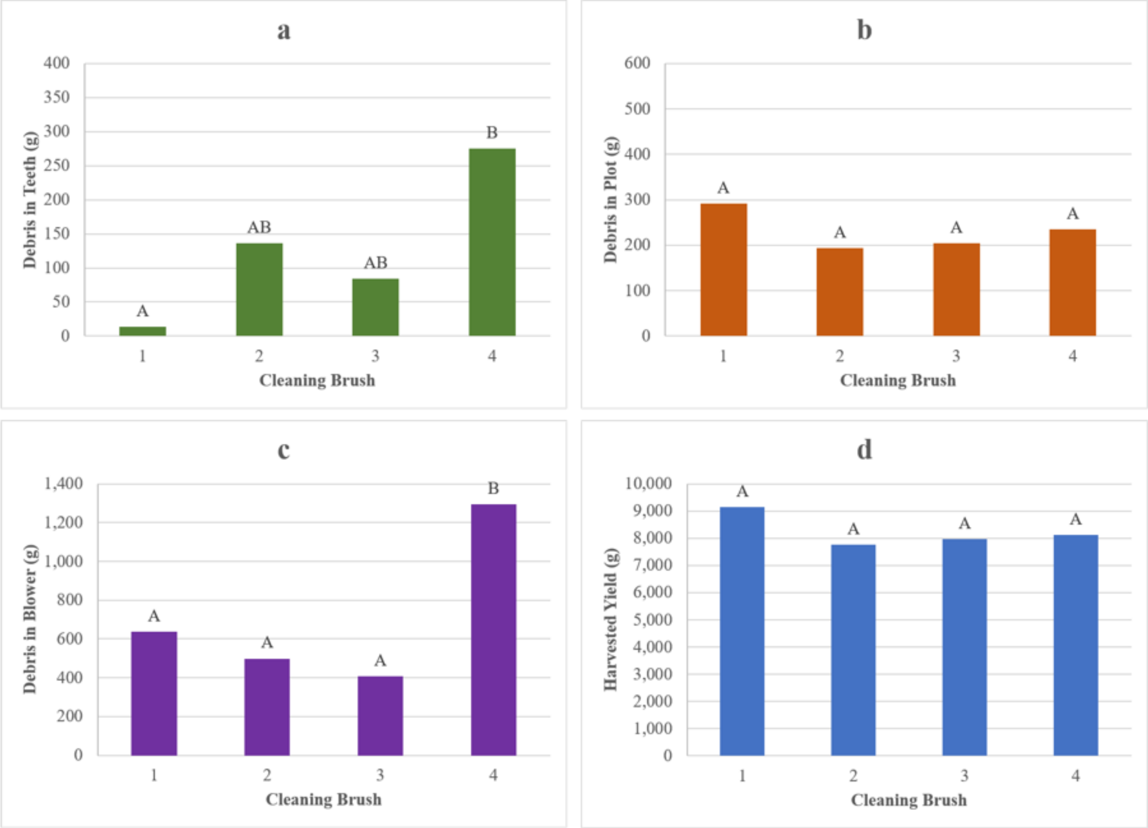
Visual observation of Fig. 4-11a suggests brush 1 having only 25.25 g of debris in the teeth may have a lower mean value than brush 3 and 4 having means of 177.3 and 248 g, respectively. However, ANOVA indicated that the bristle length had little effect on the debris remaining in teeth, debris remaining in plot, debris collected in the blower fan and harvested yield in low moisture, weedy field conditions at the Highland Village site (Fig. 4-11). Reasons for this set of non-significant results is likely due to the unavoidable variable crop and weed conditions encountered during experimentation causing large variations in standard deviation.



Means with no letter shared are significantly different at p = 0.05.

Figure 4-11: Highland Village site in low leaf wetness, weedy field conditions.

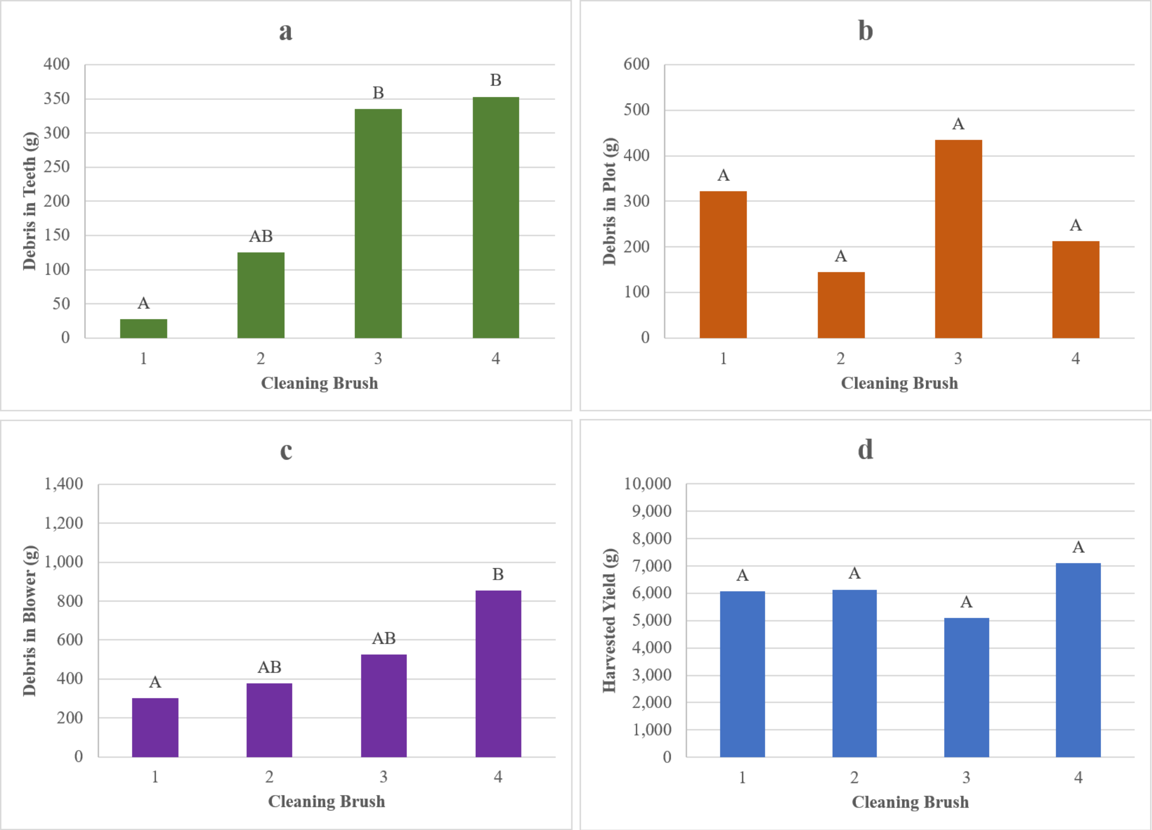
Results of means comparison indicated that brush 1 had significantly less debris (13.5 g) lodged in the picker teeth as compared to brush 4 (275 g) in high moisture, weed free plots at the Highland Village site (Fig. 4-12a). A non-significantly different amount of debris was collected from the picker teeth from brush treatments 1, 2 and 3 (Fig. 4-12a). No significant difference was found with the amount of debris left in the plot or the amount of harvested yield with each treatment combination in high moisture, weed free field conditions at the Highland Village site (Fig. 4-12b, 4-12d). A significantly higher amount of debris was collected from the blower when using brush 4 in high moisture, weed free field conditions at the Highland Village site (Fig. 4-12c). The reason for the additional debris exiting through the blower may have been a result of excess wet debris getting logged in the teeth and dropping into the conveyor rather than being thrown clear by the brush.



Means with no letter shared are significantly different at $p = 0.05$.

Figure 4-12: Highland Village site in high leaf wetness, non-weedy field conditions.

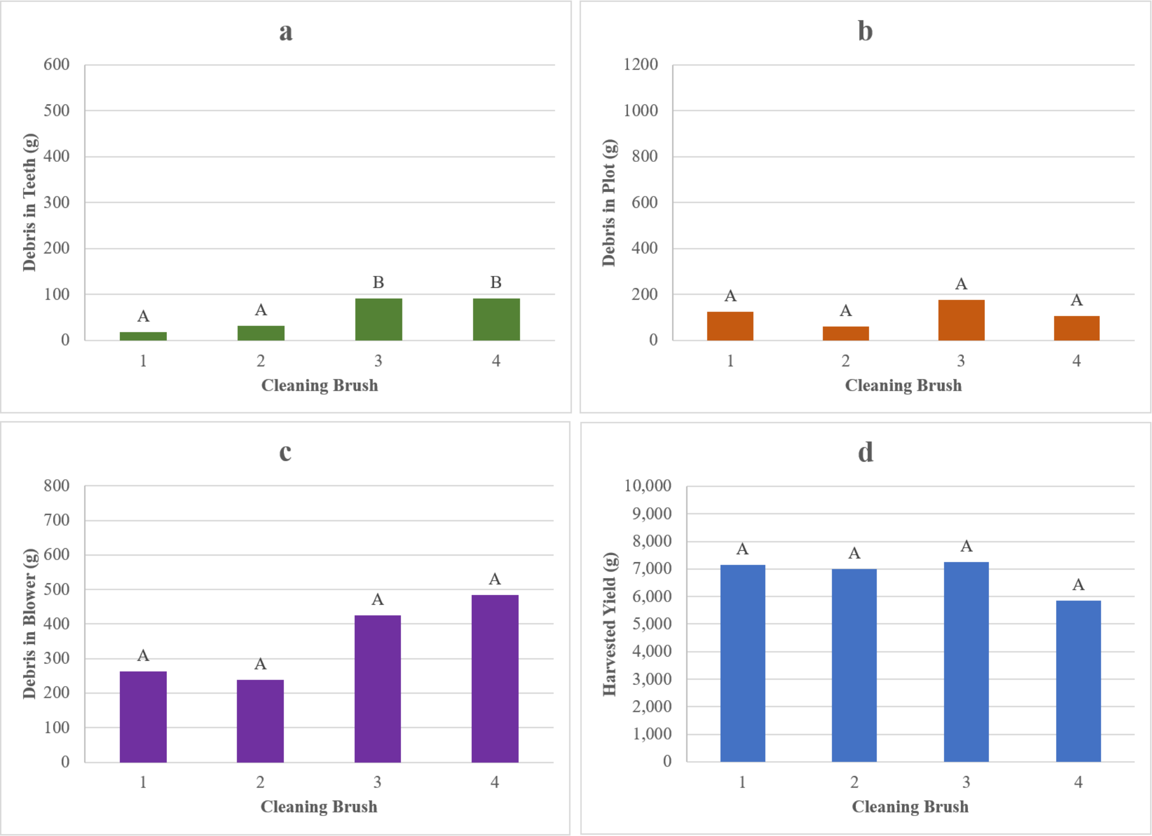
Results of the means comparison indicated that brush 1 had a significantly lower amount of debris lodged in the picker teeth (27.5 g) as compared to treatment combinations using brush 3 (335 g) and 4 (353 g) at the Highland Village site (Fig. 4-13a). Result of ANOVA indicated a non-significant difference in the amount of debris collected from the plots between the treatment combinations in high moisture, weedy field conditions at the Highland Village site. (Fig. 4-13b). Similarly, no significant difference was found with the amount of harvested yield collected from each plot. Significantly more debris was collected from the blower using brush 4 (525.8 g) as compared to brush 1 (301 g) in high moisture, weedy field conditions (Fig. 4-13c). This is a similar trend found in high moisture weed free plots indicating moisture may cause excess debris to buildup in the picker teeth and drop into the conveyor with the berries.



Means with no letter shared are significantly different at p = 0.05.

Figure 4-13: Highland Village site in high leaf wetness, weedy field conditions.

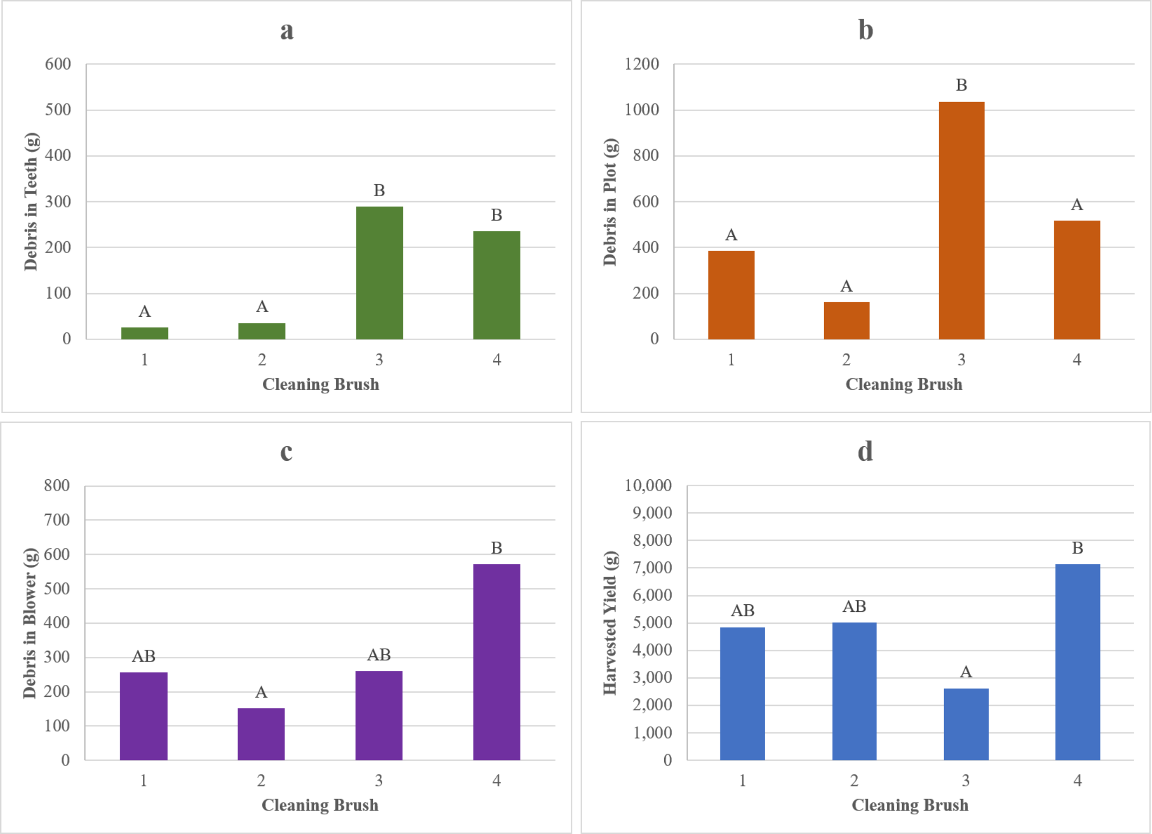
Results of the means comparison indicated that the longer bristle length had an effect on removing leaves, stems and dirt that were logged in the teeth. Brush 1 and 2 were found to have a significantly lower amount of debris collected from the picker teeth as compared to brush 3 and 4 in low moisture, weed free field conditions at the East Mines site (Fig. 4-14a). Brushes 3 and 4 both had the shortest bristle length potentially not having enough tangential velocity to effectively remove debris from getting logged in the teeth. Result of ANOVA suggested that a non-significant difference between the 4 treatment combinations in relation to the amount of debris left in plot, debris collected from blower and the harvested yield in low moisture, weed free plots at the East Mines site.



Means with no letter shared are significantly different at p = 0.05.

Figure 4-14: East Mines site in low leaf wetness, non-weedy field conditions.

Brush 1 and 2 were found to have a significantly lower amount of debris collected from the picker teeth as compared to brush 3 and 4 in low moisture, weedy field conditions at the East Mines site (Fig. 4-15a). GoPro Hero4 (GoPro, San Mateo, CA) video footage collected during experimentation for a side by side comparison also suggested that brush 3 and 4 resulted in higher amounts of debris being lodged in the picker teeth during harvesting (Fig. 4-16). Brush 3 had a significantly higher amount of debris in plot (1037.5 g) as compared to brush 1 (386.8 g), 2 (161.8 g) and 4 (519 g) in low moisture, weedy field conditions at the East Mines site.



Means with no letter shared are significantly different at p = 0.05.

Figure 4-15: East Mines site in low leaf wetness, weedy field conditions.

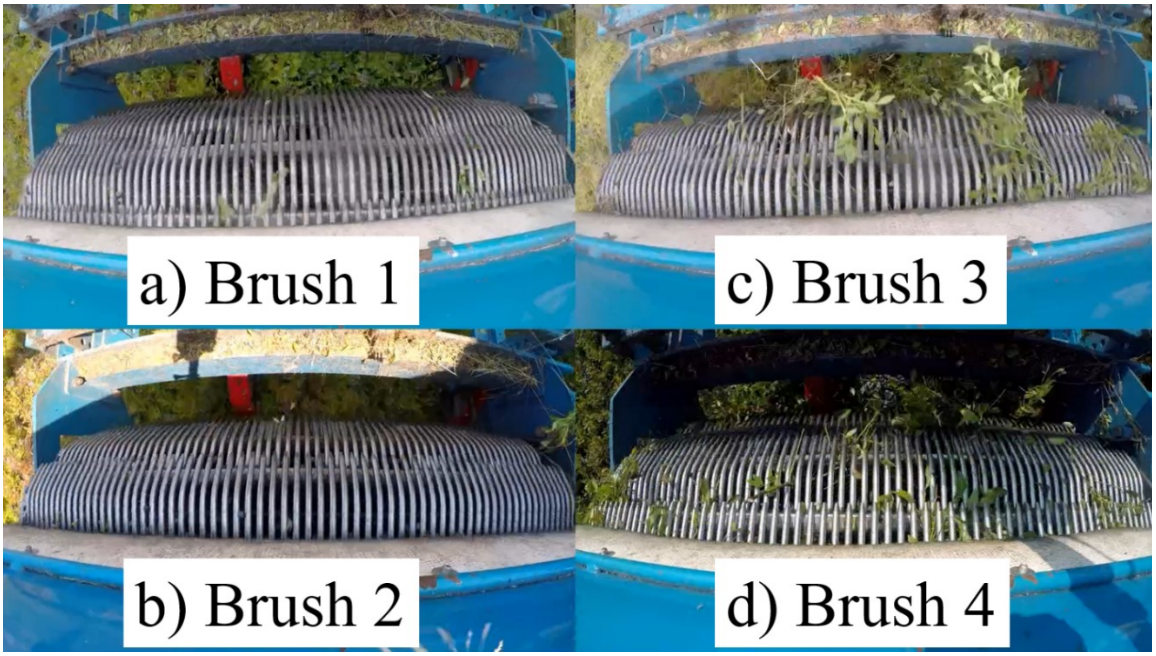
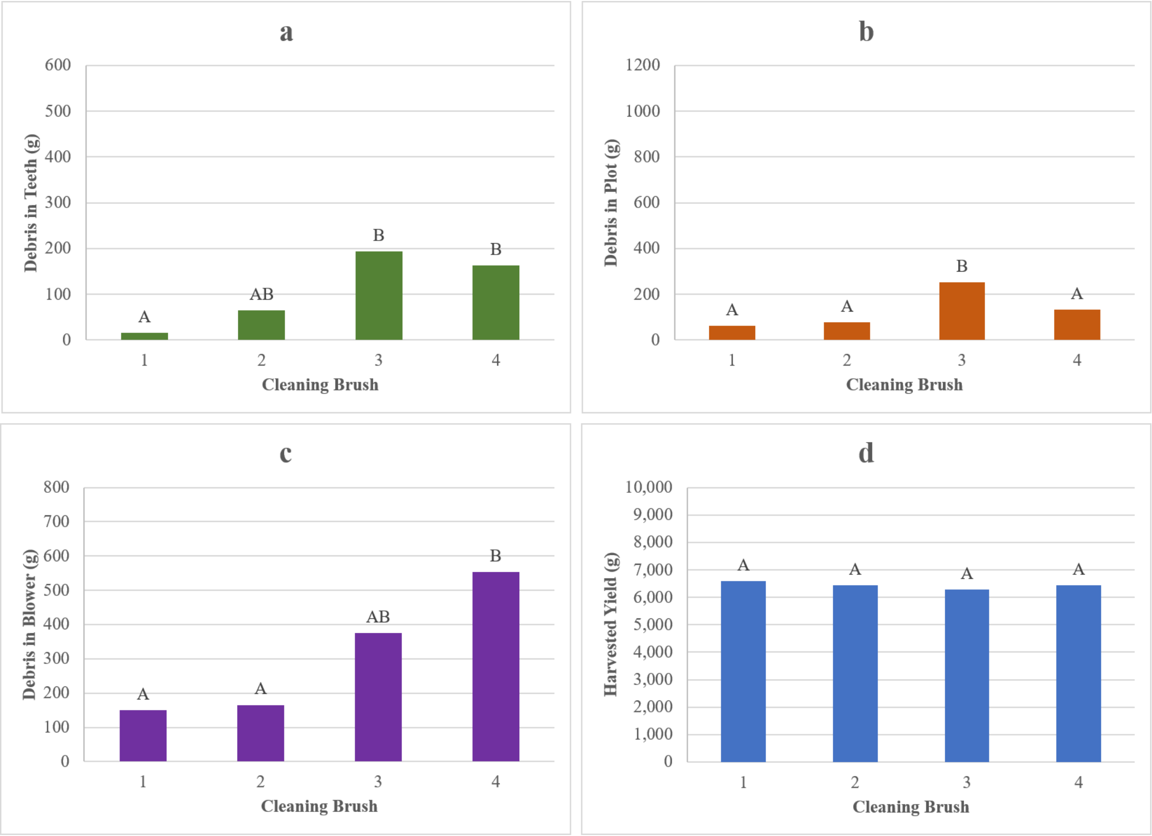


Figure 4-16: Side by side comparison of the debris lodged in picker teeth using a) brush 1, b) brush 2, c) brush 3, and d) brush 4.

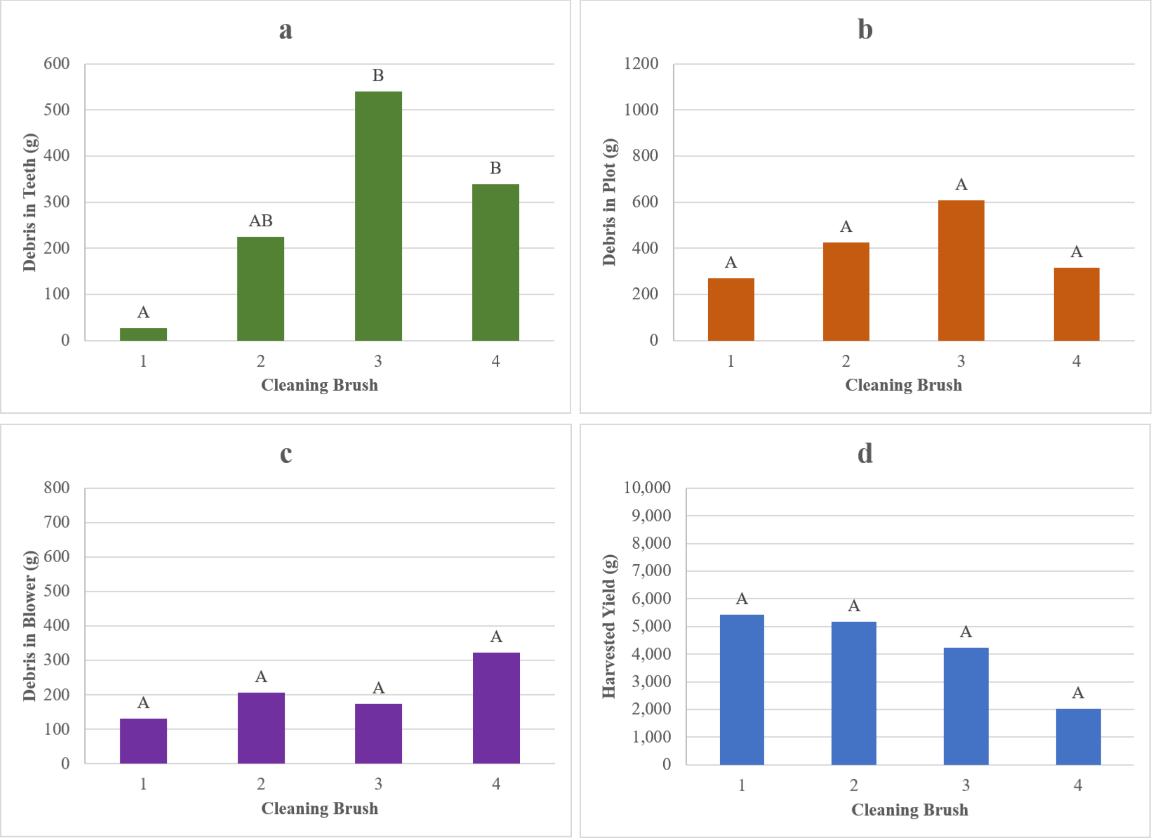
Results of the means comparison indicated that brush 1 had a significantly lower amount of debris lodged in the picker teeth as compared to brush 3 and 4 in high moisture, weed free plots at East Mines site (Fig. 4-17a). Brush 3 had a significantly higher amount of debris in the plot (253.5) as compared to using brush 1 (61.5 g), 2 (65.3 g) and 4 (133 g) in high moisture, weed free tracks at the East Mines site (Fig. 4-17b). Yield was not significantly affected by the four brush treatment combinations and ranged from 6,289 g to 6,584 g in the high moisture, weed free tracks at East Mines site (Fig. 4-17d).



Means with no letter shared are significantly different at p = 0.05.

Figure 4-17: East Mines site in high leaf wetness, non-weedy field conditions.

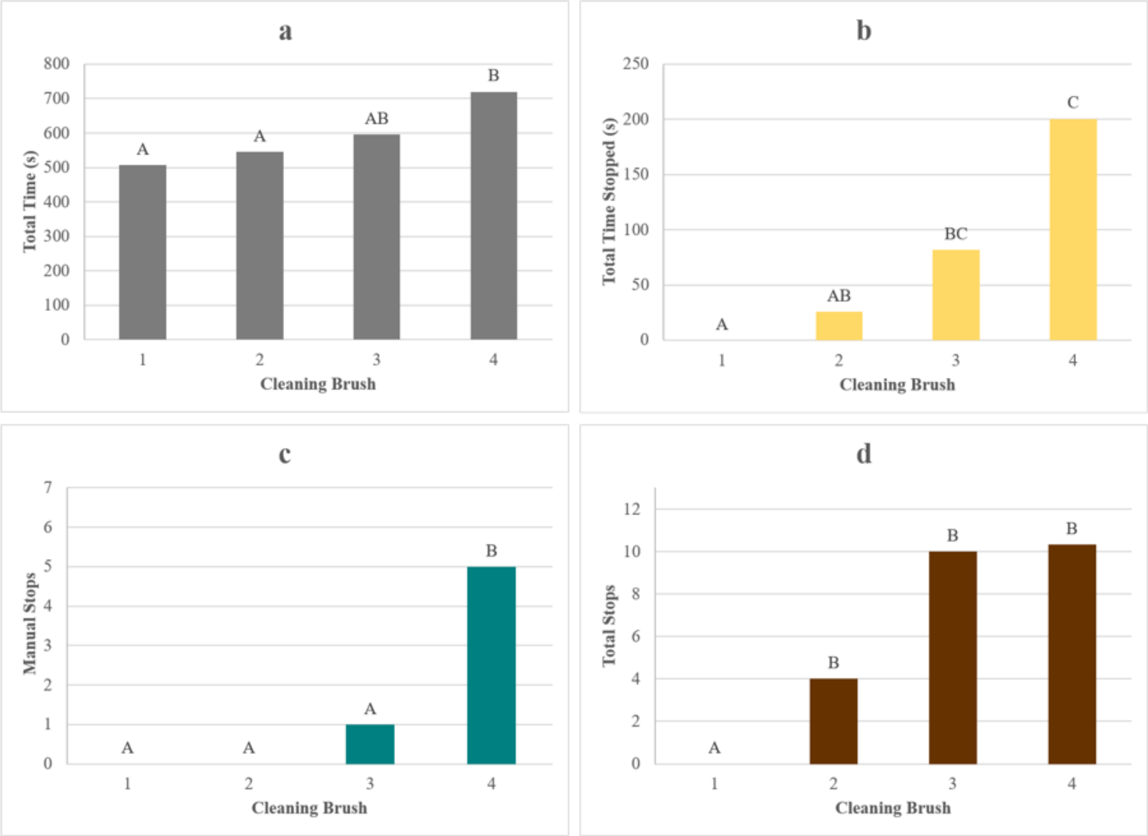
Results of means comparison indicated that brush 1 had significantly less debris (26.25 g) lodged in the picker teeth as compared to brush 3 (539.8 g) and brush 4 (339 g) in high moisture, weedy plots at the East Mines site. A non-significant difference was found in the amount of debris collected from the picker teeth using brush 2, 3 and 4 (Fig. 4-18a). No significant difference was found with the amount of debris left in the plot, debris collected from blower or the amount of harvested yield with each treatment combination in high moisture, weedy field conditions at the East Mines site (Fig. 4-18).



Means with no letter shared are significantly different at p = 0.05.

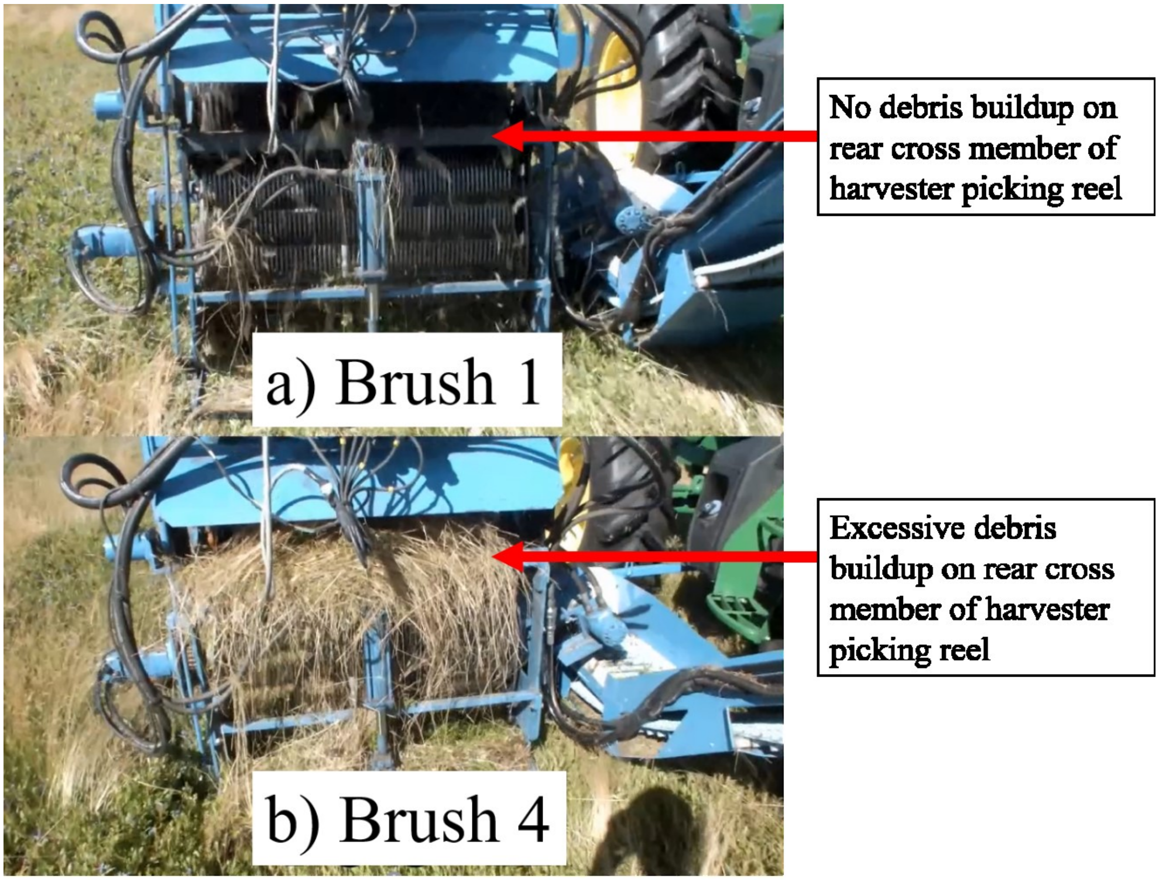
Figure 4-18: East Mines site in high leaf wetness, weedy field conditions.

Results from the 200 m plots revealed that the use of cleaning brush 4 (720.1 s) significantly increased the harvesting time as compared to using brush 1 (507.3 s) and brush 2 (546.01 s). These results suggest that using brush 4 will take 41.95% more time to harvest as compared to using brush 1 (Fig. 4-19a). However, no significant increase in harvesting time was found when using brush 1, 2 or 3 (Fig. 4-19a). Although, results also suggest a non-significant difference between the harvesting time using brush 3 or 4. Mean comparison of the total time stopped showed the use of cleaning brush 1 (0 s) and 2 (25.54 s) was significantly less than when using brush 4 (200.5 s). A steep upward curve of increasing stopped time is observed with each incremental decrease in bristle length (Fig. 4-19b). During field experimentation visual observation revealed the picker teeth stayed relatively clear of debris when operating with a brush 1 and 2. When harvesting with brush 3 and 4 it was visually apparent that a significant amount of debris was remaining in the picker teeth especially in weedy field conditions. Visual observation revealed that debris continually built up in the picker teeth in each treatment combination causing the operator to stop the tractor with the exception of when using brush 1. Stopping the tractor allows the cleaning brush to dislodge debris from the picker teeth to ensure optimum picking efficiency and maximum berry quality at the expense of increased time of harvest. Mean comparison found the use of brush 4 resulted in a significantly higher number of manual stops (5) (Fig. 4-19c). When using both brush 1 and brush 2 the operator was not required to manually exit the tractor to dislodge excessive debris buildup on the rear cross member of the harvester head (Fig. 4-19c and Fig. 4-20). The buildup was likely caused by the shorter brush bristles not having enough tangential tip velocity to allow the debris to be thrown far enough behind the harvester head to clear the rear cross member. Cleaning brush 1 was the only treatment combination that didn’t require the harvester to stop to maintain optimum picking performance during the 200 m trial. Brush 2, 3 and 4 required 4, 10 and 10.33 stops, respectively (Fig. 4-19).



Means with no letter shared are significantly different at p = 0.05.

Figure 4-19: Amount of time harvester was required to stop during 200 m trials using mechanical wild blueberry harvester with different brushes.



No debris buildup on rear cross member of harvester picking reel

Excessive debris buildup on rear cross member of harvester picking reel

Figure 4-20: Side by side comparison of debris buildup during harvesting using a) brush 1, and b) brush 4.

Results of ANOVA comparison found a non-significant difference between the collected yield sample masses from each 200 m treatment (Fig. 4-21). Reasons yields stayed similar with each treatment combination was the operator was trained to stop at the first instance that debris was beginning to buildup in the picker teeth while harvesting. Although it does take additional time, it enables maximum yield recovery during harvest.

Figure 4-21: Amount yield collected during 200 m plot using mechanical wild blueberry harvester with different brushes.

Results from both the 10 and 200 m long test plots concluded that a harvester operating with a new cleaning brush of 120 mm bristle length outperformed older brushes with wore bristles.

The developed harvester operator adjustment guide was divided into five simple steps; 1) measure the bristle length on each side of the harvester cleaning brush in either centimeters or inches (Fig. 4-22), 2) using the harvester brush adjustment chart (Table 4-9) find the corresponding adj. distance for each side of the brush based on the bristle lengths found in Step 1, 3) loosen the four bearing housing bolts on either side of the brush, 4) using a ruler adjust the brush position until the distance between the top of the bearing housing and the top of the adjustment prongs are the same distance as suggested from Table 4-9 (Fig. 4-23), 5) re-tighten the four bearing housing bolts on either side of the brush and continue harvesting. It is recommended to pay close attention to the debris cleaning performance of the brush when the bristle lengths drop below 11 cm. If operators are required to frequently stop to remove excess debris from the rear cross member of the harvester head and manually are required to remove debris buildup from the picker teeth it is recommended to replace the wore brush with a new brush.

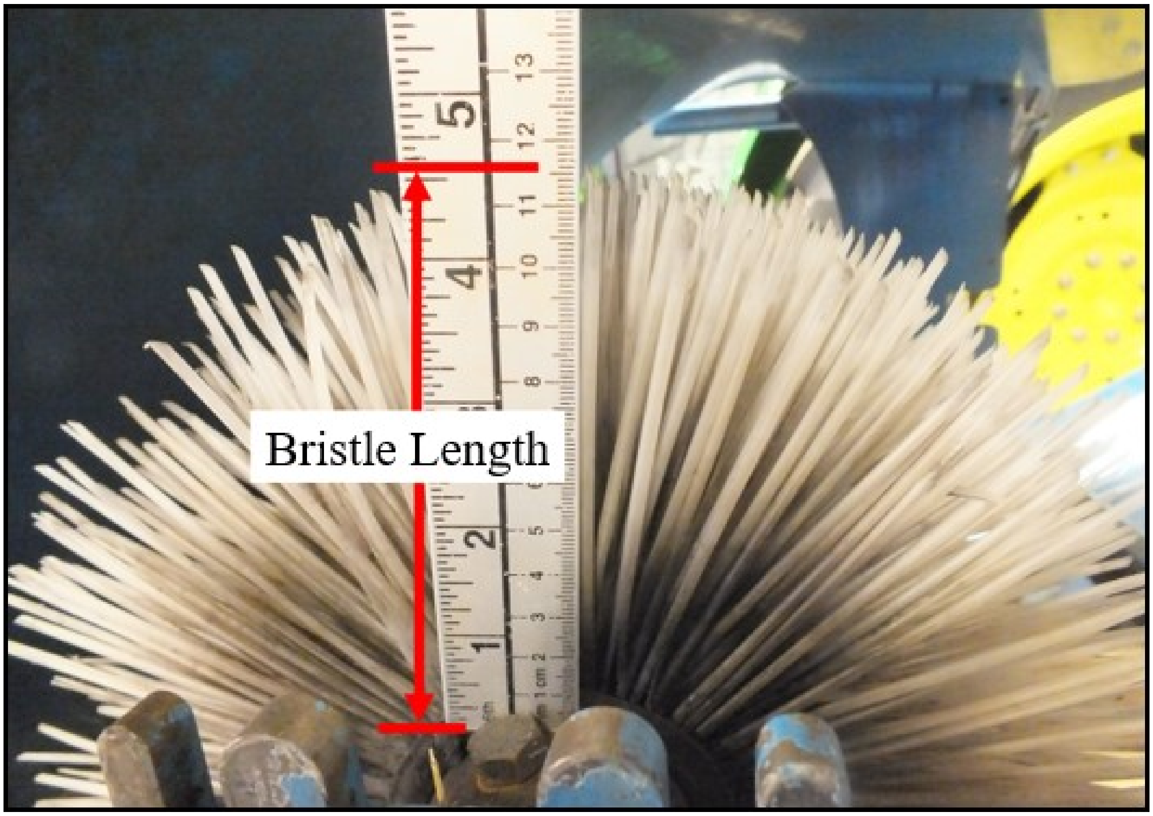


Figure 4-22: Harvester brush side view (step 1).

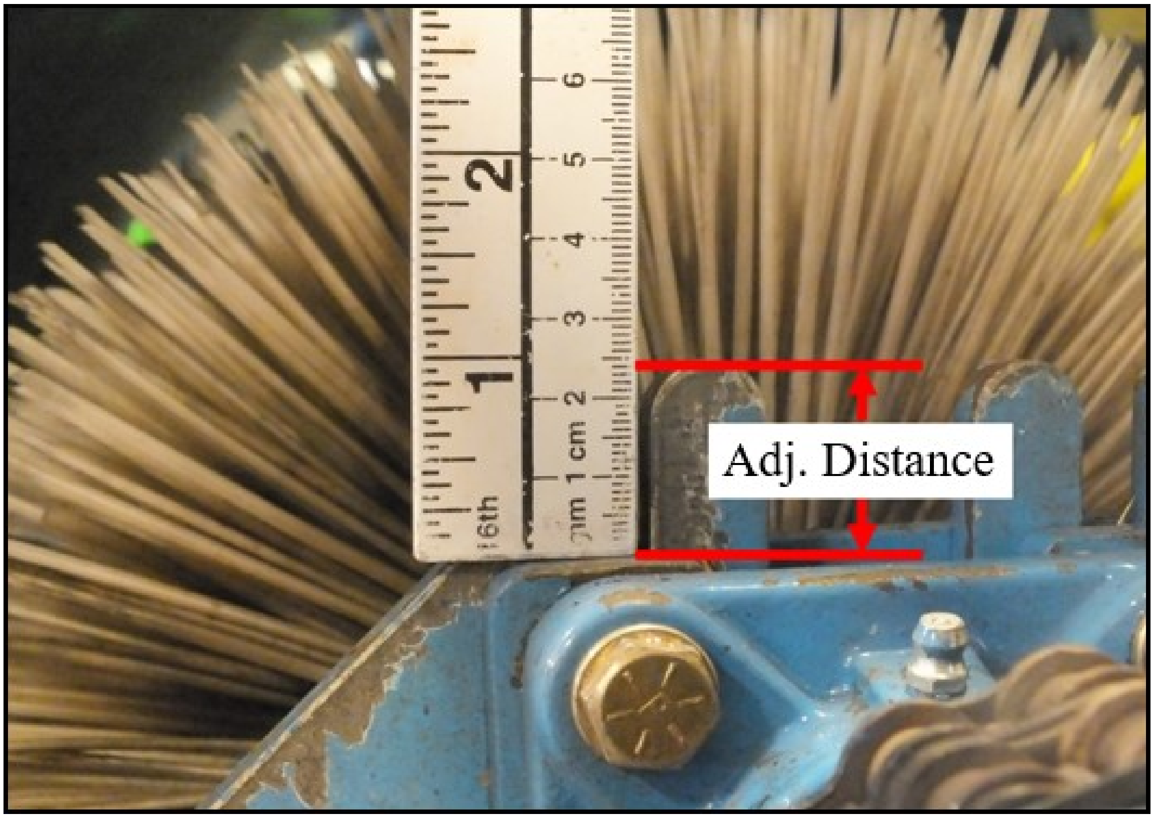
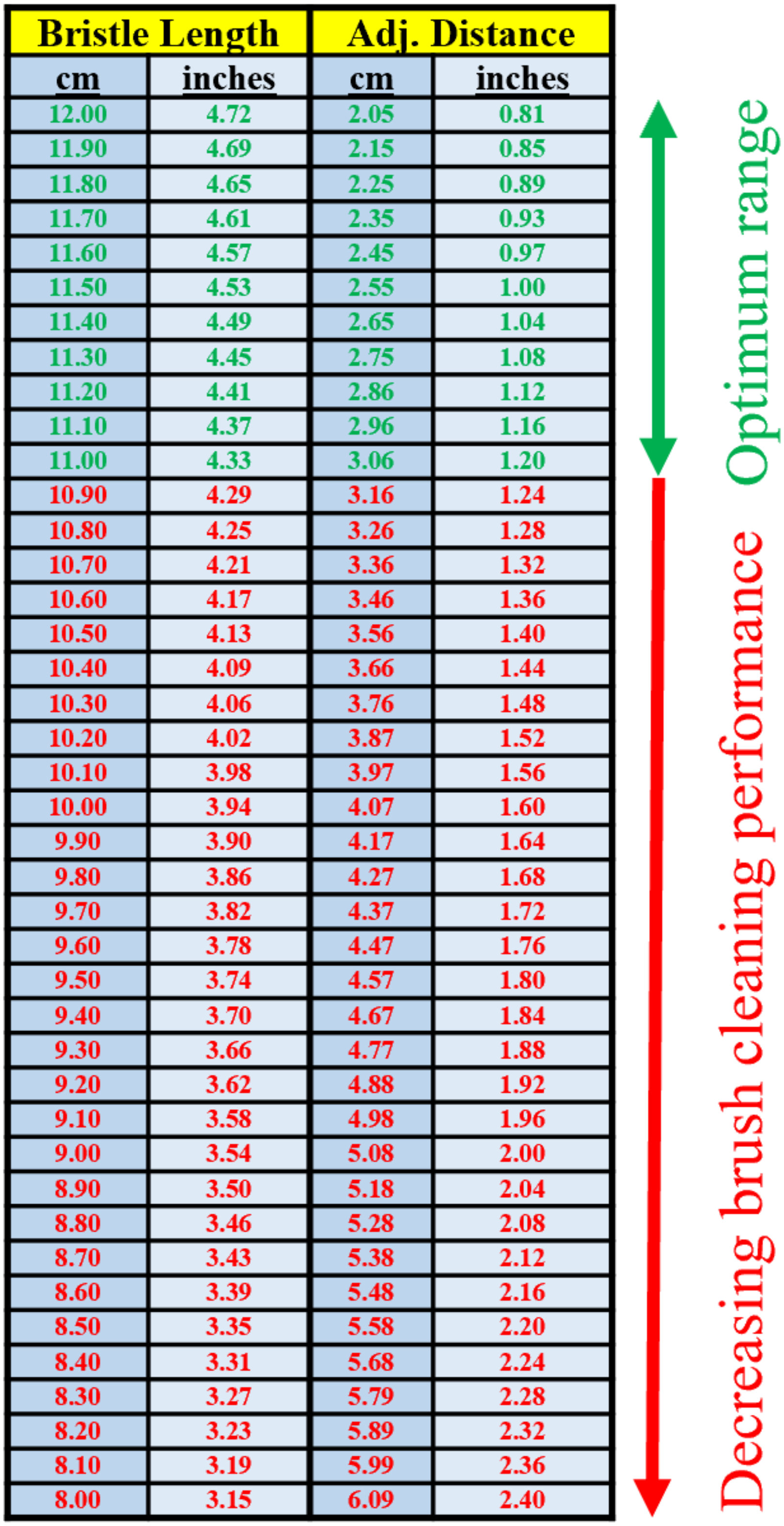


Figure 4-23: Harvester brush adj. prong side view (step 4).

Table 4-9. Harvester debris cleaning brush adjustment chart (metric and imperial measurements).



Bristle Length		Adj. Distance	
cm	inches	cm	inches
12.00	4.72	2.05	0.81
11.90	4.69	2.15	0.85
11.80	4.65	2.25	0.89
11.70	4.61	2.35	0.93
11.60	4.57	2.45	0.97
11.50	4.53	2.55	1.00
11.40	4.49	2.65	1.04
11.30	4.45	2.75	1.08
11.20	4.41	2.86	1.12
11.10	4.37	2.96	1.16
11.00	4.33	3.06	1.20
10.90	4.29	3.16	1.24
10.80	4.25	3.26	1.28
10.70	4.21	3.36	1.32
10.60	4.17	3.46	1.36
10.50	4.13	3.56	1.40
10.40	4.09	3.66	1.44
10.30	4.06	3.76	1.48
10.20	4.02	3.87	1.52
10.10	3.98	3.97	1.56
10.00	3.94	4.07	1.60
9.90	3.90	4.17	1.64
9.80	3.86	4.27	1.68
9.70	3.82	4.37	1.72
9.60	3.78	4.47	1.76
9.50	3.74	4.57	1.80
9.40	3.70	4.67	1.84
9.30	3.66	4.77	1.88
9.20	3.62	4.88	1.92
9.10	3.58	4.98	1.96
9.00	3.54	5.08	2.00
8.90	3.50	5.18	2.04
8.80	3.46	5.28	2.08
8.70	3.43	5.38	2.12
8.60	3.39	5.48	2.16
8.50	3.35	5.58	2.20
8.40	3.31	5.68	2.24
8.30	3.27	5.79	2.28
8.20	3.23	5.89	2.32
8.10	3.19	5.99	2.36
8.00	3.15	6.09	2.40

4.4 CONCLUSIONS

In this study, both commercial wild blueberry fields used for experimental evaluation of the debris cleaning brush had revealed reasonably low variability in plant height, plant density and stem diameter with CV < 35%. The Highland Village site was found to have high variability in slope likely because the field was not commercially land leveled and had significant variation in field topography. The recently land leveled East Mines site had low variability in slop within selected plots with CV < 11.71%. Field evaluation of the commercial wild blueberry harvester operating in 10 m test tracks throughout both field sites revealed that the longer bristle length on the debris cleaning brushes had a significant effect on successfully removing leaves, stems and dirt that were lodged in the teeth in dry field conditions. Results also suggested that additional debris buildup in the teeth may have led to increased debris getting intertwined and ripped from the field during harvesting. Debris cleaning brush 1 and 2 with a bristle length of 120 mm and 115 mm respectively, outperformed brush 3 and 4 with bristle lengths of 106 and 87 mm respectively, by removing more debris from the picker teeth under most operating conditions. Results of the performance testing of brush 1 revealed 13.5 to 29.25 g of unwanted debris remained after completion of a 10 m test track in both field site locations. Results from testing brush 2 revealed a wider range of debris (32.3 to 224.3 g) remaining in picker teeth suggesting decreasing performance with the shorter bristle length. Further performance testing found a very wide range 34.95 to 539.8 g of debris (brush 3) and 91.8 to 353 g of debris (brush 4) remaining in the picker teeth. Results suggest that brush 3 and 4 did not produce a bristle tip speed fast enough to effectively remove debris from the picker teeth during harvesting.

Results from the 200 m plots revealed that the use of cleaning brush 4 significantly increased the harvesting time by 41.95, 31.88 and 21.00% as compared to using brush 1, 2 and 3, respectively. However, no significant increase in harvesting time was found when using brush 1, 2 or 3. A steep upward curve of increasing stopped time is observed with each incremental decrease in bristle length. During field experimentation visual observation throughout the 200 m plot revealed the picker teeth stayed relatively clear of debris when operating with brush 1 and 2. When harvesting with brush 3 and 4 it was visually apparent that a significant amount of debris was remaining in the picker teeth especially in weedy field conditions resulting in the harvester operator having to stop several times while raising the harvester picking reel allowing time for the brush to dislodge the debris from picker teeth. Furthermore, using both brush 3 and 4 required the operator to manually exit the cab of the tractor to dislodge built-up debris from the rear cross member of the harvester picking reel. Cleaning brush 1 was the only treatment combination that didn't require the harvester to stop to maintain optimum picking performance during the 200 m trial. Brush 2, 3 and 4 required 4, 10 and 10.33 stops, respectively. These results were as expected from insufficient debris cleaning shroud air velocities found when using bristle lengths below 120 mm. Results of ANOVA comparison found a non-significant difference between the collected yield sample masses from each 200 m treatment likely because the operator stopped at the first instance that debris was beginning to buildup in the picker teeth while harvesting.

The developed harvester operator adjustment guide was divided into five simple steps that enables operators to quickly and accurately adjust the debris cleaning brush to the manufacturers recommended setting. Furthermore, the brush adjustment guide also shows the optimal bristle lengths for increased picking performance and gives recommendations for replacement when operators are required to frequently stop to remove excess debris from the rear cross member of the harvester head or manual stops are required to remove debris buildup from the picker teeth.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

An industry wide initiative to increase berry quality and lower processing shrink had initiated this vital research to evaluate the factors effecting the optimum settings for effective debris removal during harvesting. The overall goal of this study was to evaluate existing performance of the debris separation techniques on commercial mechanical wild blueberry harvesters through both lab and field analysis, to suggest optimal operating parameters for increased picking performance and optimum berry quality. A detailed evaluation of both the debris removal blower fan and the picking reel debris removal brush using both lab and field evaluation tests revealed significant optimization enhancements to lower operator error and increase berry quality while harvesting.

The single blower fan to remove unwanted debris from fruit before entering the storage bins was replaced with a new dual fan system increasing air flow and effective debris cleaning capabilities. An apparatus to measure the terminal velocity of common types of debris found while harvesting wild blueberries was developed at the Dalhousie University Faculty of Agriculture (DAL-AC) Precision Agriculture Research Lab to enable fine tuning of air speeds such that debris is successfully removed but not reducing harvested yield potential. Wild blueberries were found to have a significantly higher terminal velocity (15.65 m s^{-1}) as compared to common debris samples ($\leq$ 5.64 m s^{-1}) tested in both dry and wet experimental conditions. Results of this study also suggested that wild blueberry fruit has a significantly lower surface area to mass ratio (61 mm^2 g^{-1}) as compared to harvested debris allowing for an excellent opportunity for separation using forced air. Research results were favorable such that insufficient air flow from the single 12 V blower fan system traditionally used on commercial harvesters could be retrofitted with an improved dual fan system with two separate air flow channels (120 mm wide, 50 mm tall, 400 mm long) operating with increased air speeds of up to 23 m s^{-1} significantly lowering the unwanted debris from harvested fruit without significant yield loss. An additional benefit to existing harvester owners is the ability of the new dual fan plenum system to be retrofitted onto the existing berry handling conveyor without the need to disassemble the harvester. A variable speed handheld fan controller positioned in the cab of the harvester was also designed to allow the operator the ability to fine tune the rate of air flow and also monitor real-time for potential reductions in air flow caused by debris being lodged in the fan vanes. Two experimental wild blueberry field sites were selected to analyze the effect of using a variable speed blower fan while operating in both low and high moisture field conditions using a commercial Doug Bragg Enterprises Ltd. mechanical harvester with two styles of picker bars (63 and 65 tooth configuration) and four different blower fan speeds (B_1 = 0, B_2 = 14, B_3 = 18 and B_4 = 23 m s^{-1}). Based on field experimentations, fan speeds of 18 and 23 m s^{-1} performed equally during both low and high moisture field conditions to remove debris (98.8% and 98.6%) while harvesting. Results of the means comparison indicated that the 63 tooth picker bars significantly reduced the amount of harvested wild blueberry leaves, wild blueberry stems and dirt collected while harvesting likely because of the wider teeth spacing causing less plant pulling when the picker bars comb through the wild blueberry plant foliage. The picker bar tooth spacing did not have any significant effect on the harvested yield. Wild blueberry plants less than 250 mm tall resulted in a significant reduction in wild blueberry stems and dirt collected during harvesting as compared to plants taller than 250 mm. This was likely caused from increased plant pulling when the picker bars comb through the taller wild blueberry plant foliage. Detailed evaluation of the harvester fan system will suggest optimal operating parameters for the grower's community to increase debris separation and berry quality while reducing processing facility shrink.

The cylindrical debris cleaning brush on commercial harvesters are positioned on top of the picking reel and continuously rotates to propel debris from the picker teeth. The manufacturer recommends the bristles of the brush to penetrate into the picker teeth 0.32 cm during harvesting for maximum debris cleaning performance without berry loss or damage. A survey of commercial harvester operators found 69.2% were operating outside of the manufacturers recommended adjustment range. Inaccurate visual adjustment settings and prior knowledge of the importance of proper settings was the likely cause of the wide range of debris cleaning brush adjustment settings. To overcome the visual inaccuracies, the mechanical harvester geometry was studied to develop a method of brush adjustment that was fast and accurate to ensure the bristle length was at the proper depth into the picker teeth. Four commercially used debris cleaning brushes of varying wear were lab evaluated to determine the potential effect on debris removal performance. Wet mass of each brush showed an increased trend as compared to the dry mass however, it was non-significant at $p = 0.05$ suggesting the annealed plastic did not absorb water likely extending its expected lifespan. The brush's bristle tip speed was analyzed in relation to common tractor engine speeds (1,200, 1,400 and 1,600 rpm) with results ranging from 6.58 to 13.88 m s^{-1}. Airflow generated in the debris deflection shroud using each brush was analyzed and compared with terminal velocities suggesting a bristle length of 12 cm is required for wind velocities large enough to successfully propel the debris away from the picker teeth with bristle tip speeds ranging from 9.15 to 13.88 m s^{-1}. Further lab testing concluded the need for a variable speed hydraulic drive motor for more uniform control of the rotating brush speed-based variables such as brush bristle length, tractor engine speed, field moisture conditions and weed density while harvesting.

Field evaluation of a commercial wild blueberry harvester operating with different debris cleaning brushes revealed that longer bristle lengths had a significantly higher chance of successfully removing leaves, stems and dirt that gets lodged in the picking teeth during harvesting. Testing also suggested that additional debris buildup in the teeth may lead to increased debris getting intertwined and ripped from the field during harvesting. Debris cleaning brush 1 and 2 with bristle lengths of 120 mm and 115 mm respectively, outperformed brush 3 and 4 with bristle lengths of 106 and 87 mm respectively, by removing more debris from the picker teeth under most operating conditions. Results suggest the reason for reduced debris removal using brush 3 and 4 during harvesting was because of tapered bristle tips and a decreased bristle tip speed. Two-hundred-meter-long test tracks revealed the use of cleaning brush 4 significantly increased the harvesting time by 41.95, 31.88 and 21.00% as compared to using brush 1, 2 and 3, respectively. Visual observation revealed brush 1 and 2 to keep the picker teeth relatively clear of debris while harvesting but it was apparent that brush 3 and 4 resulted in significant debris collection in the picker teeth especially in weedy field conditions. The operator was required to stop several times raising the harvester picking reel allowing time for the brush to dislodge the debris from picker teeth using both brush 3 and 4. Furthermore, using both brush 3 and 4 required the operator to manually exit the cab of the tractor to dislodge built-up debris from the rear cross member of the harvester picking reel. The highest field efficiency was gained using cleaning brush 1 as it was the only treatment combination that didn't require the operator to stop to maintain optimum picking performance during harvesting. These results were supported from insufficient debris cleaning shroud air velocities found when using bristle lengths below 120 mm.

Results gathered from this research were summarized into an industry first harvester operator adjustment guide allowing operators to quickly and accurately adjust the debris cleaning brush to the manufacturers recommended setting. Furthermore, the brush adjustment guide also shows the optimal bristle lengths for increased picking performance and gives recommendations for replacement when operators are required to frequently stop to remove excess debris from the rear cross member of the harvester head or manual stops are required to remove debris buildup from the picker teeth.

5.2 RECOMMENDATIONS

Results of this study emphasize the importance of knowing and understanding the components of the mechanical wild blueberry harvester that have the ability to increase field efficiency, picking performance, berry quality and factors that lead to reduced shrink at the processing facilities. It is proposed to further automate the dual blower fan system using machine vision technology optimizing the air velocity in real-time depending on the debris type and quantity detected. This innovative new system has the potential to further increase berry quality, reduce processing facility shrink and lower operator stress through harvester automation. Research to study ways to reduce the debris that occasionally gets stuck in the fan air inlet vanes will further increase field efficiency and can lead to increased debris cleaning performance during harvesting. Additional research into a primary debris removal system installed at the berry drop position between the conveyor exiting the picking reel and the side conveyor could be a worthwhile endeavor. A dual debris removal setup using multi air channels could benefit the farmer by further reducing unwanted debris potentially allowing select processors to eliminate the previously instated 5% box tare in 2017 used as a global approximation of the debris that select harvester operators were picking into the bins. Additional research could be done to automate the position of the rear cross conveyor to help eliminate the potential for berry loss when travelling in steep field conditions. This research may also lead to the ability to use even higher air velocities during debris removal.

Based on the results from this study, it is suggested to further study new designs of debris cleaning brushes to determine if larger bristle lengths will further increase the debris removal from the picker teeth during harvesting. The manual adjustment of the debris cleaning brush could be automated using a linear actuator and an electric control system for real-time continuous adjustments during harvesting. A machine vision system could be installed to monitor the debris buildup in the teeth and using a variable speed hydraulic motor, the debris cleaning brush could adjust to effectively remove unwanted debris from the teeth while maximizing the effective lifespan. This research would be very valuable for increasing brush speeds when harvesting in wet or weedy field conditions or reducing brush speeds when harvesting in dry, weed free fields with low plant height when there is less chance of debris buildup.

The adoption of these improved debris removal systems will be an important step for the wild blueberry industry to improve their harvested product to better compete with the highbush blueberry market and other fruit products on the global scale. The research findings from this study can also be applied to other agricultural harvesting systems such as grapes and cranberries for potential improvement with their real-time debris removal systems during harvest.

REFERENCES

Abdel-Wahab, M., Wang, C., Vanegas-Useche, L., & Parker, G. (2011). Experimental determination of optimum gutter brush parameters and road sweeping criteria for different types of waste. *Waste Management, 31*(6), 1109-1120. doi:10.1016/j.wasman.2010.12.014

Bergenholtz, A., Gustafsson, L., Segerlund, N., Hagberg, C., & Östby, P. (1984). Role of brushing technique and toothbrush design in plaque removal. *European Journal of Oral Sciences, 92*(4), 344-351. doi:10.1111/j.1600-0722.1984.tb00901.x

Biale, J., & Young, R. (1981). Respiration and ripening in fruits-retrospect and prospect. *Recent Advances in the Biochemistry of Fruit and Vegetables*. *Academic Press, New York*, pp. 1-39.

Blanpied, G. (1969). A study of the relationship between optimum harvest dates for storage and the respiratory climacteric rise in apple fruits. *Journal of the American Society for Horticultural Science*, 94, 177–179.

Boyd, N., & White, S. (2010). PRE and POST herbicides for management of goldenrods *(Solidago spp.)* and black bulrush *(Scirpus Atrovirens)* in wild blueberry. *Weed Technology, 24*(04), 446-452. doi:10.1614/wt-09-068.1

Bragg, C. (2017). Personal communication. President, Doug Bragg Enterprises, Collingwood, Nova Scotia, Canada.

Bragg, S. (2016). Personal communication. Manager, Doug Bragg Enterprises, Collingwood, Nova Scotia, Canada.

Bragg, D., & Weatherbee, L. (1989). Apparatus for harvesting berries on low plants. U.S. Patent No. 4862683.

Brown, G., Schulte, N., Timm, E., Beaudry, R., Peterson, D., Hancock, J., & Takeda, F. (1996). Estimates of mechanization effects on fresh blueberry quality. *Applied Engineering in Agriculture, 12*(1), 21-26. doi:10.13031/2013.25435

Cardina, J., Herms, C., & Doohan, D. (2002). Crop rotation and tillage system effects on weed seedbanks. *Weed Science, 50*(4), 448-460. doi:10.1614/0043-1745(2002)050[0448:cratse]2.0.co;2

Cat® North America. (2018). Attachment brooms. Retrieved from https://www.cat.com

C.C.A.G. Crotti. (2018). Brushes for professional cleaning. Retrieved from https://www.ccgacrotti.eu/en-gb/home

Chang, Y., Chou, C., Su, K., & Tseng, C. (2005). Effectiveness of street sweeping and washing for controlling ambient TSP. *Atmospheric Environment, 39*(10), 1891-1902. doi:10.1016/j.atmosenv.2004.12.010

Chang, Y., Zaman, Q., Farooque, A., Schumann, A., & Percival, D. (2012). An automated yield monitoring system II for commercial wild blueberry double-head harvester. *Computers and Electronics in Agriculture, 81*, 97-103. doi:10.1016/j.compag.2011.11.012

Collins, G., Collins, J., & Collins, M. (1994). Lowbush berry harvester. U.S. Patent No. 5375403.

Croft, J. (1995). Nut harvester. U.S. Patent No. 5465562.

Curbell Plastics. (2017). Plastic properties table. Retrieved from https://www.curbellplastics.com

Dale, A., Hanson, E., Yarborough, D., Mcnicol, R., Stang, E., Brennan, R., . . . Hergert, G. (2010). Mechanical harvesting of berry crops. *Horticultural Reviews,* 255-382. doi:10.1002/9780470650561.ch8

DeLaval. (2018). Swinging cow brush. Retrieved from http://www.delavalcorporate.com

Devries, T., Vankova, M., Veira, D., & Keyserlingk, M. (2007). Short communication: usage of mechanical brushes by lactating dairy cows. *Journal of Dairy Science, 90*(5), 2241-2245. doi:10.3168/jds.2006-648

Eaton, L. (1988). *Nitrogen cycling in lowbush blueberry stands.* (Doctor of Philosophy dissertation). Dalhousie University, Canada.

Esau, T. (2016). *Smart sprayer for spot-application of agrochemical in wild blueberry fields.* (Doctor of Philosophy dissertation). Dalhousie University, Canada.

Farooque, A., Zaman, Q., Groulx, D., Nguyen-Quang, T., Yarborough, D., Schumann, A., . . . Esau, T. (2013). Effect of ground speed and header revolutions on the picking efficiency of wild blueberry harvester. *ASABE Conference Proceedings, Kansas City, USA*. doi:10.13031/aim.20131596449

Farooque, A., Zaman, Q., Groulx, D., Schumann, A., Yarborough, D., & Quang, T. (2014). Effect of ground speed and head revolutions on the picking efficiency of wild blueberry harvester. *Applied Engineering in Agriculture* 30(4):535-546.

Farooque, A., Zaman, Q., Schumann, A., Madani, A., & Percival, D. (2012). Response of wild blueberry yield to spatial variability of soil properties. *Soil Science, 177*(1), 56-68. doi:10.1097/ss.0b013e3182376ed6

Fennimore, S., Smith, R., Tourte, L., Lestrange, M., & Rachuy, J. (2014). Evaluation and economics of a rotating cultivator in bok choy, celery, lettuce, and radicchio. *Weed Technology, 28*(01), 176-188. doi:10.1614/wt-d-13-00051.1

Fowler, L. (2002). Sugar cane combine harvester. U.S. Patent No. 6363700.

Gaser, J. (1999). "Fundamentals of Brushing", society of manufacturing engineers, *Brush and Polish Techniques Conference Proceedings*, Florida, FC99-196

GEA. (2018). Cow brushes for optimal cow comfort. Retrieved from https://www.gea.com

Gebrehiwot, M., Baerdemaeker, J., & Baelmans, M. (2010). Effect of a cross-flow opening on the performance of a centrifugal fan in a combine harvester: Computational and experimental study. *Biosystems Engineering, 105*(2), 247-256. doi:10.1016/j.biosystemseng.2009.11.003

Georg, H., & Totschek, K. (2001). Investigation of an automatic brush for dairy cows. *LANDTECHNIK, 56*. doi:10.15150/lt.2001.1772

Gianessi, L., & Sankula, S. (2003). The value of herbicides in U.S. crop production. *National Center for Food & Agricultural Policy.* Retrieved from http://www.ncfap.org/ documents /FullText.pdf

Grierson, D., (1986). Molecular biology of fruit ripening. *Oxford Surveys of Plant Molecular and Cell Biology*, 3, 363–383. doi:10.1016/0168-9525(88)90068-6

Hall, I., Craig, D., & Lawrence, R. (1983). A comparison of hand raking and mechanical harvesting of lowbush blueberries. *Canadian Journal of Plant Science*, 63, 951-954. doi:10.4141/cjps83-119

Hayden, M., & Soule, J. (1969). Developing a blueberry harvester. *Transactions of American Society of Agricultural Engineers*. 12(1), 127-129. doi:10.13031/2013.38778

Hearin, J., Hunsucker, K., Swain, G., Stephens, A., Gardner, H., Lieberman, K., & Harper, M. (2015). Analysis of long-term mechanical grooming on large-scale test panels coated with an antifouling and a fouling-release coating. *Biofouling, 31*(8), 625-638. doi:10.1080/08927014.2015.1081687

Hoelper, A., & Yarborough, D. (1985). Hexazinone and terbacil to suppress weeds in a commercial lowbush blueberry field. *Northeastern Weed Science Society, 39*, 151-156. Retrieved from https://agricola.nal.usda.gov/vwebv/holdingsInfo?searchId=111165&recCount=10&recPointer=1&bibId=37648783.

Holden, G., Williams, D., & Hay, L. (1995). Nut harvester. U.S. Patent No. 5421147.

Holm, E., Haslbeck, E., & Horinek, A. (2003). Evaluation of brushes for removal of fouling from fouling-release surfaces, using a hydraulic cleaning device. *Biofouling, 19*(5), 297-305. doi:10.1080/0892701031000137512

Hopkins, G., Forrest, B., & Coutts, A. (2010). The effectiveness of rotating brush devices for management of vessel hull fouling. *Biofouling, 26*(5), 555-566. doi:10.1080/08927014.2010.494330

Jameel, W., Zaman, Q., Schumann, A., Farooque, A. (2016a). Impact of plant characteristics on berry losses during mechanical harvesting of wild blueberry. *ASABE International Conference Proceedings, USA*, doi:10.13031/aim.20162460764

Jameel, W., Zaman, Q., Schumann, A., Nguyen-Quang, T., Farooque, A., Brewster, G., Chattha, H. (2016b). Effect of plant characteristics on picking efficiency of the wild blueberry harvester. *Applied Engineering in Agriculture.* 32(5), 589-598. doi:10.13031/aea.32.11492

Jensen, K. (1997). *Using Hexazinone in fruiting year lowbush blueberry*. Kentville, NS: Agriculture & Agri-Food Canada, Atlantic Food & Horticulture Research Centre.

Jensen, K., & Kimball, E. (1985). Tolerance and residues of hexazinone in lowbush blueberries. *Canadian Journal of Plant Science, 65*(1), 223-227. doi:10.4141/cjps85-032

Jensen, K., & Yarborough, D. (2004). An overview of weed management in the wild lowbush blueberry-past and present. *Small Fruits Review, 3*(3-4), 229-255. doi:10.1300/j301v03n03_02

Kennedy, K., Boyd, N., & Nams, V. (2010). Hexazinone and fertilizer impacts on sheep sorrel *(rumex acetosella)* in wild blueberry. *Weed Science, 58*(03), 317-322. doi:10.1614/ws-d-09-00081.1

Kinsman, G. (1993). The history of lowbush blueberry industry in Nova Scotia 1950–1990. *NS Department of Agriculture & Marketing*, Nova Scotia, Canada. pp 153.

Klonsky, K. (2012). Comparison of production costs and resource use for organic and conventional production systems. *American Journal of Agricultural Economics, 94*(2), 314-321. doi:10.1093/ajae/aar102

Klonsky, K., Tourte, L., Chaney, D., Livingston P., & Smith. R. (1994). Production practices and sample costs for a diversified organic vegetable operation on the central coast of California. *1994 central coast organic mixed vegetable cost and return study*. Oakland, Calif.: U.C. Cooperative Extension.

Ledebuhr, R., & Hansen, C. (1985). Strawberry harvester and procedures for growing and harvesting of such fruit. U.S. Patent No. 4519191.

Malay, W. (2000). Spatial variability and yield monitor evaluation for carrots and wild blueberries. (Master of Science dissertation). Dalhousie University, Canada.

Mandel, R., & Nicol, C. (2017). Re-direction of maternal behaviour in dairy cows. *Applied Animal Behaviour Science, 195*, 24-31. doi:10.1016/j.applanim.2017.06.001

McCully, K., Sampson, M., & Watson, A. (1991). Weed survey of Nova Scotia lowbush blueberry *(Vaccinium angustifolium Ait.)* fields. *Weed Science,* 39:180–185. Retrieved from https://www.jstor.org/stable/4044913

Mehra, L., Maclean, D., Savelle, A., & Scherm, H. (2013b). Postharvest disease development on southern highbush blueberry fruit in relation to berry flesh type and harvest method. *Plant Disease, 97*(2), 213-221. doi:10.1094/pdis-03-12-0307-re

Mehra, L., Maclean, D., Shewfelt, R., Smith, K., & Scherm, H. (2013a). Effect of postharvest bio fumigation on fungal decay, sensory quality, and antioxidant levels of blueberry fruit. *Postharvest Biology and Technology*, 85, 109-115. doi:10.1016/j.postharvbio.2013.05.007

Melander, B. (1997). Optimization of the adjustment of a vertical axis rotary brush weeder for intra-row weed control in row crops. *Journal of Agricultural Engineering Research, 68*(1), 39-50. doi:10.1006/jaer.1997.0178

Metzger, H., & Ismail, A. (1976). Management practices and cash operating costs in lowbush blueberry production. *Maine Agricultural and Forest Experiment Station. Bulletin,* 723.

Miller, S. (2010). UW-Platteville pioneer farm installs swinging cow brush to improve health and happiness of cows. *Targeted News Service; Washington, D.C*. pp. 1-2.

MS Schippers. (2018). MS cow brush rotating cattle brush. Retrieved from https://www.msschippers.com

Newby, N., Duffield, T., Pearl, D., Leslie, K., Leblanc, S., & Keyserlingk, M. (2013). Use of a mechanical brush by Holstein dairy cattle around parturition. *Journal of Dairy Science, 96*(4), 2339-2344. doi:10.3168/jds.2012-6016

Owen, M. (2016). Diverse approaches to herbicide-resistant weed management. *Weed Science, 64*, 570-584. doi:10.1614/ws-d-15-00117.1

Özgen, M., Palta, J., & Smith, J. (2002). Ripeness stage at harvest influences postharvest life of cranberry fruit: physiological and anatomical explanations. *Postharvest Biology and Technology, 24*(3), 291-299. doi:10.1016/s0925-5214(01)00154-5

Peel, G. (2002). A general theory for channel brush design for street sweeping. (Doctor of Philosophy dissertation). University of Surrey, UK.

Pesticide Risk Reduction Program (PMRA). (2005). *Crop profile for wild blueberry in Canada. Annual report, Agriculture and Agri-Food Canada.* Retrieved from http://www4.agr.gc.ca/resources/prod/doc/prog/prrp/pdf/blueber ry_e.pdf

Pitt, R., Bannerman, R., & Sutherland, R. (2004). The role of street cleaning in stormwater management. *Critical Transitions in Water and Environmental Resources Management*. doi:10.1061/40737(2004)58

Pullen, D., & Cowell, P. (1997). An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. *Journal of Agricultural Engineering Research, 67*(1), 27-34. doi:10.1006/jaer.1997.0148

Ramacher, B. (1987). Trash separator for nut harvester. U.S. Patent. No. 4642977.

Rehman, T. (2017). *Development of a machine vision based weed (goldenrod) detection system for spot-application of herbicides in wild blueberry cropping system*. (Master of Science dissertation). Dalhousie Faculty of Agriculture, Canada.

Rhodes, M. (1980). The maturation and ripening of fruits. *CRC Press*, Boca Raton, FL, pp. 157–205.

Rosca, I., Butsch, M. (2016). Theoretical considerations on sweeping process. *Mechanics of Solids, Acoustics and Vibration Conference Proceedings*, ROU, 40, 306-312. Retrieved from http://icmsav.utcluj.ro/pub.html

Schieffer, J., & Dillon, C. (2015). The economic and environmental impacts of precision agriculture and interactions with agro-environmental policy. *Precision Agriculture, 16*(1), 46-61. doi:10.1007/s11119-014-9382-5

Schindelin, J., Rueden, C., Hiner, M., & Eliceiri, K. (2015). The ImageJ ecosystem: an open and extensible platform for biomedical image analysis. *Molecular Reproduction and Development, 82*, 518-529. doi:10.1364/microscopy.2018.mth2a.3

Schukken, Y., & Young, G. (2009). *Field study on milk production and mastitis effect of the DeLaval Swinging Cow Brush.* Retrieved from Novanet database

Shuknecht, L., & Shuknecht, D. (1994). Harvesting apparatus using pressurized air and improved blower for providing pressurized air. U.S. Patent No. 5376046.

Sikoriya, S. (2014). *Phenological study and management of red fescue (Festuca rubra) in wild blueberry* (Doctor of Philosophy dissertation). Dalhousie University, Canada.

Soule, H., & Gray, G. (1972). Performance tests for a lowbush blueberry harvester. *Canadian Society of Association Executives Conference Proceedings.* Saskatoon, CAN. 72-316

Stanley, G., & Sousa, R. (1991). Tractor powered nut harvester. U.S. Patent No. 5001893.

Stern, R. (2009). In-row machine weeding shows promise as hand labor replacement. The Grower. Retrieved from www.thegrower.com/Archive/ArticleLanding /tabid/57/Default.aspx?tid=1 &cid=217376&issueid=691.

Studer, H., & Olmo, H. (1976). Evaluation of fruit loss through the cleaning fans of mechanical grape harvesters. *Transactions of the ASAE, 19*(2), 0219-0221. doi:10.13031/2013.35998

Swinkels, P. (2015). Personal communication. Engineer, Doug Bragg Enterprises, Collingwood, Nova Scotia, Canada.

Trevett, M. (1962). Nutrition and growth of the lowbush blueberry. *Maine Agricultural Research Station*. Bulletin, 605.

Trevett, M., & Durgin, R. (1972). Terbacil: A promising herbicide for the control of perennial grass and sedge in unplowed lowbush blueberry fields. *Research in Life Science. 19*(15).

Tribou, M., & Swain, G. (2015). Grooming using rotating brushes as a proactive method to control ship hull fouling. *Biofouling, 31*(4), 309-319. doi:10.1080/08927014.2015.1041021

Uhl, J. & Lamp, B. (1966). Pneumatic separation of grain and straw mixtures. *Transactions of the American Society of Agricultural Engineers, 9*(2), 244-246. doi:10.13031/2013.39940

Vanegas-Useche, L., Abdel-Wahab, M., & Parker, G. (2007). Dynamics of an unconstrained oscillatory flicking brush for road sweeping. *Journal of Sound and Vibration*, 307(3-5), 778-801. doi: 10.1016/j.jsv.2007.07.010

Vanegas-Useche, L., Abdel-Wahab, M., & Parker, G. (2011). Modeling of an oscillatory freely-rotating cutting brush for street sweeping. *DYNA*, *78*(170), 204-213. Retrieved from http://www.scielo.org.co/scielo.php?script=sci_abstract&pid=S0012-73532011000600024&lng=en&nrm=iso&tlng=en

Vanegas-Useche, L., Abdel-Wahab, M., & Parker, G. (2015). Determination of the Rayleigh damping coefficients of steel bristles and clusters of bristles of gutter brushes. *DYNA*, 82(194), 230-237. doi: 10.15446/dyna.v82n194.49647.

Vargas, R., Fischer, W., Kempen, H., Wright, S., Johnson, M., Kerby, T., & Hake, K. (1996). Cotton weed management. *Cotton Production.* 3352, 187-202. Retrieved from https://ucanr.edu/About_ANR/

Vivanco, L., & Bentle, K. (2016, March 31). Street-sweeping season starts Friday (look up your address). *Chicago Tribune*. Retrieved from https://www.chicagotribune.com

Wang, C., & Parker, G. (2014). Analysis of rotary brush control characteristics for a road sweeping robot vehicle. *2014 International Conference on Mechatronics and Control (ICMC)*. doi:10.1109/icmc.2014.7231871

Weatherbee, L., & Weatherbee, B. (1999). Blueberry harvester. U.S. Patent No. 6000203.

White, S., & Boyd, N. (2016). Effect of dry heat, direct flame, and straw burning on seed germination of weed species found in lowbush blueberry fields. *Weed Technology, 30*(01), 263-270. doi:10.1614/wt-d-15-00103.1

Wilding, L. (1985). Spatial variability: Its documentation, accommodation and implication to soil surveys. *In:* D.R. Nielsen and J. Bouma (Ed.) *Soil Spatial Variability. Proc. of a workshop of ISSS and SSA Las Vegas, USA*. pp. 166-189. Pudoc Wageningen, Netherlands. Centre for agricultural publishing and documentation

William, L., Long, Z., & Rawlins, P. (1970). Cotton harvester with means for separating mature cotton from green balls and debris. U.S. Patent No. 3530652.

Wood, G. (2004). The wild blueberry industry—past. *Small Fruits Review, 3*(1-2), 11-18. doi:10.1300/j301v03n0103

Wood, M. (2018). Personal communication. Process Manager, Oxford Frozen Foods, Oxford, Nova Scotia, Canada.

Wyllie, D. (2015). Personal communication. Farm Manager, Bragg Lumber Company, Debert, Nova Scotia, Canada.

Yacht shop. (2018). Scrubbis groovy cleaning head. Retrieved from https://shop.yachtshop.ca

Yarborough, D. (1991). Progress towards the development of a mechanical harvester for wild blueberries. *Fact Sheet No. 226. University of Maine Cooperative Extension.* Retrieved from http://umaine.edu/blueberries/factsheets/production/progress towards-the-development-of-a-mechanical-harvester-for-wildblueberries/

Yarborough, D. (2006). Innovations in weed management in wild blueberry fields in maine. *Acta Horticulturae,* (715), 197-202. doi:10.17660/actahortic.2006.715.28

Yarborough, D. (2013). Wild Blueberry. *University of Maine Cooperative Extension. Orono, Maine.* Retrieved from http://umaine.edu/blueberries/newslette rs/wild-blueberrynewsletter-january-2013/

Yarborough, D., & Bhowmik, P. (1993). Lowbush blueberry-bunchberry competition. *Journal of the American Society for Horticultural Science,* 118(1), 54-62. Retrieved from http://journal.ashspublications.org/content/118/1/54.abstract

Yenish, J., Doll, J., & Buhler, D. (1992). Effects of tillage on vertical distribution and viability of weed seed in soil. *Weed Science*, 40(3), 429–433. doi:10.1017/s0043174500051869

Zaman, Q., Percival, D., Gordon, R., & Schumann, A. (2009). Estimation of wild blueberry fruit yield using digital color photography. *Acta Horticulturae,* (824), 57-66. doi:10.17660/actahortic.2009.824.6

Zaman, Q., Schumann, A., Percival, D., & Gordon, R. (2008). Estimation of wild blueberry fruit yield using digital color photography. *Transactions of the American Society of Agricultural and Biological Engineers,* 51(5), 1539-1544. doi:10.13031/2013.25302

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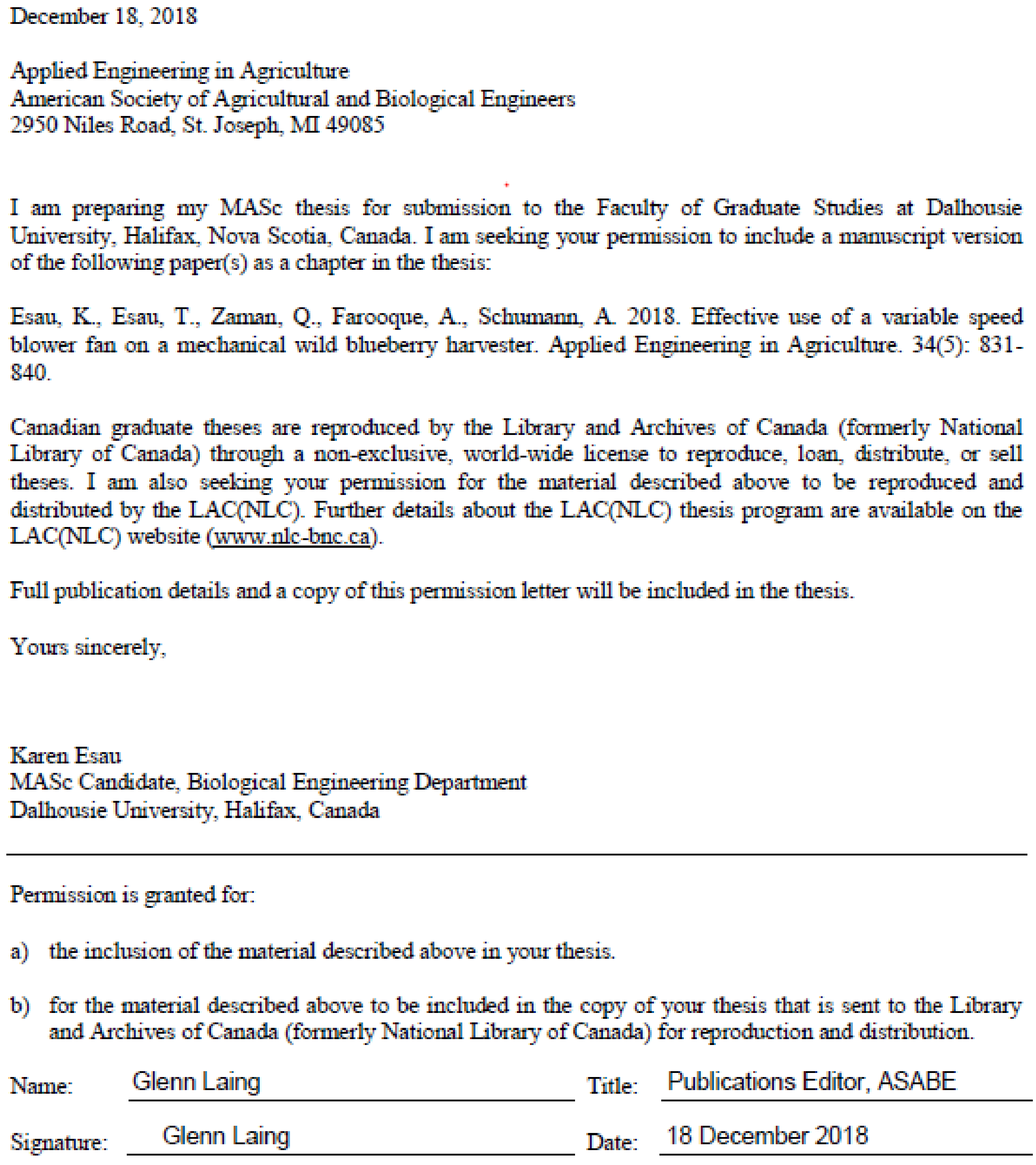

December 18, 2018

Applied Engineering in Agriculture
American Society of Agricultural and Biological Engineers
2950 Niles Road, St. Joseph, MI 49085

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Esau, K., Esau, T., Zaman, Q., Farooque, A., Schumann, A. 2018. Effective use of a variable speed blower fan on a mechanical wild blueberry harvester. Applied Engineering in Agriculture. 34(5): 831-840.

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Yours sincerely,

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