Optimizing Wild Blueberry Fruit Quality during Harvest

Project Report
Year 2

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Wild Blueberry Producers Association of Nova Scotia

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Executive Summary

Rising production costs have posed challenges for wild blueberry producers. However, producers may benefit by increasing the value of their harvested crop through fresh market sales. Research is necessary to determine optimum meteorological and field conditions required for maximizing fruit quality to remain competitive in the fresh fruit market. Understanding the conditions that optimize wild blueberry fruit quality can guide blueberry producers when harvesting.

This study answers essential questions around i) the acceptable temperature range to harvest berries to maximize fruit quality, ii) the effect of weeds on fruit quality, iii) acceptable berry firmness range during harvest to maximize fruit quality, iv) ideal weather conditions during harvest to maximize fruit quality, and v) the effect of berries stored with and without shades on berry quality. It was hypothesized that an increase in temperature will deteriorate berry quality. Therefore, the objectives of this project were to 1) classify the most critical wild blueberry fruit quality characteristics, 2) adopt/develop novel methods to measure/quantify wild blueberry fruit quality, 3) determine harvesting parameters that optimize wild blueberry fruit quality, 4) develop an economic analysis encompassing fruit quality as a top priority and, 5) develop a factsheet to outline the parameters/conditions to optimize wild blueberry fruit quality during harvesting.

To answer the above questions and meet the project objectives, a field study was conducted in August 2021. Commercial wild blueberries fields were selected in Nova Scotia to collect harvest samples from i) hand-held metal rakes, ii) walk-behind harvester, and iii) a commercial harvester mounted on a tractor (mechanical harvester). Eighteen replications of each method of harvest were analyzed during each of the four temperature ranges referred to as TH-I (≤20 °C), TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥30 °C) from here onward. The replications were repeated in plots with and without hair fescue (*Festuca filiformis* Pourr.), red sorrel (*Rumex acetosella* L.), and narrow-leaved goldenrod (*Euthamia graminifolia* (L) *Nutt*.) weeds during the clear sky and dry cloudy conditions.

Temperature (ambient air, berry fruit surface, leaf surface, and soil) values, weed density, berry plant density, berry plant height, berry fruit diameter, fruit firmness, photosynthetically active radiation (PAR) above and below the plant canopy, soil moisture content, weather conditions, and the four quality components of the harvested berries including i) good berries; i.e., berries with no bruises, soft skin and/or foreign materials, ii) bruised berries; i.e., berries with bruises and soft skin, iii) cut-split berries; i.e., poor berries having badly ruptured skin, and iv) debris comprising foreign materials and off-color small or shrunk berries, were recorded during all events of the harvest. Separately for each method of harvest, statistical analyses (including one-way analysis of variance (ANOVA), a paired 2-sample t-test for means, and descriptive statistics considered temperature at harvest and plot conditions (clean versus weedy) as factors of interest and the berry quality components as response variables in addition to other variables listed above. The effects of varying temperatures (of berries directly exposed to the sun versus shaded) on the firmness of momentarily stored berries were also assessed. The results of this study are summarised below and detailed in the body of the report.

Each field had a range of plant variability and harvest yields ranging from 2015±77.8 kg/ha to 12690±184 kg/ha. Therefore, the study results may be considered for fields conditions within the ranges of these yield limits, meteorological variables (TH-I to TH-IV), and plant characteristics presented in the Results and Discussion section.

It was important to ensure uniform conditions within and between the sampling fields to minimize the effects of internal factors of no interest for this research; e.g., berry diameter, plant height, and plant density. The plant height plant density, and berry diameter data showed that there was no bias in the sampling conditions, which provided equal testing conditions for the three methods of harvesting during the four temperature ranges.

Temperatures at harvest had significantly different ambient air temperature, fruit surface temperature, leaf temperature, soil surface temperature, and soil moisture ($P \leq 0.05$). There was no significant effect of the presence of weeds in the harvest plots on any of these variables ($P > 0.05$). The mean temperatures of berry fruit, plant leaf, and soil surface significantly increased with an increase in mean ambient air temperature. The fruit surface temperature was always greater than ambient air temperature during all ranges of temperature at harvest. The leaf and soil temperatures were lower than ambient air temperature below 25 °C and higher than ambient air when above 25 °C. In general, PAR values above and below plant canopy increased with an increase in temperature at harvest and fluctuated with varying cloud conditions. The opposite was true for soil moisture content which decreased with an increase in temperature at harvest.

The optimum temperature for berry harvest was determined by measuring the effects of temperature at harvest on fruit quality components including good berries, bruised berries, cut-split berries, and debris. The temperature at harvest had a significant effect on the berry quality components ($P \leq 0.05$). For hand raking, the acceptable temperature to harvest good quality berries was ≤20 °C when about 82% of good berries were yielded from its harvest. Above 75% good berries were yielded during

TH-II (78.2%) and TH-III (75.9%). TH-IV resulted in the least and significantly fewer good berries than the other three temperatures at harvest.

The acceptable temperature to harvest good quality berries with a walk-behind harvester was ≤20 °C when about 77% of good berries were yielded from its harvest. The temperatures at harvest greater than 20 °C yielded less than 70% good berries, e.g., 68.3% for TH-II, 64.7% for TH-III, and 56.9% for TH-IV. Results of the analysis of mechanical harvester samples revealed that the acceptable temperature for harvesting the good quality berries also remained ≤20 °C. Economic analysis showed harvesting at ≤20 °C had a significantly different and higher income than harvesting at temperature > 20 °C ($P \leq 0.05$) when considering the amount of good quality berries. The income decreased by 8.08, 13.5, and 28.8% while harvesting at TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥ 30 °C), respectively.

Weeds had a significant effect on all quality components of the harvest samples except for debris collected with hand raking. Percent of mean good berries found in the harvest of clean plots was significantly different and higher than their values obtained from the harvest of weedy plots ($P \leq 0.05$). This showed an adverse effect of weeds on berry quality characteristics as good berries decreased and bruised, cut-split berries and debris increased in the harvest samples due to the presence of weeds in the plots.

Other questions included the optimal fruit firmness and ideal weather conditions to maximize fruit quality during harvest. The analysis of the data showed that the acceptable berry firmness during harvest to maximize fruit quality can be considered as 128 – 160 ± 22.2 g/mm. For various cultivars of highbush blueberry, Cappai et al. (2018) reported mean firmness to range from 128 to 183 g/mm. A study conducted at Longaví, Chile reported 1.55-1.60 N firmness of highbush blueberries (*Vaccinium corymbosum* L). Harvesting under dry cloudy conditions produced firmer fruit and less shrink during harvest as compared to harvesting under clear hot weather conditions. This observation was closely linked to lower ambient air temperatures during the cloudy harvesting intervals. For the hand raking, walk-behind harvester and mechanical harvester samples, the observed cloudy conditions versus clear weather conditions produced 81.7 versus 70.8, 74.2 versus 62.5, and 77.5 versus 67.0% good berries, respectively.

The results of the 2-sample t-test to compare the effect of berry storage conditions (i.e., temperatures of unshaded berries versus temperature of those stored under the shade) showed that the mean temperature of berries without a shade (32.1 °C) remained more than one and a half times higher and significantly different than the temperature of berries stored under a shade (i.e., 20.0 °C). The effect of the rise of fruit temperature was also observed on fruit firmness.

The firmness of berries (stored with and without a shade) had a considerable difference during the afternoon hours despite the drop of ambient air temperature in the evening. The data sets of berry firmness of the two storage conditions were also analyzed using a 2-sample t-test to determine if the difference in the fruit firmness of the two storage conditions was statistically significant. From the results of the t-test for the mean comparison of berry temperature and berry firmness under the two storage conditions, it is recommended that to maximize berry quality, the berries are stored under a shade when waiting to be transported to the processing facility instead of keeping them directly under the sunlight.

The temperature at harvest had significant effects on mean values of firmness of good and bruised berries. The mean firmness of good and bruised berries was significantly different and greatly decreased with an increase in temperature at harvest from TH-I to TH-IV for the three methods of harvest. There was no significant effect of plot conditions (clean versus weedy plots) on the firmness of good and bruised berries for all methods of harvest. This may be because the effects of external impacts on the fruit surface do not deteriorate its firmness right after the collusion but the change in berry firmness is a continuous process that may become more relevant after the berries are stored.

The temperature of the temporarily stored berries had a negative power-function effect on the firmness of the stored fruits, i.e., increase in temperature of berries (before their harvest) linearly decreased (R^2 = 0.64) the firmness of the berries (measured right after their harvest). A similar relationship was determined between the fruit firmness and ambient air temperature.

Results of the 2-sample t-test to compare the effect of berry storage conditions (i.e., temperatures of berries stored without a shade versus those stored under the shade) revealed a significant effect of storage conditions of berries on their temperature. The mean temperature of berries stored under the shade (21.3 °C) remained significantly lower than those stored without a shade (33.1 °C). However, the temperature of berries stored without a shade continued rising until it reached even double the temperature of shaded berries (~20 versus 40 °C).

Considering the acceptable firmness of 142 g/mm, the relationship "Temperature = (Firmness – 239)/-4.62" (developed from the pooled data of firmness of berries stored under the shade and ambient air temperature) resulted in about 21 °C, which is in the lower half of TH-II. For optimum quality at harvest, it can be implied that the necessary ambient air temperature can be considered as ≤20 °C (i.e., TH-I) to produce berries of acceptable firmness for the fresh market. A summary of answers to the questions within the scope of this study is tabulated below.

Table 1: Short answers to the fundamental questions on optimizing wild blueberry fruit quality during harvest.

Questions	Answers
What is an acceptable temperature range to harvest to maximize fruit quality?	≤20 °C for all methods of harvesting i.e., hand rakes, walk-behind, and mechanical harvesters.
What effect do weeds (sheep sorrel, goldenrod, fescue) have on fruit quality?	The presence of weeds deteriorates berry quality regardless of the method of harvesting.
What is the acceptable berry firmness range during harvest to maximize fruit quality?	128 – 160 ± 22.2 g/mm
What conditions during harvest help to maximize fruit quality?	Preferably cool cloudy dry field conditions.
What effect do berries stored with and without shade have on berry quality?	The increase in ambient air temperature increases temperature and decreases the firmness of the berries stored without a shade.

Results of the 2021 investigations confirmed the findings of the 2020 study whereby one-way ANOVA of the 2020 data had also shown a significant effect of temperature at harvest on quality components of berries harvested by hand raking or a mechanical harvester. In 2020, the non-significant effect of temperature on berry quality components of the walk-behind harvester was due to the berries not being harvested with this method at all levels of temperature including, at ≥30 °C. Moreover, the three methods of harvesting used different plots each time during 2020; whereas the same plots were used during 2021 for all methods of harvesting in each field. This approach is believed to reduce bias in the harvest data of 2021. The increase in ambient air temperature in 2020 also increased the temperature and deteriorated the firmness of the stored berries regardless of their methods of harvest. Acceptable berry firmness was recorded with a storage temperature below 20 °C during both years. There was also no considerable difference in the shrinkage (i.e., about 20-40%) of berries during 2020 and 2021.

Further investigations are recommended for evaluating different combinations of methods of harvest and temperatures during picking and their effects on chemical components, i.e., nutritious value, of the harvested/stored berries grown in Nova Scotia.

1. Introduction

Nova Scotia's wild blueberries (*Vaccinium angustifolium* Ait.) are a leader among agricultural exports. Together with highbush blueberries (*Vaccinium corymbosum* L.) the lowbush wild blueberries are ranked as the second most economically important berries, after strawberries, in North America (USDA, 2013). Blueberries have a world-class high economic value bearing the title of "the king of berries" (Hu et al., 2006; Nie and Zang, 2014; Li et al., 2015; Zhang et al., 2015). They contribute to a healthy diet with different beneficial bioactive compounds such as flavonoids with multiple phytonutrients (Lila, 2004; Wang et al., 2005), which help to avoid dangerous human diseases including different cancers (IARC, 2003; WCRF/AICR, 2007). With antioxidant capacity, blueberry fruits are rich in anthocyanins and low in sugar and fat (Kalt et al., 2020).

Wild blueberries grow to an approximate height of 25 cm and thrive in the colder regions of northern North America (Farooque et al. 2020). Smaller in size than the highbush blueberries, wild blueberries have consistently higher anthocyanins, total phenolics, and antioxidant capacity than the highbush blueberries (Kalt et al., 2001). Atlantic Canadian provinces and Quebec are exemplary in wild blueberry cultivation (Yarborough et al., 2004). Some of the wild blueberry fields in Nova Scotia are inundated with weeds. According to Lyu et al. (2021), the common wild blueberry field weeds include red sorrel (*Rumex acetosella* L.), poverty oatgrass (*Danthonia spicata* L. *Beauv.*), haircap moss (*Polytrichum commune Hedw.*), hair fescue (*Festuca filiformis Pourr.*), narrow-leaved goldenrod (*Euthamia graminifolia* (L) *Nutt.*), tickle grass (*Agrostis hyemalis* (Walter) BSP.), woolly panicum (*Panicum lanugosum Ell.*), cow wheat (*Melampyrum lineare Desr.*), bunchberry (*Cornus canadensis* L.), and yellow hawkweed (*Hieracium caespitosum Dumort*).

The cultivation of the wild blueberries differs from other fruit crops in numerous ways as they are not planted but developed from deforested farmlands (Trevett, 1962). Therefore, the unleveled topography of the Nova Scotia farmlands poses challenges during the harvesting of the wild blueberries (Zaman et al., 2010). These challenges range from uneven walking of the workers while harvesting the berries with hand rakes to the obstacles in the smooth running of harvesting machines in the fields (Hall, 1955). Furthermore, harvesting with hand-held metal rakes is highly labor-intensive and requires round-the-clock personnel to complete harvesting within the short span of the harvesting season of wild blueberry. The presence of weeds in blueberry fields poses challenges during the harvesting of berries. Biomass from weeds gets stuck in the harvesters' teeth, interacts with the fruits, and damages the fruit quality during harvest.

About 90% of the total wild blueberry crop area in Canada is mechanically harvested and the remaining berries are harvested with a metal-based hand rake (Ali, 2016). Mechanical harvesters started replacing hand raking during the early 1950s (Kinsman, 1993) with the major underlying factors including high labor costs, short quality of labor, and short harvesting seasons (Yarborough, 1992). Hall et al. (1983) reported that numerous mechanical harvesting systems had been developed to improve berry recovery and reduce harvesting losses, but a viable commercial machine was not adopted until the 1980s due to the low stature of plants, uneven field topography, and the presence of weed species, which present formidable obstacles to mechanical harvesters (Yarborough, 2002). Therefore, operators of the harvesters keep their picker teeth clean of weed/plant biomass to reduce berry loss and damage.

A two-wheeled manually pushed but motor-operated walk-behind blueberry harvester is another mechanically operated harvesting tool. It is commonly equipped with a series of teeth that revolve around a rotary header that is pushed through the berry plants at a walking pace. Harvested berries are conveyed into a replaceable storage bin located between the push handles of the harvester. Darlington cranberry harvester was modified for wild blueberry harvesting (Dale et al., 1994) but due to the limitations of unresolved difficulties in field terrain, the developed harvester had a harvest efficiency of only 56% (Yarborough, 1992). Dale et al. (1994) indicated that a successful harvester was developed by Doug Bragg Enterprises (Collingwood NS, Canada) in 1979. This harvester picked 68% berries in weedy fields and 75% in well-managed fields (Hall et al., 1983).

Two basic concepts during the postharvest decision making include 1) the fruit is alive and responsive to its environment and, 2) the fruit's quality potential never increases after the fruit has been picked (Beaudry, 1992). A high storage temperature develops a bitter taste and storage flavor in the stored samples (Rosenfeld et al., 1999). Good quality harvested fruit may sustain such external effects to a certain extent. Definition of good fruit quality includes firm, clean, dry, and damage-free fruit. Good quality fruit is especially susceptible to mechanical damage, with injured berries resulting in loss of firmness leading to reduced fruit quality and shelf-life (Xu et al., 2015).

Field conditions such as the presence of weeds as well as the meteorological variables and their concurring impacts, and the harvesting methods affect the quality of the harvested berries (Yarborough, 1994). In most crops, the prevailing meteorological conditions, particularly ambient air temperature, relative humidity, and solar radiation, are critical determinants of the levels of health-promoting compounds and should be considered when planning optimal harvesting dates for a specific area and specific crops (Kårlund et al., 2014). Prevailing meteorological conditions of a region may affect differently to the quality of the harvest. Several factors associated with the time of day can influence the physiology and postharvest quality of horticultural commodities (Edgley et al., 2019). Meteorological and environmental variables such as temperature, sun exposure, humidity, and moisture content have all been reported to affect firmness and bruise susceptibility across a range of horticultural commodities including strawberries, apples, and apricots (Paull, 1999; Sams, 1999; Hussein et al., 2018). Paniagua et al. (2013) reviewed the causes of deterioration of blueberry firmness and concluded that the mechanisms defining postharvest firmness changes in blueberries are not completely understood, although fruit moisture loss (Forney et al., 1998), skin toughness, presence of stone cells (Bunemann et al., 1957; Allan-Wojtas et al., 2001) and cell wall modifications (Allan-Wojtas et al., 2001; Angeletti et al., 2010) have been related to this phenomenon. All the causes mentioned by Paniagua et al. (2013) are related to weather/temperature conditions and mechanical impact on berry surface during harvest.

Unlike for harvesting of several fruits and vegetables, very limited research has been done to evaluate proper harvesting techniques and conditions for wild blueberries in relation to fruit quality. Weather and field conditions have less of a burden on operator comfort with the advancement of mechanized harvesting and cabbed tractors with climate control. Literature has suggested that harvesting in wet conditions results in reduced harvesting efficiency (Zaman, n.d.). A report published by Zaman (n.d.) on precision harvesting technologies to improve berry yield and quality summarizes work on developing i) sensor fusion system for quantification of blueberry fruit yield losses and ii) models for identification of sources of losses to improve harvesting efficiency to increase fruit yield. Extensive literature search has revealed that limited work has been done to understand the factors that dictate berry quality. Harvest of wild blueberries is highly time-sensitive requiring several operators working through sub-par environmental conditions to get the job done. Nonetheless, rising production costs, adverse weather conditions, and fluctuating farm gate prices have decreased the profit margins for wild blueberry growers. However, farmers may benefit from efforts with increasing the berry field price by entering the fresh fruit market to increase their profit margins.

Performance of the harvesting methods has been assessed with emphasis on improving and/or automation of blueberry harvesting technology (see Farooque et al. 2020 and the references therein) but the effects of meteorological variables (e.g., the temperature at harvest (TH) during events of harvesting) and plant characteristics (e.g., presence of weeds, berry fruit surface temperature, plant leaf temperature, plant height, plant density, weed density, fruit firmness, and fruit diameter) soil properties (soil moisture content and soil temperature), and weather conditions on the quality of berries harvested with different methods have yet to be fully explored. Numerous other factors of interest such as on-field storage conditions of berries and their impact on berry quality have not been studied and/or reported in the literature.

Research is needed to understand and benchmark the parameters that help to maintain berry quality while factors and conditions that reduce berry quality need to be realized and quantified. It was hypothesized that TH, weed presence, and the fruit storing temperature will deteriorate various berry quality characteristics. It was further hypothesized that shading the harvested fruit will restrict them from being heated from solar radiation. Therefore, the objectives of this project were to:

1) classify the most critical wild blueberry fruit quality characteristics,
2) adopt/develop novel methods to measure/quantify wild blueberry fruit quality,
3) determine harvesting parameters that optimize wild blueberry fruit quality,
4) develop an economic analysis encompassing fruit quality as a top priority and,
5) develop a factsheet to outline the parameters/conditions to optimize wild blueberry fruit quality during harvesting.

Through a scientific analysis of multiple harvesting techniques coupled with different meteorological, environmental, plant, and management parameters this project aimed at achieving the project objectives and aiding the wild blueberry farmers, processors, and stakeholders in making informed decisions when pursuing harvesting wild blueberries for fresh market by answering the following questions.

1) What is an acceptable temperature range to harvest to maximize fruit quality?
2) What effect do weeds (sheep sorrel, goldenrod, fescue) have on fruit quality?
3) What is the acceptable berry firmness range during harvest to maximize fruit quality?
4) What are the suitable weather conditions during harvest to maximize fruit quality?
5) What effect do berries stored with and without shades have on berry quality?

It was important to ensure that all the data collection arrangements and conditions were unbiased among the methods of harvest (i.e., hand raking, and harvesting with a walk-behind and a mechanical harvester) and similar throughout the study (i.e., during all the temperatures at harvest events). Therefore, the data were carefully collected to avoid bias across the dataset.

2. Materials and Methods

2.1 The Study Sites

This study was conducted during the 2021 harvesting season of wild blueberry in various fields of Nova Scotia located in Middle Musquodoboit, Portapique, and New Glasgow. These fields were well managed but had instances of common weed infestations including hair fescue, red sorrel, and narrow-leaved goldenrod (Fig. 1).

(a) (b) (c) (d)

Figure 1: Images of (a) clean field sections versus areas affected with (b) hair fescue (Festuca filiformis Pourr.), (c) red sorrel (Rumex acetosella L.), and (d) narrow-leaved goldenrod (Euthamia graminifolia (L) Nutt.) weeds.

2.2 Sampling Plots, Tools, and Methods

Sampling plots were flagged for harvesting with the hand rakes, walk-behind, and mechanical harvester (Fig. 2). Five meters long plots were needed for data collection with the mechanical harvesting method. The length (5 m) and width (1.69 m) of plots were based on the time of travel of the harvested berries to be transported to the rear storage tote of the mechanical harvester. Harvest samples of the hand raking method and walk-behind harvester were collected from the same plots.

(a)

(b)

(c)

Figure 2: The tools and methods used to harvest wild blueberries included (a) hand-held metal rake, (b) manually controlled but a motor-operated walk-behind harvester and (c) a Doug Bragg Enterprises mechanical harvester mounted on a farm tractor.

Harvesting was conducted with three methods namely hand-held metal rakes (Fig. 2a), manually controlled but a motor-operated walk-behind (push-type cart of 0.8 m head width) harvester (Fig. 2b) developed by Maine Blueberry Equipment Co. (Columbia Falls, Maine 04623, United States), and a Doug Bragg Enterprises double head mechanical harvester (Collingwood, Nova Scotia, Canada) mounted on an agricultural farm tractor (Fig. 2c) with the harvester picking width of 1.69 m.

2.3 Temperature at Harvest

Berry data was collected from multiple replications of hand raking and harvests of walk-behind and mechanical harvesters during four temperature ranges namely TH-I (≤20 ºC), TH-II (20.1-25 ºC), TH-III (25.1-29.9 ºC), and TH-IV (≥30 ºC) in clean and weedy plots (Table 2). Each of the four temperatures at harvest (i.e., TH-I: 8:30 am-11:00 am, TH-II: 11:00 am-1:30 pm, TH-III: 1:30 pm-4:00 pm, and TH-IV: 4:00 pm-6:30 pm) events had 6 to 9 harvesting events for the three methods of harvesting totaling to 92 and 83 replications from clean and weedy plots, respectively.

Table 2: Ambient air temperature (˚C) and total replications during the data collection events from clean and weedy plots for the four temperature at harvest ranges (TH-I to TH-IV).

Temperature at harvest	Temperature range, ºC	Clean plots	Weedy plots
TH-I	≤20	14.9, 17.0, 18.1, 18.3, 18.2, 18.5, 19.8, 19.9, 20.0	14.9, 17.0, 18.1, 18.3, 18.5, 19.8, 19.9, 20.0
TH-II	20.1-25	20.1, 20.4, 20.6, 20.7, 21.6, 23.3, 23.5	20.1, 20.4, 20.5, 21.6, 23.9, 23.5, 23.9
TH-III	25.1-29.9	25.5, 26.9, 27.2, 27.7, 28.0, 28.5, 29.1	26.9, 27.1, 27.2, 27.7, 28.0, 28.5, 29.1, 29.4
TH-IV	≥30	30.3, 30.5, 31.0, 31.1, 31.5, 31.9	30.3, 30.5, 31.1, 31.0, 31.9, 32.3,
Total replications for each temperature at harvest		28[TH-I], 20[TH-II], 20[TH-III], 24[TH-IV] = 92	25[TH-I], 21[TH-II], 21[TH-III], 18[TH-IV] = 85

2.3.1 Weather station

For local and precise measurement of the prevailing temperature of the harvesting events, a stand-alone portable weather station (HOBO U30-NRC-SYS-C; Onset, Hoskin Scientific, Saint-Laurent QC, Canada) was installed at each sampling site (Fig. 3). The readings for meteorological variables were recoded, on data sheets, for the specific time of sampling in addition to downloading time-series data from the datalogger of the weather station.

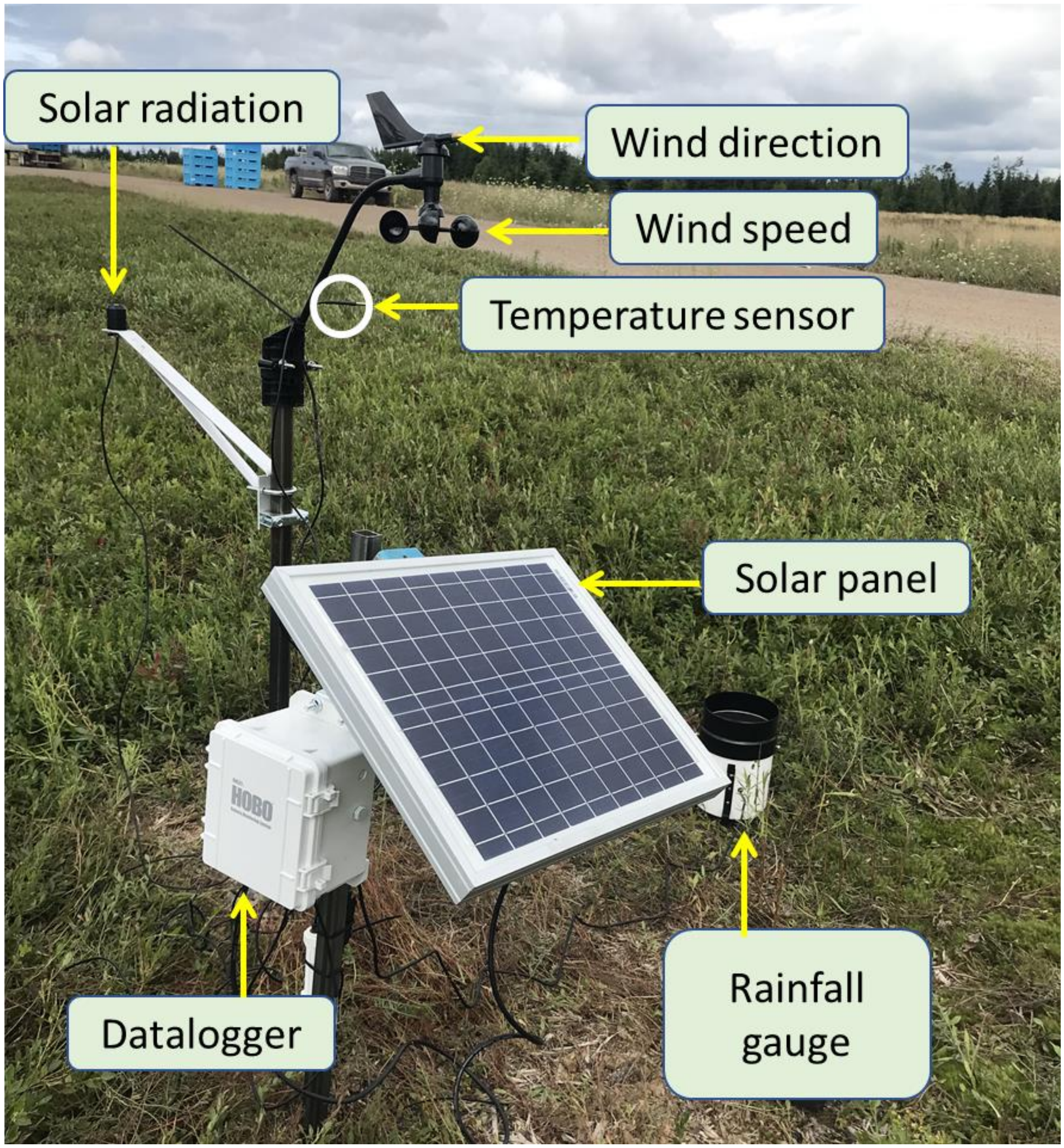

Figure 3: A portable weather station installed at the Middle Musquodoboit, NS field for real-time recording of the meteorological variables.

2.4 Pre-harvest Sampling

2.4.1 Temperature of fruit on plant and soil

A FLIR ONE (Oregon, US) thermal imaging camera was used to determine the temperature of the plot soil, berry surface, and plant leaves before each harvesting event (Fig. 4). The camera was operated via the FLIR ONE App (Version 4.2.0) of an IOS system. Temperature measurements were taken while the fruit was on the plant before its harvest (Fig. 4a) with the help of the thermal imaging camera (Fig. 4b). Screen shots of the soil and fruit temperature captured from the screen (Fig. 4c) with a zoomed-in close view are shown in Fig. 4d. Lower temperatures are shown in blue, and higher temperatures are displayed in red.

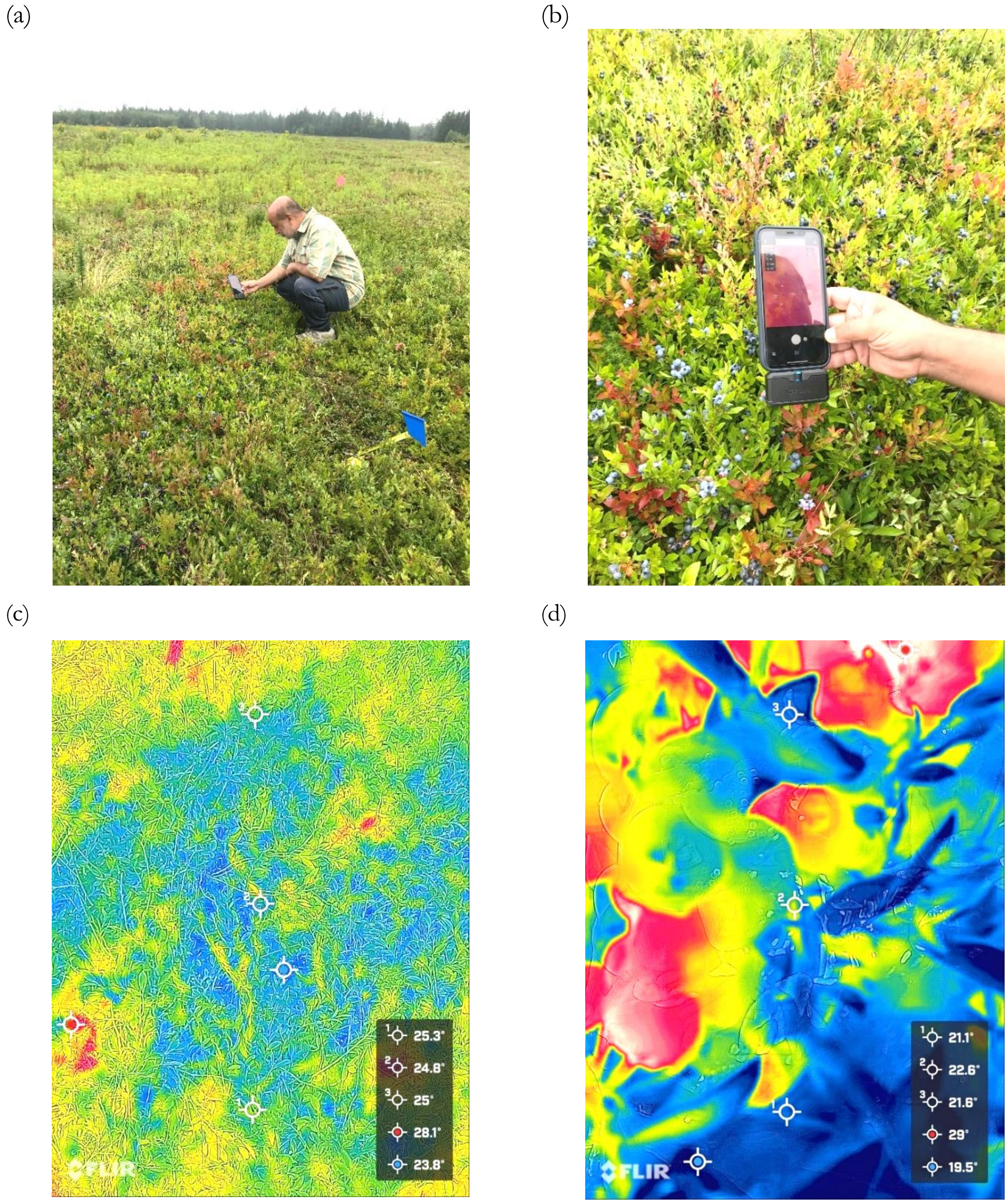

Figure 4: Measurement of berry temperature while the fruit was on the plant before its harvest (a) with the help of FLIR ONE thermal imaging camera connected with a smartphone (b). Screen shots of the soil and fruit temperature were captured from the phone screen (c) with a zoomed-in close view(d). Lower temperatures are shown in blue, and higher temperatures in red.

2.4.2 Plant density and height measurements

Four measurements of plant density (number of plants per unit area) and weed density (in case of harvesting from weedy plots) were also made from each plot using a 15 cm × 15 cm wooden quadrat (Fig. 5a). Four values of plant height were also taken from each plot using a measuring tape (Fig. 5b).

(a)

(b)

Figure 5: Determining (a) plant density with the help of a 15 cm × 15 cm wooden quarter and (b) plant height using a measuring tape.

A Time Domain Reflectometry probe TDR-300 (Spectrum Technologies, Aurora IL, USA) measured four readings of soil moisture levels (Fig. 6a), which were averaged for the plot/replication. An external photosynthetically active radiation (PAR) sensor was used to measure PAR above and below the plant canopy (Fig. 6b). The PAR sensor (ACCUPAR LP 80, METER Group Inc. Pullman, USA) used in this study had a resolution of 1 $\mu mol/m^2s$ and accuracy of ±5% for the measuring range of PAR from 0 to 4000 $\mu mol/m^2s$. Photosynthetically active radiation has wavelengths of 400-700 nm and is the portion of the light spectrum utilized by plants for photosynthesis. This spectral region corresponds closely with the range of light visible to the human eye.

(a) (b)

Figure 6: Determining of (a) soil moisture levels with a Time Domain Reflectometry probe TDR-300 and (b) photosynthetically active radiations (PAR) above and below the plant canopy using a PAR external sensor.

2.4.6 Berry fruit sampling from three methods of harvest

Berry fruit samples were collected from the harvest of three methods of harvesting (Fig. 7). The samples were collected from clean and weedy plots. For each harvesting method and/or the specific replication of the three harvesting methods, the same plots were used to collect fruit samples. The samples were collected with the three harvesting methods within the same time interval of each event to avoid the effects of varying internal and external factors.

2.5 Post-sampling Measurements

The harvested berries were immediately transferred to the temporary setups made for segregating the samples to the four components of harvest quality including i) good blueberries acceptable for fresh market, ii) bruised berries, iii) cut-split berries that were poor in quality due to badly ruptured skin, and iv) debris that comprised all foreign materials, such as plant stems, soil particles, and off-color small or shrunk berries. (Fig. 8). The individual components i, ii, iii, and iv segregated from the raw/composite harvest sample (Fig. 9) were carefully poured into an empty container that was zeroed on a battery-operated scale prior to weighing (Fig. 10). Weights of individual components were then divided by the total weight of the raw sample and multiplied by 100 to obtain percent values of individual components.

Figure 7: Collection of berry harvest samples with (a) walk-behind manually operated harvester (b) hand raking, and (c) Doug Bragg Enterprises mechanical harvester.

Figure 8: Temporary arrangements for segregating raw harvest samples into i) good berries, ii) bruised berries, iii) cut-split berries, and iv) debris.

Figure 9: A harvested raw sample of wild blueberries (left) from weedy patch segregated into A) good berries (berries without any bruise and/or foreign materials), B) bruised berries having soft and/or damaged skin, C) cut-split berries (poor berries having badly ruptured skin), and D) debris comprising foreign materials and off-color small or shrunk berries.

(a) (b)

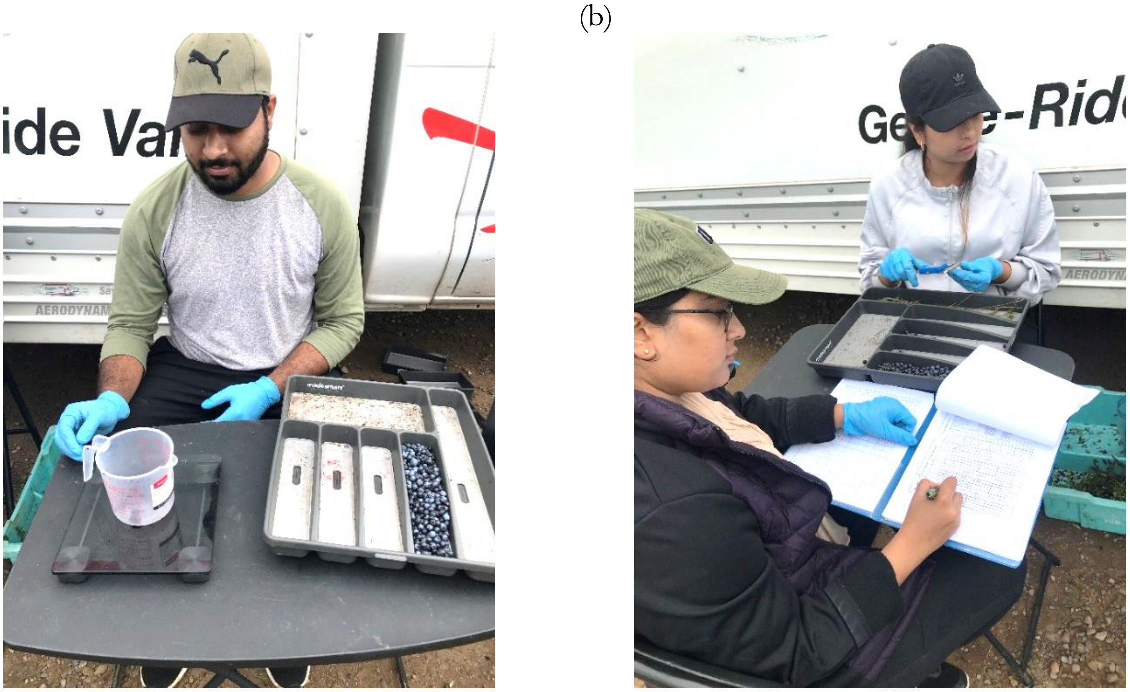

Figure 10: Precise weighing of berry quality contents including i) good berries, ii) bruised berries, iii) cut-split berries, and iv) debris) and recording of measurements on a field data sheet.

A digital vernier caliper (Mastercraft; Part Number: 058-6800-4) and a FruitFirm 1000 (CVM Inc. 7066-D Commerce Circle Pleasanton, CA 94588, USA) were used to measure the diameter and firmness of good and bruised berries, respectively (Fig. 11). The FruitFirm device measures firmness of two berries at a time and reports the average of the two values in the firmness units of mm/g. Mean values of fruit diameter and firmness were computed by taking an average of five readings per replication separately for the three methods of harvest and TH.

Figure 11: A vernier caliper (top) and FruitFirm 1000 instrument (bottom) to measure fruit diameter and firmness, respectively.

Berry yield samples were collected using a 0.5 m^2 sampling quadrat separately in all sampling fields from representative patches of the low, medium, and good yielding parts of the field, and the yield was converted to kg/ha to determine the range of yield from the study fields (Fig. 12).

(a)

(b)

(c)

Figure 12: Random measurement of fruit yield using a 0.5 m^2 sampling quadrat in representative a) high, b) medium, and c) low yielding patches of a field.

2.6 Effect of Post Harvest Field Berry Temperature on Fruit Firmness

The impact of varying temperatures on berry firmness was also assessed to understand the effect of temporarily storing the harvested berries without a shade (Fig. 13a) and the shade (Fig. 13b). The goal was to develop a relationship of berry firmness with fruit temperature to help growers make informed decisions based on the field storing the harvested berries before shifting the harvest to processing plants. The temperature of the unshaded and shaded berries was continuously recorded at intervals of 15 minutes using a datalogger (WatchDog 1000, Micro station) using a temperature sensor (Spectrum Technologies, Aurora, IL 60504) buried 5 cm below the surface in the center of the storage tote placed under the shade and in direct sunlight (Fig. 13c). The berry surface temperature of these totes was also intermittently measured with the help of FLIR ONE thermal imaging camera to obtain surface temperature after every 15-20 minutes (Fig. 13d). The berry temperature and firmness data were pooled to understand the effect the increase in temperature had on fruit firmness.

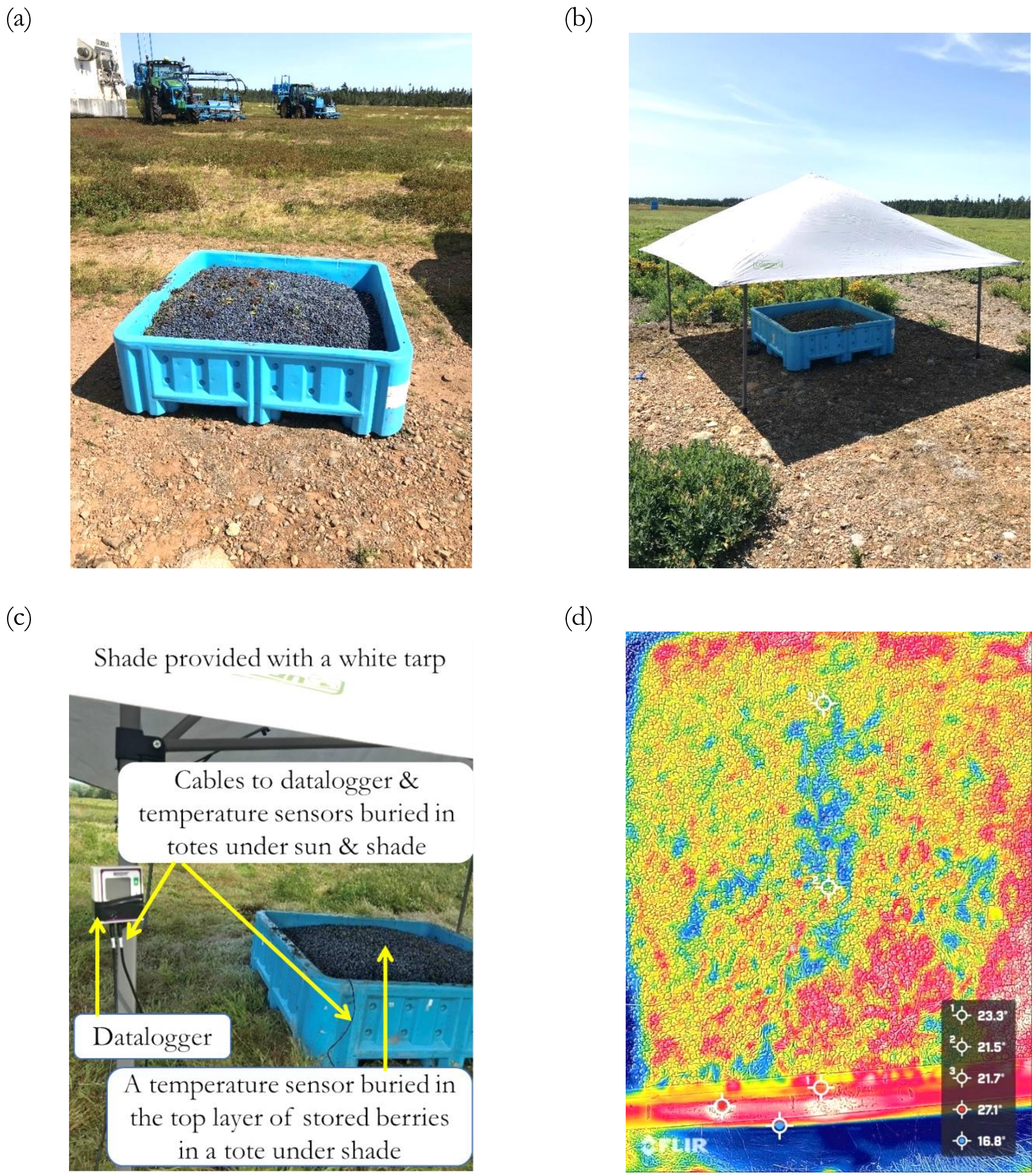

Figure 13: Berries kept (a) under without a shade and (b) under the shade to determine the effect of solar radiation on berry temperature measured with (c) a temperature sensor attached to a datalogger and buried in the center of the tote and (d) FLIR ONE thermal imaging camera.

2.7 Drone-assisted Data

In the modern era, drones have been used for field data collection. The information from drone-assisted / remotely sensed data can be plotted as field maps to extract elevation information that allows researchers to study field variability caused by factors affected by field topography. Remotely sensed imagery was captured using a DJI M300 RTK Drone (Simmons Blvd. Brampton, L6V 3W5, ON, Canada) to produce a digital elevation model of fields for relating changes in the soil and crop properties with the topography of the fields. Agisoft Metashape software is a stand-alone software product to perform photogrammetric processing of digital images and generate 3D spatial data used to process drone-captured data. Field imagery was captured at 60 m above ground level with 75 percent side and frontal overlap.

A MicaSense Altum camera (1300 N Northlake Way Suite 100, Seattle, WA 98103, USA) that combines a radiometric thermal camera with five high-resolution narrow bands, producing high-resolution multispectral and advanced thermal imagery in one flight for advanced analytics was connected with the drone and calibrated before the flight (Fig. 14). The drone was flown for aerial image acquisition (Fig. 15). Field images captured with the calibrated sensor were then processed to produce thermal and normalized difference vegetation index (NDVI) maps of the blueberry research fields.

(a) (b)

Figure 14: A drone MicaSense Altum sensor connected with a drone (a) was calibrated (b) prior to and after each flight.

(a) (b)

Figure 15: A google image of the whole field bordered red (a), coverage for drone flight shown in green lines, and (b) a 2D view of the area of the flight coverage.

2.8 Data Analysis

An economic analysis was conducted to determine the effect of temperature at harvest on the income of farmers based on the collection of good quality fruit. The effects of temperature at harvest on the farmers' income were evaluated by constructing a one-way analysis of variance (ANOVA) using Minitab 19 (State College, Pennsylvania State University, PA: Minitab, Inc.). The average yield of blueberries was used to convert percent values of good berries and shrinkage (the sum of bruised berries, cut-splits, and debris), calculated from data of the three methods of harvest and the four temperatures at harvest, into yield (kg/ha) of good berries and shrinkage. Farm income was calculated by considering the berry field rate of $1.76 /kg for selling good berries to the processing units.

One-way ANOVA was also conducted for evaluating the significance of mean difference among the berry quality components including the good, bruised, cut-split, and debris under the effects of temperature at harvest and weeds separately for each method of harvest (i.e., hand raking, walk-behind harvester, and mechanical harvester). The two factors of interest (i.e., the temperature at harvest and plot conditions) had four levels of temperature at harvest including TH-I, TH-II, TH-III, and TH-IV, and two types of plot conditions, i.e., clean versus weedy plots, respectively. Means of meteorological, plant, field, and fruit variables were compared for the weather and plot conditions using one-way ANOVA. The meteorological, fruit, plant, and field variables included ambient air temperature, fruit diameter, fruit firmness, PAR above and below the canopy, fruit surface temperature, berry plant leaf temperature, plant density, soil surface temperature. It is pertinent to mention here that the berries were not harvested under wet conditions Harvesting took place only during sunny and/or dry cloudy conditions depending upon the prevailing weather. The two plot conditions compared weedy to clean plots. The impact of varying temperature on the firmness of berry was also assessed to understand the effect of temporarily storing the harvested berries with and without shades before transport to the fruit processing/packing facilities.

The ANOVA determined the difference between the means of response variable at 95% confidence level for their significant difference $P \leq 0.05$. Since sample size varied due to uncontrolled bulk sampling during the use of hand rakes and the moving harvesters; therefore, the percent values of the four berry quality components were calculated on a weight basis from the total weight of the composite sample and the individual weights of the four quality components. The percent means were then used to construct ANOVA, while significantly different means were separated with Fisher's Least Significant Difference (LSD) letters. Significantly different ($P \leq 0.05$) means were labeled with different LSD letters and non significantly different ($P > 0.05$) means were labeled with similar or combinations of LSD letters. A paired 2-sample t-test for means and descriptive statistics was also used to statistically compare the means of the two sets of data of temperature and firmness for their difference under the impacts of meteorological variables and factors of interest.

3. Results and Discussion

Data collected was analyzed and results are discussed in this section to address five important questions including i) acceptable temperature range to harvest fields for maximizing fruit quality, ii) if the weeds (sheep sorrel, goldenrod, fescue grass) affect fruit quality during harvest, iii) the acceptable berry firmness range during harvest to maximize fruit quality, iv) the ideal weather conditions to harvest berries to maximize fruit quality, and vi) the effect of berries stored with and without a shade on berry quality. Section 3.1 is based on results about meteorological conditions when the berries were harvested, plant height and density, fruit size, and soil conditions. Answers to the stated questions (discussed in Sections 3.2-3.6) have been evaluated under the impacts of two factors of interest including i) the temperature at harvest and ii) plot conditions (clean versus weedy).

3.1 Meteorological, Plant, and Fruit Conditions

3.1.1 Meteorological variables

The temperature at harvest was based on ambient air temperature. The mean temperature values for TH-I, TH-II, TH-III, and TH-IV were 17.5, 22.0, 27.3, and 31.8 ^{o}C, respectively (Tables 3). The mean PAR values above the plant canopy during TH-I, TH-II, TH-III, and TH-IV were 1025, 1463, 1007, and 1234 μmol/m^{2}s, respectively. Below canopy mean PAR values during TH-I, TH-II, TH-III, and TH-IV were 206, 178, 195, and 187 μmol/m^{2}s, respectively. The PAR did not follow the trends of temperature at harvest because of the effects of the presence of clouds during various events of TH. Clouds reduce PAR by interacting the solar radiations with aerosol particles (Yamasoe et al. 2006). If the atmosphere is more stable and drier, fewer clouds can be formed producing a semi-direct aerosol effect (Hansen et al., 1997; Koren et al., 2004).

Table 3: Summary of the data of mean ambient air temperatures (°C) and photosynthetically active radiations (PAR) above and below plant canopy (μmol/m2s) recorded during sampling intervals of temperature at harvest TH-I (≤20 °C), TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥30 °C).

Temperature events	T_{min}-T_{max}	T_{mean}±SD	PAR-A_{mean}±SD	PAR-B_{mean}±SD
TH-I	14.9-20.0	**17.5**±3.61	**1025**±70.9	**206**±30.2
TH-II	20.1-23.9	**22.0**±2.69	**1463**±76.7	**178**±32.8
TH-III	25.5-29.1	**27.3**±2.55	**1007**±63.5	**195**±20.2
TH-IV	30.3-32.3	**31.3**±1.41	**1234**±68.1	**187**±32.2

T: temperature, min: minimum values, max: maximum values, SD: standard deviation from the mean, PAR-A: above canopy photosynthetically active radiation, PAR-B: below canopy photosynthetically active radiation.

3.1.2 Field conditions

The fields of Middle Musquodoboit, Portapique, and New Glasgow had the Nova Scotia representative wild blueberry cultivation and environmental conditions. Their topography varied from flat (Middle Musquodoboit, Portapique) to slopy (New Glasgow). The fields were well managed with scattered weed patches. Analysis of the representative yield samples collected from healthy, normal, and poor patches resulted in the harvest yield ranging from 628 to 641 g per 0.5 m^2 (12690±184 kg/ha), 129 to 314 g per 0.5 m^2 (4425±2623 kg/ha), and 98.0 to 104 g per 0.5 m^2 (2015±77.8 kg/ha). Therefore, the study results may be considered for fields conditions within the ranges of these yield limits. It would be interesting but might be difficult, with the existing experimental design, to determine if the yield of a field (because of thick or thin canopies) also contributed to the effects of temperature at harvest on the harvest quality. Any future endeavor may explore this point.

3.1.3 Plant height and density

No significant differences were found between the mean values of plant height and plant density measured from the clean and weedy sampling plots (Fig. 16). For clean sampling plots, the mean plant height was 19.7 cm. For weedy sampling plots, the mean plant height was 21.3 cm. Similarly, the mean plant densities in clean and weedy plots were ~20 plants per 225 cm^2. This provided equivalent field conditions for the three methods of harvesting during all four temperatures at harvest in both clean and weedy plots.

No bias was therefore assumed among the sampling plots as the respective means of plant height and density, in clean and weedy plots, were not statistically different from one another as shown by $P > 0.05$ as well as by the similar and/or shared LSD letters (Table 4) and also depicted from overlapping standard error bars (Fig. 16). As seen in Table 4, the plots used to evaluate the three harvesting methods for their temperature at harvest yielding the best quality of berries shared the same LSD letters (A and/or AB). Statistically, the group means labeled with similar (A, A) and/or shared LSD letters (A, AB) are not significantly different from one another.

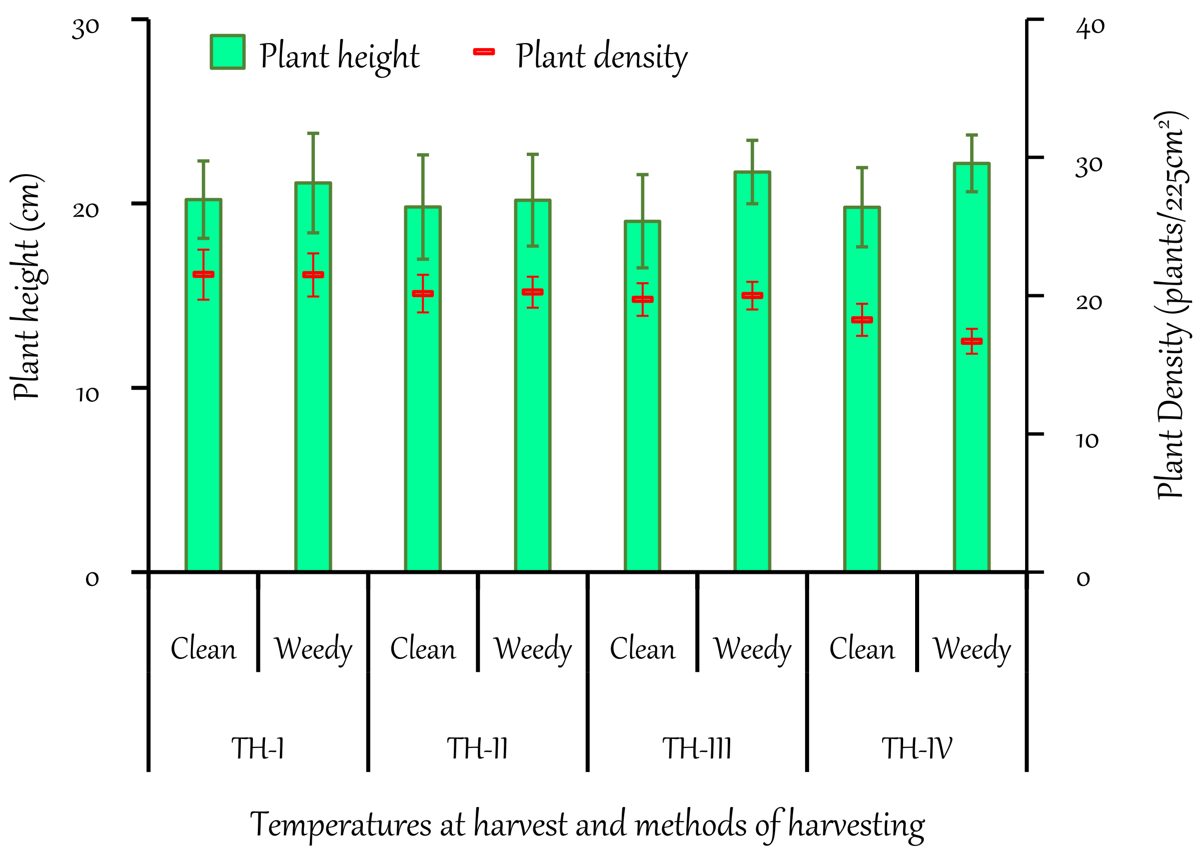

Figure 16: Plant height (primary y-axis) and plant density (secondary y-axis) accompanied by standard deviation from means heights and densities of plants in clean and weedy plots plotted against temperatures at harvest (i.e., TH-I to TH-IV) reflecting no substantial variations or bias in the experimental plots.

Table 4: Analysis of variance P values and Fisher's least significant difference (LSD) letters to reflect no statistically significant difference between the means of plant height and plant density measured from the clean and weedy sampling plots used for berry harvest samplings with hand raking, walk-behind harvester, and mechanical harvester during the four temperatures of harvest (TH-I to TH-IV).

Sampling plots	P value	TH-I	TH-II	TH-III	TH-IV
<u>Plant height</u>					
Clean	0.862	A	A	A	A
Weedy	0.482	A	A	A	A
<u>Plant density</u>					
Clean	0.452	A	A	A	A
Weedy	0.148	A	AB	AB	B

Statistically, the group means labeled with similar (A, A) and/or overlapping (A, AB) LSD letters are not significantly different from one another. The level of significance was set as 95%.

3.1.4 Diameters of berry fruits from good and bruised berry samples

The berries collected from the clean and weedy plots were also not different in their diameter providing additional evidence of no bias among the plant conditions available for the three harvesting methods (Fig. 17). Averaged mean diameters of the good berries harvested from clean and weedy plots during the four temperatures at harvest were 10.3±1.16, 10.5±1.03, 10.6±0.94, and 10.2±1.03 mm^2, respectively. Similarly, the averaged mean diameters of bruised berries harvested from clean and weedy plots during the four temperatures at harvest were 7.07±1.35, 7.60±1.29, 7.42±1.04, and 8.15±1.21 mm^2, respectively. The values of P exceeded 0.05, except for bruised berries of clean plots (Table 5). The mean values were labeled with similar LSD letters except for bruised berries of clean plots that had shared LSD letters with other treatments. This reflected no statistical difference between the mean diameters presented in Fig. 17, except for bruised berries of clean plots.

Measuring the diameter of bruised berries is challenging as it is hard to locate the unbruised sides of the berries for Vernier caliper adjustment around the regular surface of a fruit. Additionally, results about the fruit diameter may be considered carefully for the fact that the good and bruised berries were sorted manually and the diameter of the bruised berries changes as they de-shape/reshape with resettling on surfaces they are placed. However, the size of the berry might be one of the causes of damage; damage caused by the mechanical impact of teeth of harvesters. Therefore, an unexpected significant difference between the mean diameters of bruised berries from clean plots may be because of the reasons quoted above for challenges and difficulties in measuring the precise diameter of the bruised berries. This argument gets support from the findings of Zoecklein et al. (1992) who studied the effects of fruit zone leaf removal on yield, fruit composition, and fruit rot incidence of chardonnay and white riesling (*Vitis vinifera* L.) grapes and reported that the quality of fruit that matures in dense canopies can be further reduced by various infections partially caused by biological reasons and partially induced by pressure and high temperature of a thick plant canopy on fruit surfaces.

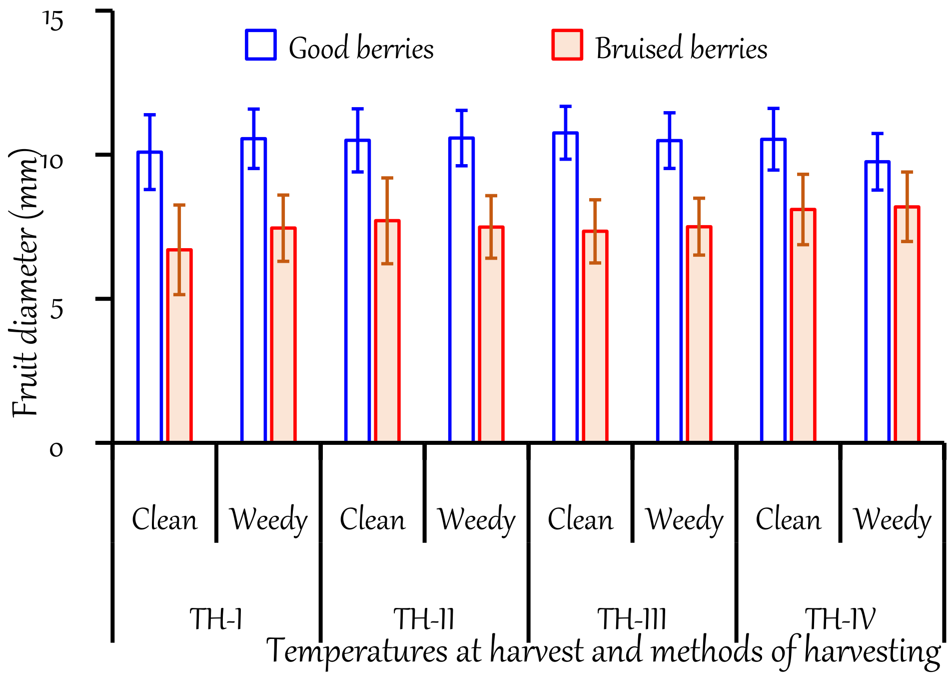

Figure 17: Mean diameter and standard deviations from means of good and bruised berries, of clean and weedy plot samples, plotted against four temperatures at harvest (i.e., TH-I to TH-IV).

Table 5: Analysis of variance (ANOVA) P values and Fisher's least significant difference (LSD) letters to reflect the statistically significant difference (if any) between the mean diameters of good and bruised berries for the experimental plots used to sample harvests of hand raking, walk-behind harvester, and mechanical harvester during the four ranges of temperature (TH-I to TH-IV).

Berries	**Good berries**		**Bruised berries**	
Plot	**Clean**	**Weedy**	**Clean**	**Weedy**
P value	0.669	0.212	0.008	0.207
LSD for TH-I	A	A	B	A
LSD for TH-II	A	A	A	A
LSD for TH-III	A	A	AB	A
LSD for TH-IV	A	A	A	A

Statistically, the group means labeled with similar (A, A) LSD letters are not significantly different from one another. The level of significance was set as 95%.

3.2 Acceptable Temperature Range to Harvest Fields for Maximizing Fruit Quality

Tables 6 and 7 present the results of one-way ANOVA for the difference in percent means of ambient air temperature, fruit surface temperature, berry plant leaf temperature, soil surface temperature, PAR above and below plant canopy, and soil moisture content during four temperatures at harvest for clean and weedy plots, respectively. All variables mentioned in Table 6 were significantly different during the four events of temperature at harvest ($P \leq 0.05$) except PAR below plant canopy ($P > 0.05$). This showed that the ambient air temperature, which is categorized in the four events of temperature at harvest of this study, had the same direct impact on fruit surface temperature, berry plant leaf temperature, soil surface temperature, PAR above the canopy, and soil moisture content of clean as well as weedy plots. The plant canopy, however, impacted PAR below the plant canopy. This also reflects interrelation and thus interdependence of the selected berry plant, fruit, and soil characteristics with ambient air temperature in wild blueberry fields of Nova Scotia. Such interdependence is extremely dangerous during frost events when the cold temperature damages the wild blueberry crop. The importance of ambient air temperature or temperature at harvest thus becomes important to explore for determining the range of temperature at harvest considered the best to harvest fields for maximizing fruit quality.

Table 6: One-way analysis of variance (ANOVA) results for the difference in mean values of ambient air temperature, fruit surface temperature, berry plant leaf temperature, soil surface temperature, photosynthetically active radiation above and below the canopy, and soil moisture content of clean plots harvested at the four temperatures at harvest.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Ambient air temperature (°C)					
Temperature at harvest	3	1675.39	558.463	313.86	0.000
Error	56	99.64	1.779		
Total	59	1775.03			
Berry fruit surface temperature (°C)					
Temperature at harvest	3	1816	605.39	46.69	0.000
Error	116	1504	12.97		
Total	119	3320			
Leaf temperature (°C)					
Temperature at harvest	3	1278	425.91	36.54	0.000
Error	116	1352	11.66		
Total	119	2630			
Soil surface temperature (°C)					
Temperature at harvest	3	1526	508.68	34.77	0.000
Error	116	1697	14.63		
Total	119	3223			
Photosynthetically active radiation above the canopy (µmol/m^{2}s)					

Temperature at harvest	3	4271131	1423710	6.13	0.001
Error	56	13015512	232420		
Total	59	17286643			
Photosynthetically active radiation below canopy (µmol/m^{2}s)					
Temperature at harvest	3	50680	16893	2.21	0.091
Error	116	887819	7654		
Total	119	938500			
Soil moisture (%)					
Temperature at harvest	3	176.9	58.97	4.76	0.004
Error	116	1437.0	12.39		
Total	119	1613.9			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. The level of significance was set as 95%.

Table 7: One-way analysis of variance (ANOVA) results for the difference in mean values of ambient air temperature, fruit surface temperature, berry plant leaf temperature, soil surface temperature, photosynthetically active radiation above and below the canopy, and soil moisture content of weedy plots harvested at the four temperatures at harvest.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Ambient air temperature (°C)					
Plot type	1	96.04	96.04	3.23	0.074
Error	138	4099.28	29.70		
Total	139	4195.32			
Berry fruit surface temperature (°C)					
Plot type	1	4.18	4.181	0.15	0.700
Error	118	3316.01	28.102		
Total	119	3320.19			
Leaf temperature (°C)					
Plot type	1	56.62	56.62	2.60	0.110
Error	118	2573.22	21.81		
Total	119	2629.85			
Soil surface temperature (°C)					
Plot type	1	19.07	19.07	0.70	0.404
Error	118	3203.81	27.15		
Total	119	3222.88			
Photosynthetically active radiation above the canopy (µmol/m^{2}s)					
Plot type	1	310447	310447	1.15	0.285
Error	138	37199022	269558		
Total	139	37509470			
Photosynthetically active radiation below canopy (µmol/m^{2}s)					
Plot type	1	5454	5454	0.69	0.408
Error	118	933046	7907		
Total	119	938500			
Soil moisture (%)					
Plot type	1	38.36	38.36	2.87	0.093
Error	118	1575.54	13.35		
Total	119	1613.90			

DF: degree of freedom, SS: sum of squares, MS: mean of squares. The level of significance was set as 95%.

3.2.1 Ambient air, fruit surface, plant leaf, and soil temperatures

The mean plant leaf, soil surface, and fruit temperatures significantly increased with the increase in mean ambient air temperature during the four temperatures at harvest (Fig. 18; $P \leq 0.05$). The fruit surface temperature was always greater than ambient air temperature during all events of TH, whereas the leaf and soil temperatures were lower than ambient air temperature during the first two temperatures at harvest (i.e., TH-I and TH-II) and vice versa at TH-III and TH-IV.

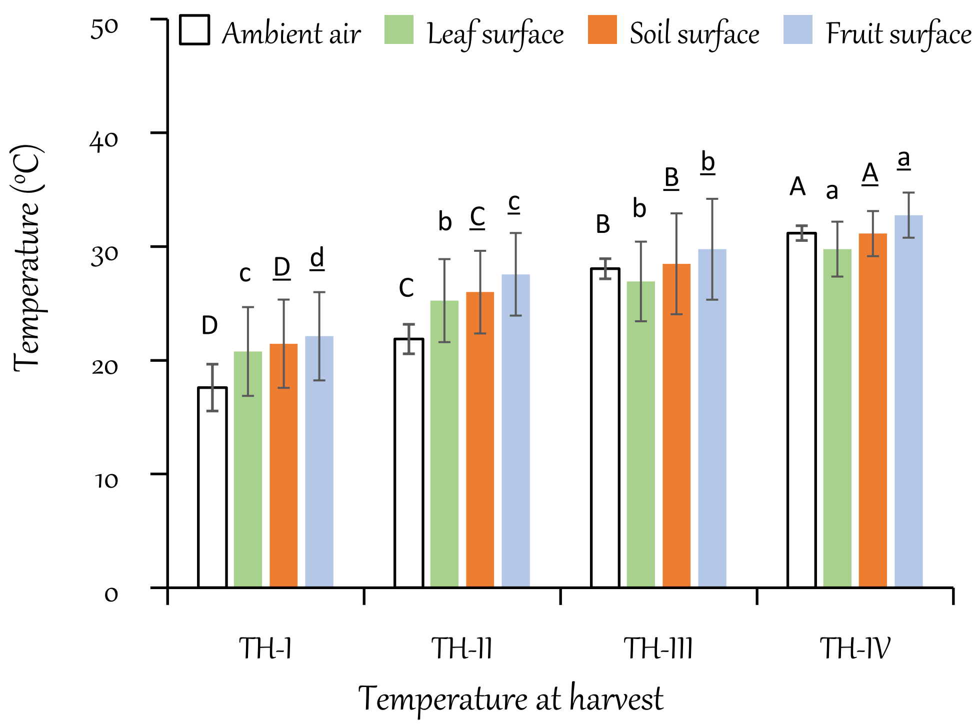

Figure 18: Mean temperature values (°C) and standard deviations from the means for ambient air, leaf surface, soil surface, and berry surface measured during replications of harvesting of four temperatures at harvest (TH-I to TH-IV). The respective significantly different means have been separated and labeled with Fishers' Least Significant Difference (LSD) letters (lower and upper cases with and without underlines) for their significant difference among the four temperatures at harvest.

The relationship between sunlight exposure and the temperature of fruit clusters is important to berry composition and metabolism (Spayd et al., 2002). Bergqvist et al. (2001) who studied the separation of sunlight and temperature effects on the composition of merlot berries (*Vitis vinifera* cv.), suggested that to achieve maximum color development in warm regions, prolonged exposure of clusters to sunlight should be avoided. Millar (1972) in his study of the thermal regime of grapevine, showed that berry temperatures paralleled the diurnal solar radiation curve. This means that that the differences in temperature between ambient air and the exposed fruits increase as solar radiation increases and wind speed decreases, as one might expect from heat transfer principles. Smart and Sinclair (1976) indicated that solar radiation and wind velocity were the two most important determinants of fruit temperature: during the day shortwave radiation was the primary source of fruit warming and convection was the primary source of heat transfer away from the cluster.

3.2.2 Drone-acquired information

Orthomosaic surface model of one of the experimental fields is shown in Figure 19. The map shows spatial attributes of the field including tree lines along the left and rightward sides of the field as well as a main road and a cross road passing through the field from east to west used by the harvesting machinery.

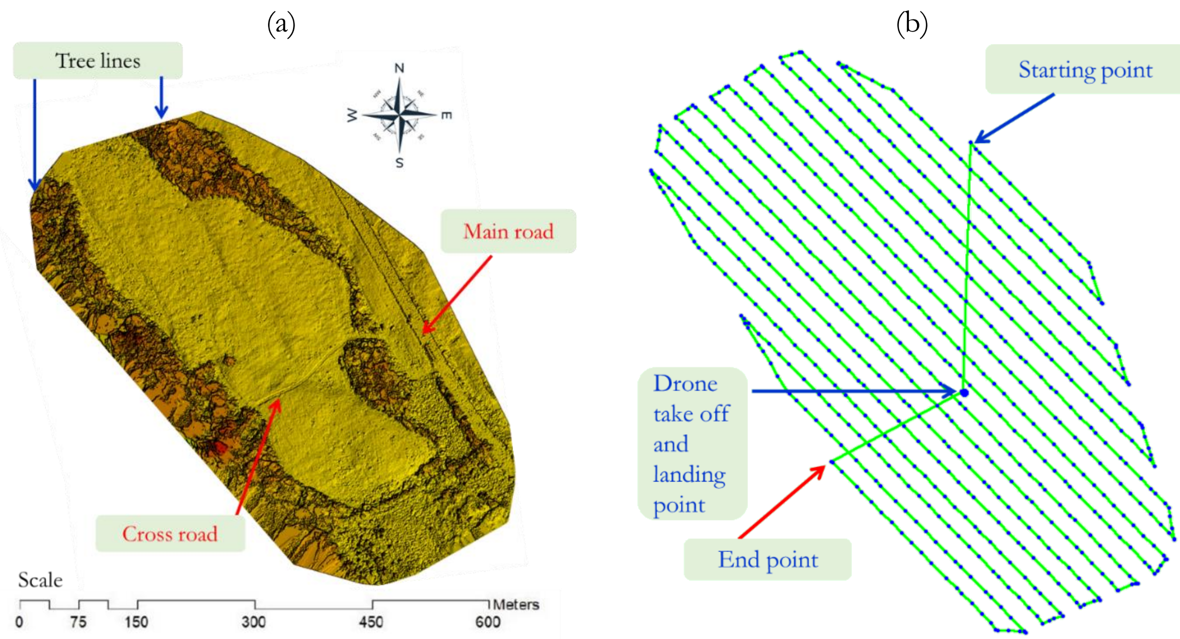

Figure 19: Orthomosaic map of the field showing physical attributes of the field including surrounding trees, crossroad and the main road (a) obtained after processing data obtained by flying drone above the field shown on the flight route reflected with green lines and blue points of image squassation (b).

Processing the drone imagery showed a variation in the temperature of berry plant and/or soil surfaces (Figs. 19, 20a). Figure 19a shows orthomosaic map of the field reflecting elevated and low-lying areas of the fields. Figure 20a shows, the temperature of the wild blueberry plant and bare soil (especially the main and the crossroads). The images processed to produce maps of Figures 19 and 20 were captured during the morning hours of the day. Figure 20a reflects about 3 °C difference between the temperatures of the plants in the areas of high elevation (or roads and bare spots) and the low elevations (Fig. 20a). There was about a 5 °C difference between the temperature of trees and that of areas of higher elevation including the gravel road running beside the blueberry field.

Similarly, the NDVI maps reflected the presence of green trees and foliage represented with the red color or NDVI close to 1 (Fig. 20b). The NDVI of berry plants is shown between 0 and 1. NDVI of the gravel road surface is also shown as 0 and in blue color because of the absence of green foliage.

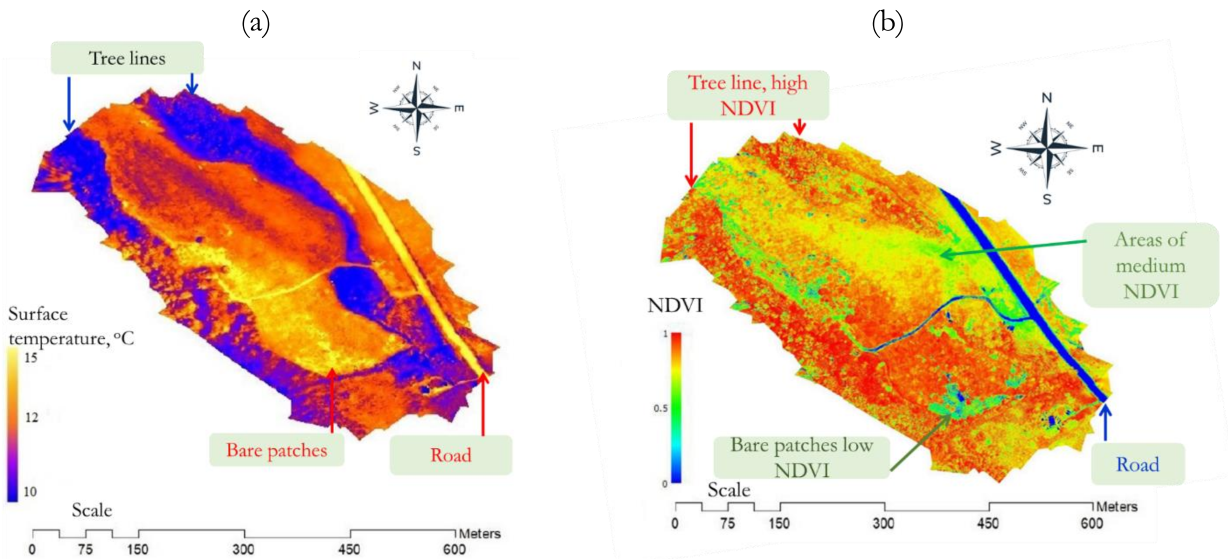

Figure 20: Spatial variations in (a) berry plant and/or soil surface temperature and (b) normalized difference vegetation index (NDVI) with the filed physical attributes including trees, roads, bare patches, and blueberry plant occupied field areas.

Although, determining chemical components was not part of this research but it is important to mention fruit chemical components can be related to ambient air temperature; for example, anthocyanins are a type of flavonoid, a class of compounds with antioxidant effects. Found naturally in fruits, anthocyanins are the pigments that give red, purple, and blue plants their rich coloring. Smart and Sinclair (1976) have correlated air temperatures with anthocyanin composition and concentration, with the caution that air temperature may not represent fruit temperature at a given time. The temperature of the berries inside a cluster might have been different from the values of outer fruits. Bergqvist et al. (2001) reported that the fruit response to sunlight varied based on a cluster located within the canopy. At the same exposure level or PAR, mid-day berry temperature was generally 3 to 4 C greater for clusters on the Southside of the canopy compared to clusters on the North of their experimental fields.

3.2.3 Photosynthetic active radiation above and below plant canopy and soil moisture

In general, PAR above and below plant canopy increased with an increase in ambient air temperature or temperature at harvest (Fig. 21). The opposite was true for soil moisture content that decreased with an increase in temperature at harvest. As shown by Fisher's LSD letters, the mean value of the above canopy PAR during TH-I was significantly lower than the corresponding values during the higher temperature at harvest ($P \leq 0.05$). Likewise, the mean soil moisture decreased with an increase in temperature at harvest and its values below 30 C (i.e., TH-I to TH-III) were significantly higher than that at TH-IV (≥30 C) ($P \leq 0.05$). Anomalies noticed for the above canopy PAR at TH-III (i.e., a value between those of TH-II and TH-IV) may be attributed to the cloudy conditions experienced during some of the TH-III data collection events. Anomalies noticed for below canopy PAR at TH-II (i.e., value less than that at TH-I) may be attributed to the dense plant canopies encountered during the specific event of sampling.

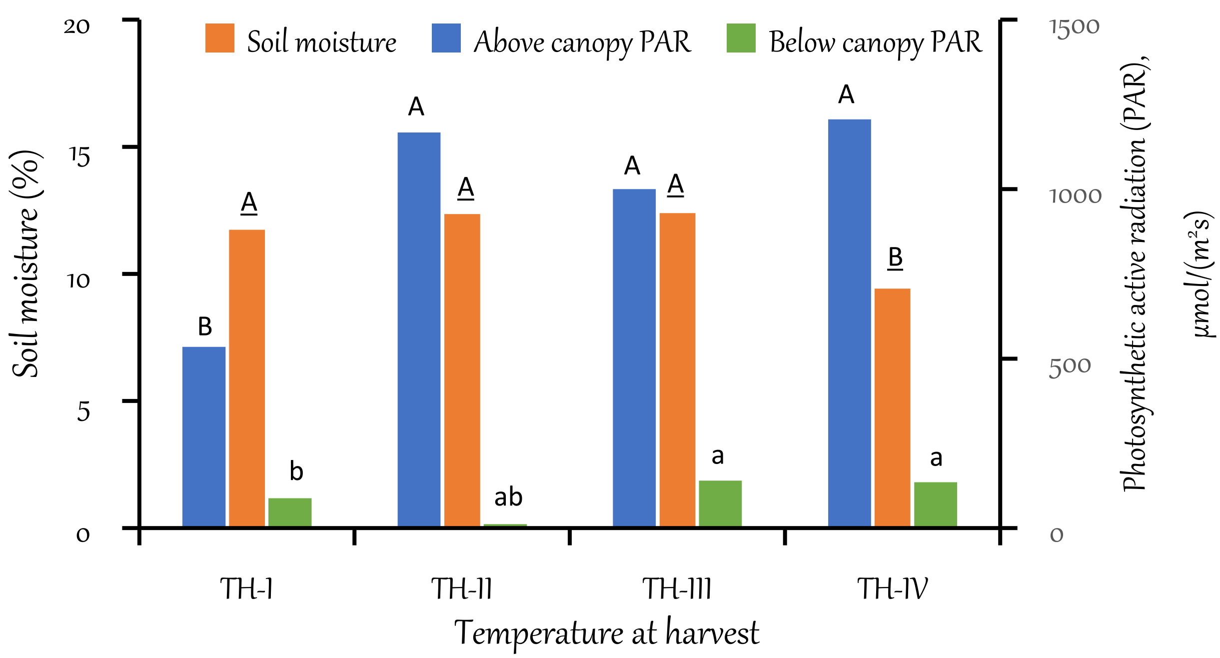

Figure 21: Mean soil moisture (plotted on the primary y-axis), and above and below canopy photosynthetic active radiations (plotted on the secondary y-axis) for the four temperatures at harvest (TH-I to TH-IV). The means labeled with similar respective LSD letters (i.e., capital, lower-cases, or underlined) are not significantly different from one another.

3.2.4 Acceptable temperature for berry harvest

The optimum temperature for berry harvest was determined by measuring the effects of temperature at harvest on fruit quality components including good berries, bruised berries, cut-split berries, and debris. Results of one-way ANOVA for the effects of temperature at harvest on the selected quality components of the harvest samples were calculated for hand raking (Table 8a), walk-behind harvester (Table 8b), and mechanical harvester data (Table 8c). The temperature at harvest had a significant effect on all quality components of the harvest samples except for debris ($P \leq 0.05$).

For the three methods of harvest, the mean percent of good berries decreased with an increase in temperature at harvest. Except for TH-I, the mean percent values of the other fruit quality components including bruised berries, cut-split berries, and debris significantly increased with an increase in temperature at harvest. For hand raking methods, the acceptable temperature to harvest good quality berries was ≤20 °C when about 82% of good berries were yielded from its harvest (Fig. 22). Above 75% good berries were yielded during TH-II (78.4%) and TH-III (75.9%). TH-IV (i.e., > 30 °C) resulted in the least (62.5%) and significantly fewer good berries than the other three temperatures at harvest. The analysis reflects a significantly greater presence of percent bruised and percent cut-split berries in the harvest samples of TH-IV (15.4 and 13.1%, respectively) that were significantly different from the percent bruised and percent cut-split berries generated during TH-I (5.18, 4.39%, respectively), TH-II (7.61, 6.61%, respectively), and TH-III (9.30, 7.86%, respectively). There was no significant effect of temperature at harvest on percent debris produced by hand raking during TH-I to TH-IV ($P > 0.05$).

Table 8a: Results of one-way analysis of variance (ANOVA) for the significance of the effect of temperature at harvest on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for hand raking samples.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	**P Value**
Good berries (%)					
Temperature at harvest	3	6502	2167.44	28.81	0.000
Error	116	8728	75.24		
Total	119	15231			
Bruised berries (%)					
Temperature at harvest	3	1710	570.14	17.89	0.000
Error	116	3696	31.86		
Total	119	5407			
Cut-split berries (%)					
Temperature at harvest	3	1232	410.68	20.13	0.000
Error	116	2366	20.40		
Total	119	3598			
Debris (%)					
Temperature at harvest	3	79.95	26.65	0.78	0.507
Error	116	3957.32	34.11		
Total	119	4037.28			

DF: degree of freedom, SS: sum of squares, MS: mean of squares.

Table 9b: Results of one-way analysis of variance (ANOVA) for the significance of the effect of temperature at harvest on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for walk-behind harvester samples

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Good berries (%)					
Temperature at harvest	3	6102	2034.0	15.97	0.000
Error	116	14775	127.4		
Total	119	20877			
Bruised berries (%)					
Temperature at harvest	3	1578	525.85	9.60	0.000
Error	116	6357	54.80		
Total	119	7934			
Cut-split berries (%)					
Temperature at harvest	3	1225	408.50	9.56	0.000
Error	116	4955	42.71		
Total	119	6180			
Debris (%)					
Temperature at harvest	3	39.99	13.33	0.37	0.777
Error	116	4211.49	36.31		
Total	119	4251.48			

Abbreviations are defined under Table 8a.

Table 10c: Results of one-way analysis of variance (ANOVA) for the significance of the effect of temperature at harvest on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for mechanical harvester samples.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Good berries (%)					
Temperature at harvest	3	6912	2304.0	18.41	0.000
Error	116	14514	125.1		
Total	119	21426			
Bruised berries (%)					
Temperature at harvest	3	2194	731.38	17.13	0.000
Error	116	4953	42.70		
Total	119	7147			
Cut-split berries (%)					
Temperature at harvest	3	1571	523.57	10.72	0.000
Error	116	5667	48.85		
Total	119	7238			
Debris (%)					
Temperature at harvest	3	56.91	18.97	0.96	0.413
Error	116	2287.66	19.72		
Total	119	2344.57			

Abbreviations are defined under Table 8a.

The acceptable temperature to harvest good quality berries with a walk-behind harvester was ≤20 ºC when about 77% of good berries were yielded from its harvest (Fig. 23). The temperatures at harvest greater than 20 ºC yielded less than 70% good berries, e.g., 68.3% for TH-II, 64.7% for TH-

III, and 56.9% for TH-IV. The analysis reflects significantly different means of percent bruised and percent cut-split berries in the harvest samples of TH-IV (17.4 and 15.7%, respectively) that were significantly larger than those generated during TH-I (7.30, 7.19%, respectively), TH-II (13.4, 8.95%, respectively), and TH-III (13.4, 11.6%, respectively). No significant effect of temperature at harvest was found on the percent debris produced by the walk-behind harvester during the four ranges of temperatures at harvest ($P \leq 0.05$).

Results of the analysis of mechanical harvester samples revealed that the acceptable temperature for harvesting the good quality berries with this method was also ≤20 ºC. Mechanical harvesting produced the highest percentage (80.5%) of good berries during TH-I that was statistically different and significantly greater than the percent means of good berries produced during TH-II (73.2%), TH-III (68.9%), and TH-IV (59.5%) (Fig. 24). This trend was reflected in the effect of temperature at harvest on the production of bruised and cut-split berries during TH-IV that had significantly different and higher production of bruised (17.1%) and cut-split berries (17.3%) that were statistically different and greater than the berries produced during TH-I (7.10%). As the effect of temperature at harvest on debris produced during hand raking and walk-behind harvester, there was no significant effect of temperature at harvest on debris produced by mechanical harvester during TH-I to TH-IV ($P > 0.05$).

About 60-80% of good berries collected from the harvest samples of the three harvesting methods reflect 20-40% shrinkage, which seems to be practically on the higher end. The possible reason for this high percent shrink can be the strict rules followed for placing all berries with sensible slight soft skin or light bruises in the category of bruised berries. The other reason may be the effect of temperature on berry quality. Presumably, berries with slight soft skins or light bruises are allowed through cleaning/processing lines. Practically, all such berries are not discarded, but they have a valuable consumption for their uses in making yogurt, juices, or milkshakes as less than 10% of berries are consumed fresh, and the rest are sold frozen or in the forms of their value-added products.

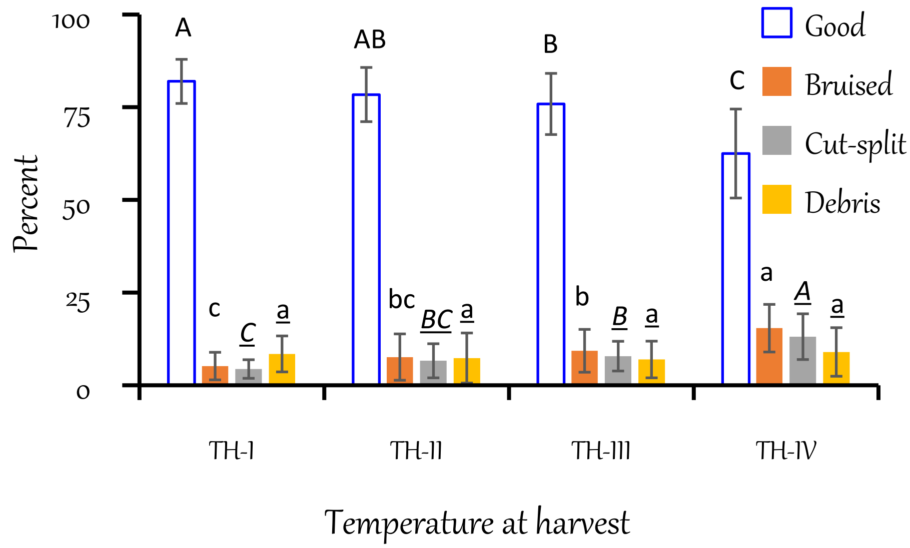

Figure 22: Percent means of berry quality components plotted against four temperatures at harvest (TH-I to TH-IV) for hand raking samples. The percent means have been separated and labeled by standard error bars and Fishers' LSD letters (A, a, *A*, and a) for their significant difference at four temperatures at harvest. The means with similar respective LSD letters (i.e., upper and lower case regular, and/or underlined italic letters) are not significantly from one another.

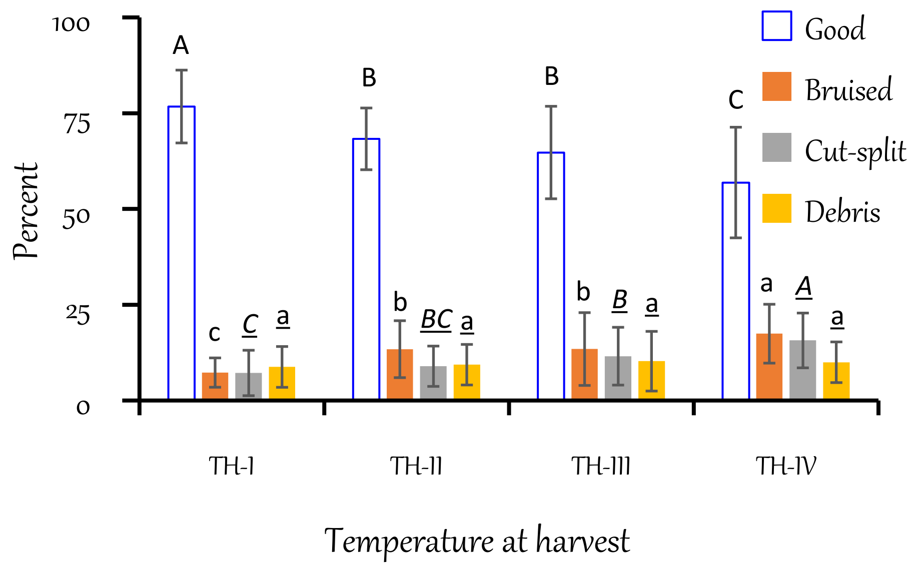

Figure 23: Percent means of berry quality components plotted against four temperatures at harvest (TH-I to TH-IV) for walk-behind harvester samples. The percent means have been separated and labeled by standard error bars and Fishers' LSD letters (A, a, *A*, and a) for their significant difference at four temperatures at harvest. The means with similar respective LSD letters (i.e., upper and lower case regular, and/or underlined italic letters) are not significantly from one another.

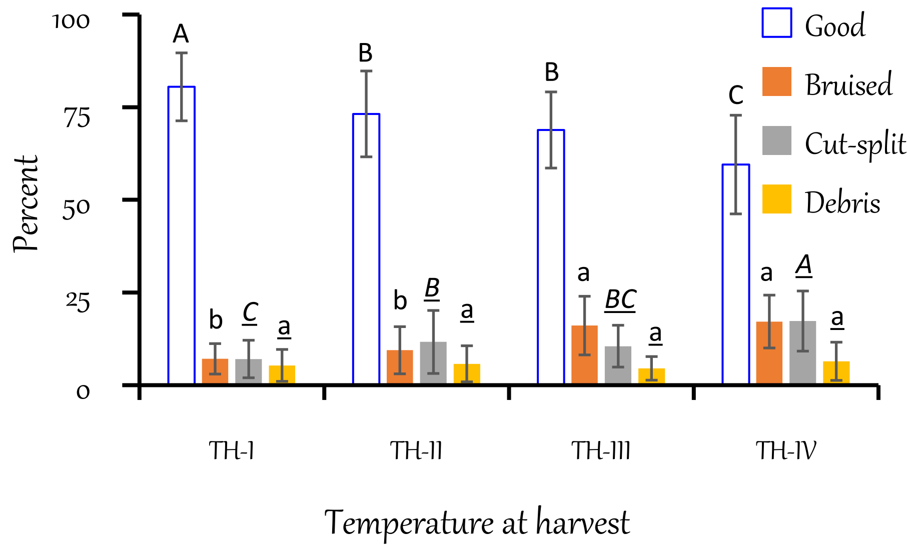

Figure 24: Percent means of berry quality components plotted against four temperatures at harvest (TH-I to TH-IV) for mechanical harvester samples. The percent means have been separated and labeled by standard error bars and Fishers' LSD letters (A, a, *A*, and a) for their significant difference at four temperatures at harvest. The means with similar respective LSD letters (i.e., upper and lower case regular, and/or underlined italic letters) are not significantly from one another.

3.3 The Effect of Weeds on the Harvest Quality

Separately for the three methods of harvesting, the effect of the presence of weeds in the harvest plots was assessed on the quality components of the harvest by calculating a one-way ANOVA for the significant effects of weeds on good berries, bruised berries, cut-split berries, and debris. The pooled set of data collected from the two plot types (clean and weedy) was analyzed and the ANOVA results were tabulated for hand raking (Table 9a), walk-behind harvester (Table 9b), and mechanical harvester (Table 9c). Weeds had a significant effect on all quality components of the harvest samples except for debris collected with the hand raking method.

The percent of good berries found in the harvest of clean plots were significantly different and higher than their values obtained from the harvests of weedy plots (Figs. 25-27). Except for debris in the hand raking samples (Fig. 25) and bruised berries in the mechanical harvesting samples (Fig. 27), the three berry quality components including bruised berries, cut-split berries, and debris of all the three methods of harvesting were significantly affected and higher in the weedy plot than in clean plot samples ($P \leq 0.05$). This showed an adverse effect of weeds on berry quality characteristics as good berries decreased and bruised, cut-split berries and debris increased in the harvest samples due to the presence of weeds in the plots ($P \leq 0.05$)

Table 11a: Results of one-way analysis of variance (ANOVA) for the significance of the effect of weeds on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for hand raking samples.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	**P Value**
Good berries (%)					
Plot type	1	1524	1524.0	13.12	0.000
Error	118	13707	116.2		
Total	119	15231			
Bruised berries (%)					
Plot type	1	198.3	198.29	4.49	0.036
Error	118	5208.2	44.14		
Total	119	5406.5			
Cut-split berries (%)					
Plot type	1	187.9	187.88	6.50	0.012
Error	118	3410.3	28.90		
Total	119	3598.2			
Debris (%)					
Plot type	1	126.6	126.56	3.82	0.053
Error	118	3910.7	33.14		
Total	119	4037.3			

DF: degree of freedom, SS: sum of squares, MS: mean of squares.

Table 12b: Results of one-way analysis of variance (ANOVA) for significance of the effect of weeds on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for walk-behind harvester samples.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	**P Value**
Good berries (%)					
Plot type	1	4860	4860.2	35.81	0.000
Error	118	16017	135.7		
Total	119	20877			
Bruised berries (%)					
Plot type	1	824.3	824.28	13.68	0.000
Error	118	7110.0	60.25		
Total	119	7934.2			
Cut-split berries (%)					
Plot type	1	502.0	502.02	10.43	0.002
Error	118	5678.2	48.12		
Total	119	6180.2			
Debris (%)					
Plot type	1	345.9	345.92	10.45	0.002
Error	118	3905.6	33.10		
Total	119	4251.5			

Abbreviations are defined under Table 9a.

Table 13c: Results of one-way analysis of variance (ANOVA) for the significance of the effect of weeds on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for mechanical harvester samples.

Source	**DF**	**Adjusted SS**	**Adjusted MS**	**F Value**	**P Value**
Good berries (%)					
Plot type	1	1721	1720.6	10.30	0.002
Error	118	19705	167.0		
Total	119	21426			
Bruised berries (%)					
Plot type	1	113.6	113.63	1.91	0.017
Error	118	7033.1	59.60		
Total	119	7146.8			
Cut-split berries (%)					
Plot type	1	481.1	481.12	8.40	0.004
Error	118	6756.7	57.26		
Total	119	7237.8			
Debris (%)					
Plot type	1	92.54	92.54	4.85	0.030
Error	118	2252.03	19.08		
Total	119	2344.57			

Abbreviations are defined under Table 9a.

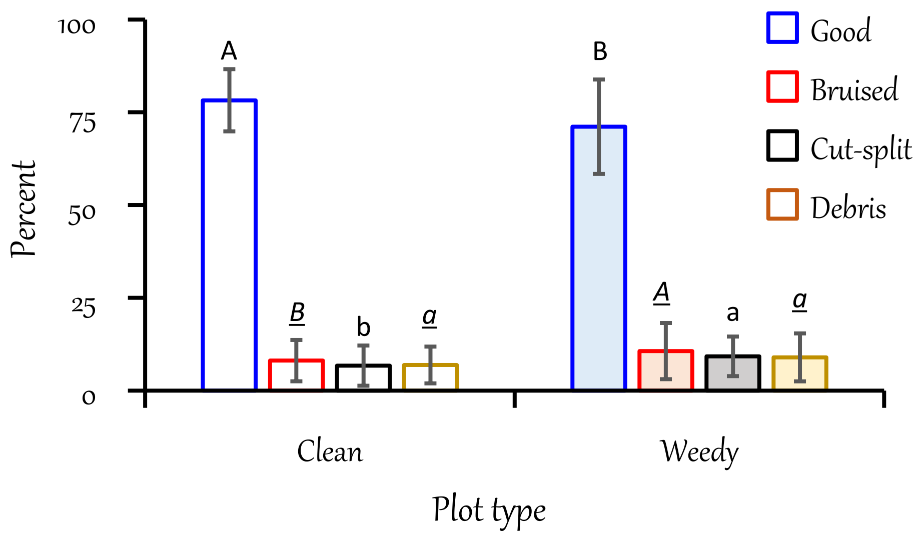

Figure 25: Percent berry quality components of clean and weedy plots for hand raking samples. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, A, and a) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

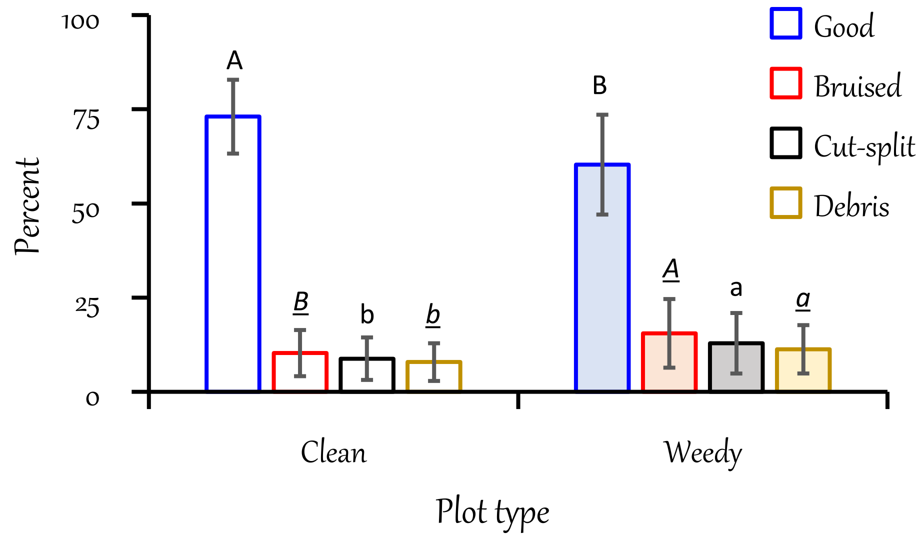

Figure 26: Percent berry quality components of clean and weedy plots for walk-behind harvester samples. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, *A*, and *a*) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

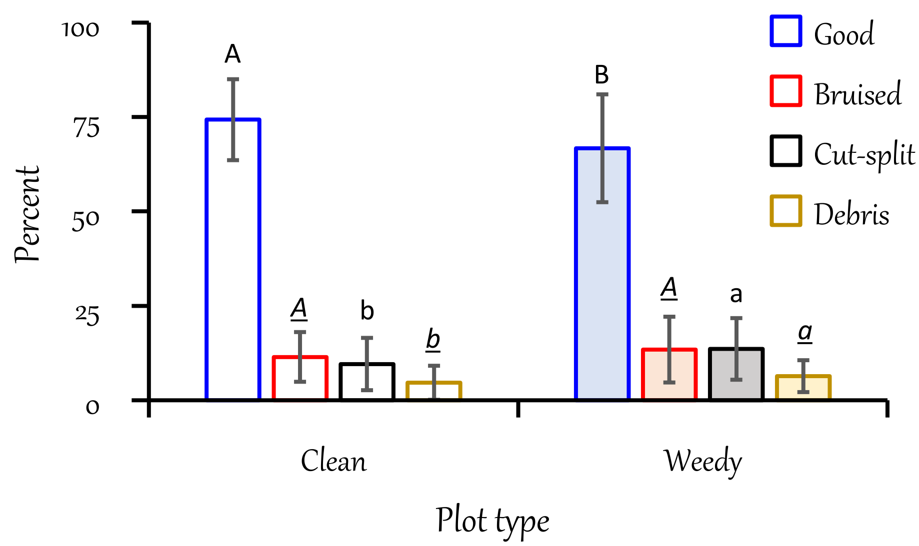

Figure 27: Percent berry quality components of clean and weedy plots for mechanical harvester samples. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, *A*, and *a*) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

3.4 Acceptable Berry Firmness during Harvest to Maximize Fruit Quality

The acceptable berry firmness was determined from the firmness values of fresh fruits sorted from samples of the three harvest methods during morning or mid-morning hours of the days when the ambient air temperature fell in the categories of TH-I and TH-II (i.e., < 25 °C). Table 10 presents the mean values of firmness of good berries collected from clean plots during TH-I and TH-II with the three methods of harvest. It can be extracted from the data presented in Table 10 that the acceptable berry firmness during harvest to maximize fruit quality can be considered in the range 128 – 160 ± 22.2 g/mm. These findings concur with the literature as for the southern highbush, northern highbush, half-high, and Rabbiteye cultivars of blueberry, Cappai et al. (2018) reported mean firmness to range from 128 – 183 g/mm. Moggia et al. (2017) reported 1.55 – 1.60 N as the firmness of a highbush variety of blueberries during their investigation in Longaví, Chile. They concluded that conditions that restrict blueberry water loss are likely to be beneficial in retaining acceptable berry firmness. Low temperature conditions during the harvest and at storage can restrict water loss from berries. Cloudy weather conditions could be one of the natural ways of restricting water loss from berries. Results about the effect of weather conditions on berry quality components are discussed in section 3.5.

Table 14: Mean firmness of good berries and standard deviation from mean collected from clean plots during TH-I and TH-II with the three methods of the harvest to determine acceptable berry firmness.

	Hand raking (g/mm)	**Walk-behind harvester** (g/mm)	**Mechanical harvester** (g/mm)
TH-I (≤ 20 ˚C)	160 ± 21.9	156 ± 22.8	153 ± 21.1
TH-II (20.1 – 25 ˚C)	134 ± 21.9	131 ± 22.4	128 ± 23.9
Acceptable firmness range	134 – 160 ± 21.9	131 – 156 ± 22.6	128 – 153 ± 22.5
Overall acceptable range	128 – 160 ± 22.2		

3.5 Ideal Weather Conditions during Harvest to Maximize Fruit Quality

There was a significant effect of weather conditions on components of berry quality except for debris ($P \leq 0.05$) from samples of hand raking (Table 11a), walk-behind harvester (Table 11b), and mechanical harvester (Table 11c). Cloudy conditions resulted in a significantly higher percentage of good berries than during clear sunny conditions for the three methods of harvesting (Figs. 28-30). Bruised and split berries were produced at significantly lower rates during cloudy conditions than during clear sunny conditions. This might have been due to a decrease in ambient air and berry temperatures during cloudy conditions. Warmer days with clear sunny weather conditions had deteriorated the quality of the harvested berries. Therefore, cloudy weather conditions can be considered favorable during harvest to maximize fruit quality.

Table 15: Results of one-way analysis of variance (ANOVA) for the significance of the effect of weather conditions on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for hand raking samples.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Good berries (%)					
Weather conditions	1	3865	3865.2	31.42	0.000
Error	142	17470	123.0		
Total	143	21335			
Bruised berries (%)					
Weather conditions	1	1424	1424.43	29.94	0.000
Error	142	6756	47.58		
Total	143	8181			
Cut-split berries (%)					
Weather conditions	1	878.3	878.26	29.76	0.000
Error	142	4190.1	29.51		
Total	143	5068.3			
Debris (%)					
Weather conditions	1	27.10	27.10	0.81	0.369
Error	142	4732.92	33.33		
Total	143	4760.02			

DF: degree of freedom, SS: sum of squares, MS: mean of squares.

Table 16: Results of one-way analysis of variance (ANOVA) for the significance of the effect of weather conditions on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for walk-behind harvester samples.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Good berries (%)					
Weather conditions	1	4441	4440.6	28.93	0.000
Error	142	21798	153.5		
Total	143	26238			
Bruised berries (%)					
Weather conditions	1	1406	1405.82	23.01	0.000
Error	142	8675	61.09		
Total	143	10081			
Cut-split berries (%)					
Weather conditions	1	801.9	801.90	15.56	0.000
Error	142	7316.4	51.52		
Total	143	8118.3			
Debris (%)					
Weatherconditions	1	0.68	0.6817	0.02	0.896
Error	142	5601.65	39.4482		
Total	143	5602.33			

Abbreviations are defined under Table 11a.

Table 17: Results of one-way analysis of variance (ANOVA) for the significance of the effect of weather conditions on berry quality components including good quality berries, bruised berries, cut-split berries, and debris for mechanical harvester samples.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Good berries (%)					
Weather conditions	1	2957	2956.6	18.89	0.000
Error	118	18469	156.5		
Total	119	21426			
Bruised berries (%)					
Weather conditions	1	760.0	759.97	14.04	0.000
Error	118	6386.8	54.13		
Total	119	7146.8			
Cut-split berries (%)					
Weather conditions	1	924.8	924.81	17.29	0.000
Error	118	6313.0	53.50		
Total	119	7237.8			
Debris (%)					
Weather conditions	1	9.51	9.514	0.48	0.489
Error	118	2335.06	19.789		
Total	119	2344.57			

Abbreviations are defined under Table 11a.

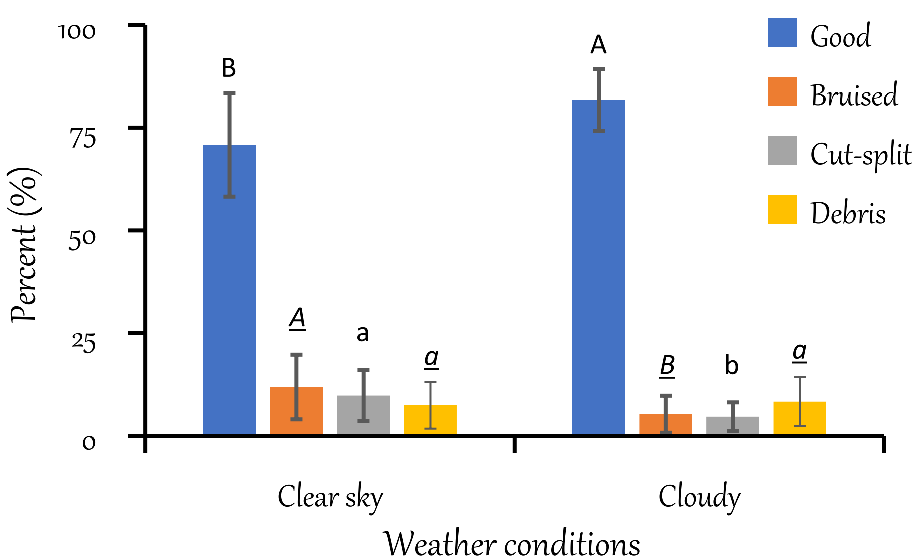

Figure 28: Percent berry quality components of hand raking samples collected under clear and cloudy weather conditions. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, A, and a) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

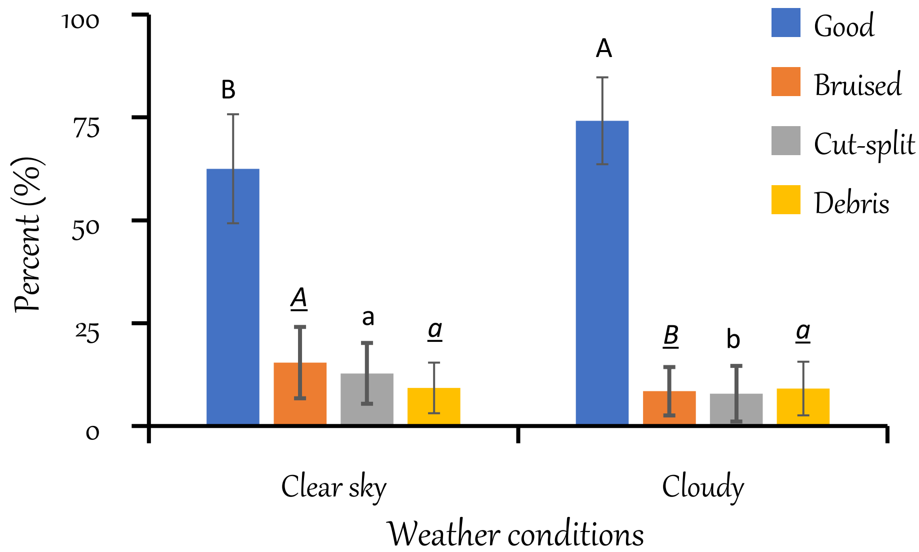

Figure 29: Percent berry quality components for walk-behind harvester samples collected under clear and cloudy weather conditions. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, *A*, and *a*) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

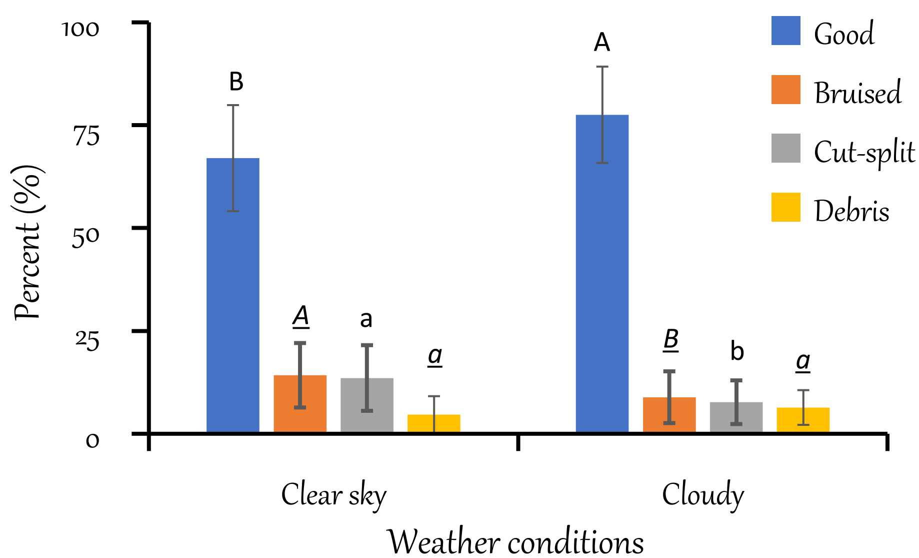

Figure 30: Percent berry quality components for mechanical harvester samples collected under clear and cloudy weather conditions. The percent means have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, a, *A*, and *a*) for their significant difference among temperatures at harvest. The means with similar respective LSD letters (i.e., regular, capital, and/or underlined letters) are not significantly from one another.

3.6 The Effect of Berries Stored with and without a Shade on Berry Quality

Regardless of the method of harvest, the ambient air temperature had a significant effect on berry quality components as described in Tables 8a-c. However, the effect of air temperature varied with the field storing conditions of berries. For example, the berries stored without a shade entrapped more heat than those stored under shade (Fig. 31). During the early hours of the day, when the ambient air temperature was in the range of TH-I and TH-II (i.e., <25 °C), there was no substantial difference between the temperatures of berries stored in the two conditions. However, during the later hours of the day, starting from just before noon till late evening, there was a considerable difference between temperatures of the fruit stored with and without shade even by sunset when the ambient air temperature typically drops. The data sets of the two storage conditions were therefore analyzed using a 2-sample t-test for means to determine if the difference in the fruit temperature of the two storage conditions was statistically significant.

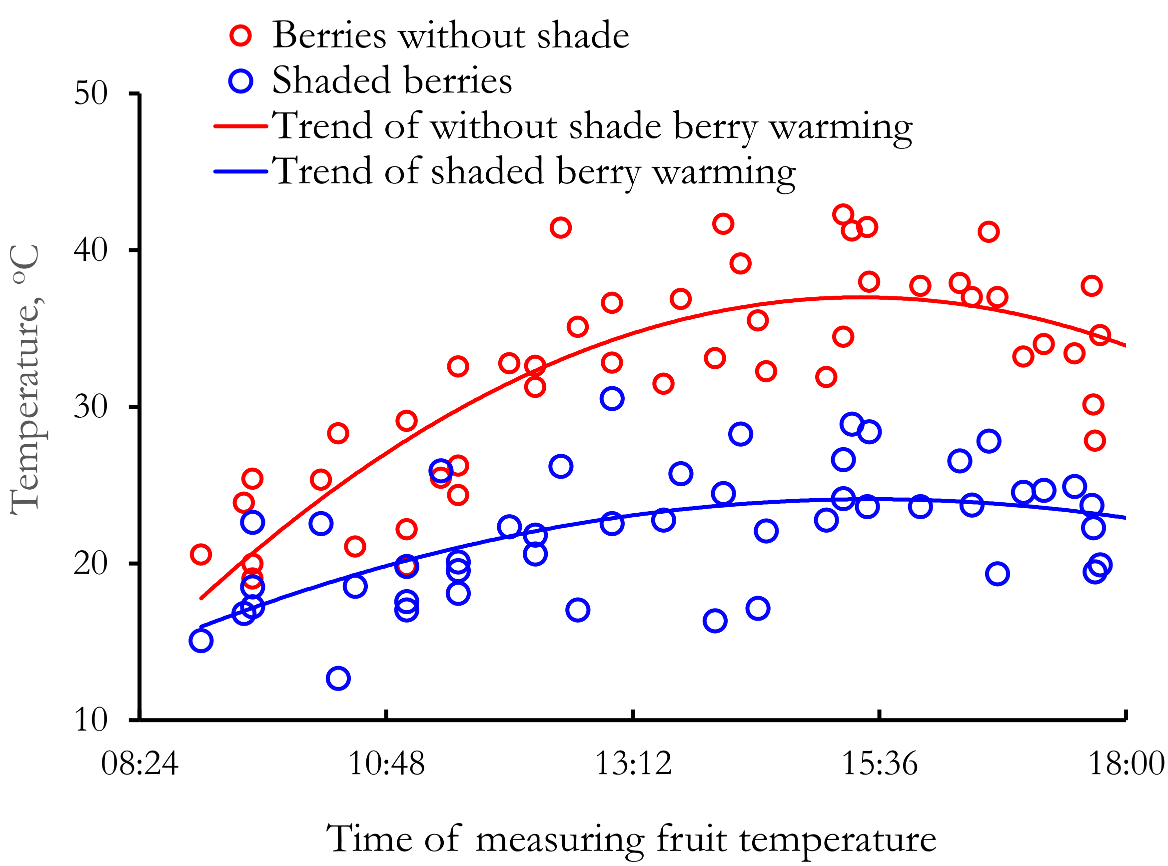

Figure 31: Trends of rising berry fruit temperature stored with and without a shade with an increase in ambient air temperature. The temperature readings were intermittently taken during the study period in August 2021.

The results of the 2-sample t-test for means to compare the effect of berry storage conditions (i.e., temperatures of berries stored with versus without a shade) are given in Table 12. The mean temperature of berries stored without a shade (32.1 °C) remained more than one and a half times higher and significantly different than the temperature (20.0 °C) of those stored under a shade ($P \leq 0.05$). Since there were larger variations in the temperature of berries stored under both conditions, higher values of standard deviation from mean and standard error of mean were recorded. However, these variations were larger because some days were cloudy or overcast or wind speed was more causing a cooling effect and the other days were sunny, hot, and calm.

Table 18: Results of 2-sample t-test for means and descriptive statistics for the set of temperature data of berries stored with and without a shade.

Condition	**Number of observations**	**Mean (°C)**	**Stand Deviation from mean (°C)**	**Standard Error of Mean (°C)**	**P value**
No Shade	48	32.13	6.56	0.95	0.000
Shade	48	22.04	4.01	0.58	

The effect of the rise of fruit temperature was also studied for its effect on fruit firmness. The firmness readings were instantly taken after their temperature measurement (plotted in Fig. 31) during the study period throughout August 2021. Similar to the trends of temperature difference, the firmness of berries had considerable difference during afternoon hours of the day despite the drop of ambient air temperature in the evenings (Fig. 32). The data sets of berry firmness of the two storage conditions were also analyzed using a 2-sample t-test for means to determine if the difference in the fruit firmness of the two storage conditions was statistically significant.

Data of firmness of good and bruised berries were analyzed using one-way ANOVA to distinguish the effect of temperature of harvest and the presence of weeds on berry firmness. Mean comparison separately made for hand raking, walk-behind harvester, and mechanical harvester data of firmness of good and bruised berries collected during the four temperatures at harvest from clean and weedy plots is presented in Table 13. The temperature at harvest had significant effects on mean values of firmness of good and bruised berries ($P \leq 0.05$). The mean firmness of good and bruised berries was significantly different and greatly decreased with an increase in temperature of harvest from TH-I to TH-IV for the four methods of harvest. There was no significant effect of plot conditions (clean versus weedy plots) on the firmness of good and bruised berries for all methods of harvest.

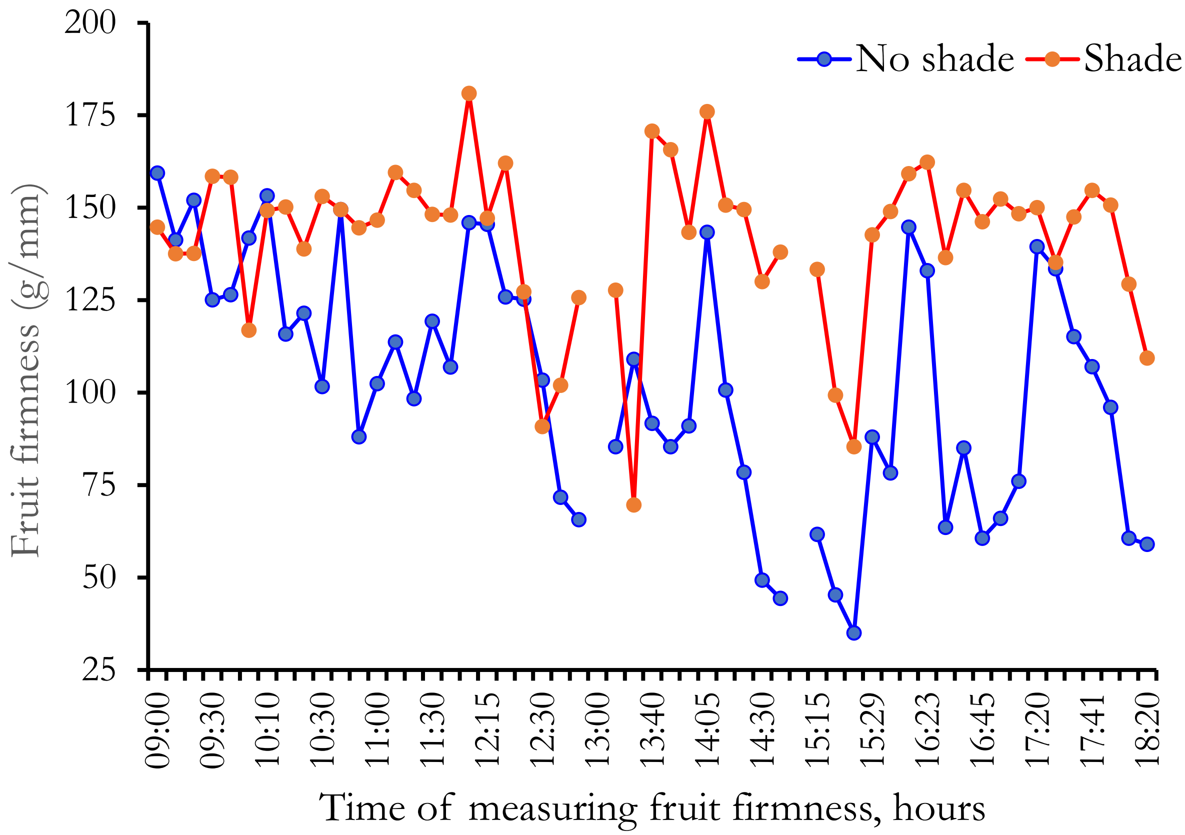

Figure 32: Comparison of firmness of berries (stored with and without shade measured during the study period in August 2021.

The results about the fruit firmness must be considered carefully for the fact that the good and bruised berries were sorted manually rather than with a machine vision-based automated sorter. The static and dynamic forces originating from the harvesting or post-harvest handling operations may mechanically harm berry firmness differently (Opara, 2007, Montero et al., 2009). Such mechanical damage can range from the shape deformation, superficial rupture, and/or destruction or crushing of berries (Montero et al., 2009; Polat et al., 2012).

The literature revealed that harvesting at higher temperatures, especially harvesting with machines, can diminish fruit quality, e.g., firmness by increasing fruit softening and mass deterioration as a consequence of bruising (caused by a drop of the harvested fruits from a height), membrane damage (caused by picker's teeth) and higher respiration rates from the fruit's surface especially during high ambient air temperature (Huang and Bourne, 1983; Patten et al., 1988; Nunez-Barrios et al., 2005).

Table 19: Mean comparison of values of fruit firmness (g/mm), standard deviation from means, and Fisher's least significant difference (LSD) letters of good and bruised berries for samples collected during the four temperatures at harvest for clean and weedy plots. The data were analyzed separately for the effect of temperature at harvest (TH-I to TH-IV) and plot conditions (clean versus weedy) for the three methods of harvesting. The means labeled with similar respective LSD letters or their combinations (i.e., capital, lower-cases, italic, or underlined) are not significantly different from one another.

Method of harvest	**Quality component**	**TH-I**	**TH-II**	**TH-III**	**TH-IV**
<u>Effect of temperature at harvest</u>					
Hand raking	Good	160±21.9 A	135±21.9 B	114±32.4 C	92.5±8.87 D
	Bruised	88.5±15.5 <u>A</u>	68.3±14.5 <u>B</u>	61.8±19.8 <u>B</u>	48.8±9.18 <u>C</u>
Walk-behind harvester	Good	115.8±22.8 a	131.9±22.4 b	111.6±24.5 c	95.0±9.38 d
	Bruised	79.5±14.5 <u>a</u>	71.5±16.8 <u>b</u>	58.8±17.8 <u>c</u>	51.0±10.2 d
Mechanical harvester	Good	153±21.1 *A*	129±23.9 *B*	114±24.9 *C*	91.9±7.37 *D*
	Bruised	76.9±10.6 <u>*A*</u>	74.1±20.4 <u>*A*</u>	59.5±15.8 <u>*B*</u>	48.1±8.96 <u>*C*</u>
<u>Effect of plot conditions</u>		**Clean**		**Weedy**	
Hand raking	Good	127±36.1 A		124±31.6 A	
	Bruised	67.4±22.6 <u>A</u>		65.6±17.6 <u>A</u>	
Walk-behind harvester	Good	124±33.2 a		123±28.1 a	
	Bruised	63.6±16.3 <u>a</u>		66.7±20.6 <u>a</u>	
Mechanical harvester	Good	119.5±32.4 *A*		124.1±25.0 *A*	
	Bruised	62.4±16.1 <u>*A*</u>		65.8±20.8 <u>*A*</u>	

The temperature of the temporarily stored berries had a negative linear relationship with the firmness of the stored berries, i.e., increase in temperature of berries (before their harvest) linearly (R^2 = 0.64) decreased the firmness of the berries (measured right after their harvest) (Fig. 33). A similar relationship was determined between the fruit firmness and ambient air temperature (Fig. 34). In addition to the mechanical damage to the fresh blueberries during harvesting or postharvest handling (Xu et al., 2015), ambient air and/or storage temperature of blueberries also limits postharvest life and firmness of berries (Davies and Flore, 1986). Moggia et al. (2017) who evaluated if firmness of highbush blueberries at harvest impacts postharvest fruit softening found that the effects of variations in an ambient temperature between both seasons of their study were different between seasons and cultivars. They found that temperature extremes of 27, 29, and 32 °C led to early softening of the fruit. Literature suggests that an ideal range of temperatures for northern highbush blueberries might range 20–25 °C (Davies and Flore, 1986).

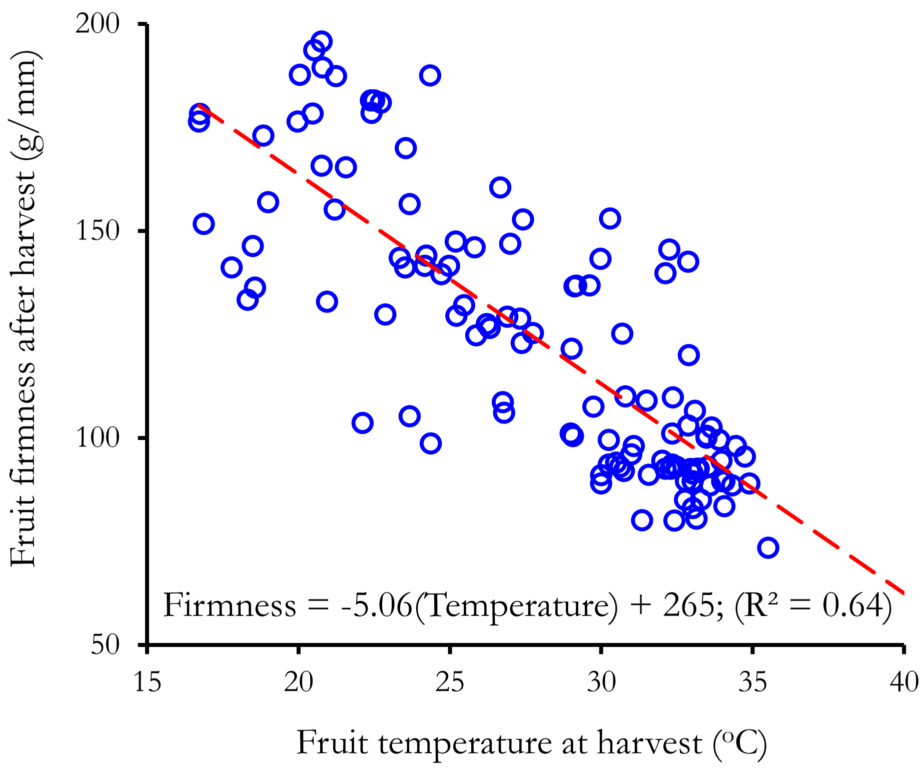

Figure 33: A negative linear relationship between berry firmness with their surface temperature is shown with a broken red line through scattered firmness data points that are drawn as hollow blue circles.

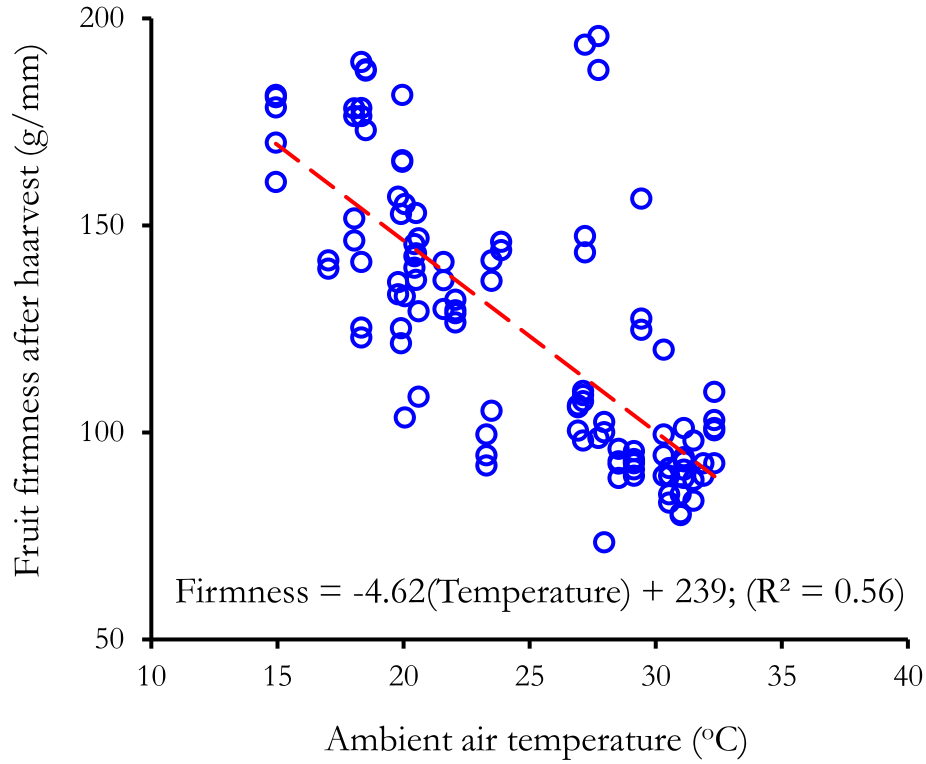

Figure 34: A negative linear relationship between berry firmness with ambient air temperature shown with a broken red line through scattered firmness data points that are drawn as hollow blue circles.

There was more increase in the temperature of the berries stored without a shade than in the temperature of shaded berries (Fig. 35). The temperature of shaded berries remained below the ambient air temperature. From 9:30 to 14:30, the temperature of berries under shade remained about 4 to 5 °C below ambient air temperature. The two temperatures became closer to one another from 15:00 to 18:00. However, the temperature of berries stored without a shade continued rising until it reached double the temperature of berries stored under the shade (about 20 versus 40 °C). The effect of cloud cover during different times of the day (notably during 11:15-11:30, 12:15-12:30, 13:30-14:00) is obvious in the temperature of berries kept under the sun. No effect of the presence of clouds was observed on the temperature of berries under the shade. The temperature of berries stored without a shade raised acutely during TH-III and TH-IV. A lesser effect was noticed during temperatures of TH-I and TH-II than the two high ranges of temperature at harvest.

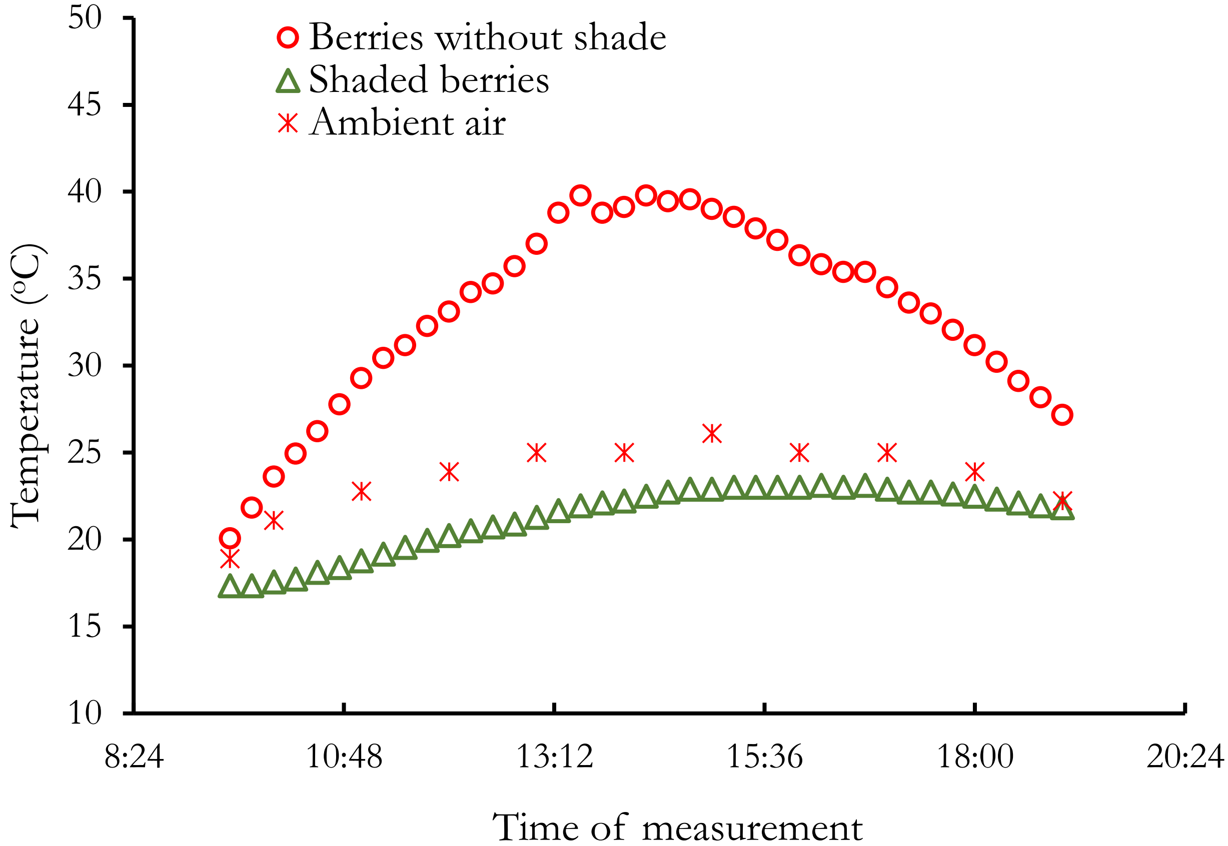

Figure 35: Temperatures of ambient air, berries stored with and without a shade measured from 9:30 through to 19:30 on August 22, 2021.

Table 14 contains results of a 2-sample t-test to compare the effect of berry storing conditions (i.e., temperatures of berries stored with versus without a shade). The results revealed a significant effect of storing conditions of berries on fruit temperature (P≤0.05). The mean temperature of berries stored under the shade (21.3 °C) remained significantly different and lower than the temperature of those stored without a shade (33.1 °C). Since there were larger variations in temperature of berries stored without a shade than the variations in temperature of berries stored under the shade (Fig. 35), standard deviations from the mean of the latter were lower than the former (Table 14).

Table 20: Results of the 2-sample t-test for means to compare the sets of fruit firmness data for berries stored with and without a shade.

Condition	**Number of observations**	**Mean (°C)**	**Stand Deviation from mean (°C)**	**Standard Error of Mean (°C)**	**P value**
Shade	39	21.26	1.91	0.31	0.000
No Shade	39	33.13	5.32	0.85	

3.7 Economic Analysis

Economic analysis showed a significantly different and higher income while harvesting at temperature ≤ 20 ºC than harvesting at > 20 ºC when considering the sale of soley good quality berries (Table 15). The field price income decreased by 8.08, 13.5, and 28.8% with harvesting at higher temperatures than 20 ºC, i.e., TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥ 30 °C), respectively (Fig. 36). This resulted in calculated losses of 721, 1,112, and 2,254 $/ha for harvesting and selling berries at TH-II, TH-III, and TH-IV, respectively than at TH-I.

Table 21: Results of one-way analysis of variance (ANOVA) for the significance of the effect of temperature at harvest on income ($/ha) of farmers selling good berries to a processor at a market rate of 1.76 $/kg.

Source	DF	Adjusted SS	Adjusted MS	F Value	P Value
Temperature at harvest	3	7987271	2662424	11.65	0.003
Error	8	1827510	228439		
Total	11	9814781			

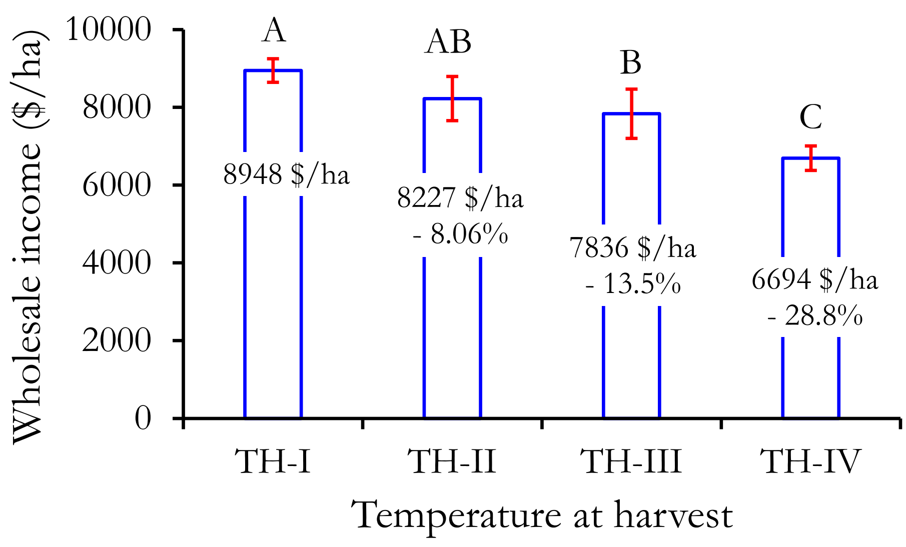

Figure 36: Decrease in income and percent decrease in the income of farmers for selling good berries, harvested at four temperatures at harvest including TH-I (≤ 20 °C), TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥ 30 °C) to processors at a market rate of 1.76 $/ha. The mean income values have been separated and labeled by standard error bars and Fishers' Least Significant Difference (LSD) letters (A, B, and C) for their significant difference among temperatures at harvest. The means with similar and/or shared LSD letters (i.e., A and AB) are not significantly from each other.

4. Conclusion and Recommendations

The project activities were performed in commercial wild blueberry fields of Nova Scotia in August 2021. The projective objectives included to 1) classify the most critical wild blueberry fruit quality characteristics, 2) adopt/develop novel methods to measure/quantify wild blueberry fruit quality, 3) determine harvesting parameters that optimize wild blueberry fruit quality, 4) develop an economic analysis encompassing fruit quality as a top priority and, 5) develop a factsheet to outline the parameters/conditions to optimize wild blueberry fruit quality during harvesting. The goal of this project was to aid wild blueberry farmers, processors, and stakeholders in making informed decisions about favorable harvesting conditions to maintain optimum fruit quality when harvesting wild blueberries for the fresh market. The project's targets were achieved through collecting and analyzing data to answer common questions about i) acceptable temperature range to harvest fields for maximizing fruit quality, ii) if the weeds (sheep sorrel, goldenrod, fescue grass) affect fruit quality, iii) the acceptable berry firmness range during harvest to maximize fruit quality, iv) the ideal weather conditions to harvest for maximizing fruit quality, v) the effect of berries stored with and without a shade on berry quality, and vi) if shading harvested berries has any effect on berry quality.

Harvest data were collected from grower fields in Middle Musquodoboit, Portapique, and New Glasgow, Nova Scotia that had the Nova Scotia representative wild blueberry cultivation and weather conditions. The fields were well managed with scattered weed patches. Each field had a blueberry harvest yield in the range of 12690±184, 4425±2623, and 2015±77.8 kg/ha, respectively. Therefore, the study results may be considered for fields conditions within the ranges of these yield limits, meteorological variables, and plant characteristics presented in the Results and Discussion section.

The study explored the effect of two factors of interest including i) the temperature at harvest and ii) plot conditions (clean versus weedy) on berry quality. The temperature at harvest had four levels comprising TH-I, TH-II, TH-III, and TH-IV to represent temperature ranges of ≤20, 20.1-25, 25.1-29.9, and ≥30 °C, respectively. The plot conditions had two levels/types of plots, i.e., clean and weedy plots. Berries were harvested with three harvesting methods namely hand raking, walk-behind harvester, mechanical harvester. The temperatures at harvest, weeds, and weather conditions significantly affected the berry quality. The high temperature at harvest, presence of weeds, and clear sunny weather conditions deteriorated the quality of the harvest berries. Ideal conditions for harvesting were below 20 °C and weed-free plots. Since temperature had a significant effect on berry quality, it is recommended to store the harvested berries under a shade to keep their temperature lower than the ambient air temperature before shifting them to the processing plants.

About 20-40% shrinkage was calculated from 60-80% of good berries that were collected with the three harvesting methods. Regardless of the harvesting methods, the shrinkage increased with an increase in temperature at harvest. This seemingly high shrinkage can be due to the strict rules followed for placing all berries with sensible slight soft skin or slight bruises in the category of bruised berries. The other reason may be the effect of temperature on berry quality. Presumably, berries with slight soft skins or light bruises are allowed through cleaning/processing lines. Practically, all such berries are not discarded, but they have a valuable consumption for their uses in making yogurt, juices, or milkshakes as less than 10% of berries are consumed fresh, and the rest are sold frozen or in the forms of their value-added products. Further, the economic analysis reflected that the calculated income decreased by 721, 1,112, and 2,254 $/ha for harvesting and selling berries at TH-II (20.1-25 °C), TH-III (25.1-29.9 °C), and TH-IV (≥ 30 °C), respectively than at TH-I (≤ 20 °C).

Most results of 2021 study concurred the findings of literature and those of the 2020 investigations. Further investigations are recommended for evaluating different combinations of methods of and temperatures at harvest and their effects on chemical components, i.e., nutritious value, of the harvested/stored berries of a variety of species grown in various parts of Canada. It would also be interesting to explore if the yield of a field (because of dense or sparce canopies) also contributes to the effects of temperature at harvest on the harvest quality.

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