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Harvest of Southern Highbush Blueberry with a Modified, Over-The-Row Mechanical Harvester: Use of Handheld Shakers and Soft Catch Surfaces

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Abstract: Fresh market southern highbush blueberries are typically hand-harvested which requires an extensive labor force over a relative short period of time. With rising production costs and labor availability issues, interest in mechanical harvesting options is increasing. In 2017, an over-the-row (OTR) harvester was modified to reduce purchase cost while making hand labor more efficient. The picking heads were removed and dual worker stations were added on each side of the unit. Handheld olive shakers were suspended at each station. Experimental catch plates were installed on one side of the OTR harvester and soft, inclined surfaces over the rigid conveyors on both sides. 'Meadowlark' and 'Farthing' blueberries were harvested with this system and compared to those manually harvested by a commercial harvest crew. Samples from each harvest method were then commercially cooled and mechanically harvested fruit were commercially packed to determine packout data. Fruit firmness, bruise severity and composition were determined after one day at room temperature (22 °C) and after seven and fourteen days of storage at 1 °C. Average packout was very high for mechanically harvested fruit, 87% for 'Meadowlark' and 91% for 'Farthing'. Initial firmness of both cultivars was lower for mechanically harvested fruit (208 g/mm) than hand-harvested fruit (243 g/mm). Fruit from the three treatments softened during storage, and although 'Meadowlark' remained firmer than 'Farthing' during storage, there were no differences due to catch surfaces. Hand-harvested fruit had no severe bruising (>20% of cut surface area) at harvest, increasing to 2% after seven days, while mechanically harvested fruit from both fruit collection surfaces had 3% initial severe bruising that increased to 22% during storage. 'Farthing' had slightly higher soluble solids content and significantly higher total titratable acidity compared to 'Meadowlark'. Additional modifications must be made to the next-generation OTR harvester to further reduce blueberry harvest and handling impacts.

Keywords: machine harvest; catch plate design; fruit quality; bruising; packout

1. Introduction

The vast majority of blueberry cultivars commercially grown in subtropical regions like Florida are the southern highbush blueberry type (*Vaccinium darrowi* × *V. corymbosum*). An advantage to growing southern highbush blueberries (SHB) in Florida is that they ripen from March or earlier in South Florida to May in North Florida. Historically, Florida-grown blueberries were the first domestic fruit available in the United States [1] and brought the highest prices on a per-pound basis ($8.18/kg) [2] due to declining availability of fruit from South America in February and March [2]. However, increasing shipments of blueberries from Mexico into the United States during this early season is reducing wholesale prices received by Florida blueberry growers. From 2009 to 2016, U.S. blueberry exports have remained flat (approximately 18,145 metric tons), while U.S. imports during that same period almost tripled [2]. SHB cultivars have historically been softer than northern highbush blueberry (NHB) (*V. corymbosum*) cultivars, limiting SHB to hand-harvest for fresh market. SHB are only mechanically harvested during the latter part of the season when it is no longer economical to harvest by hand. Mechanically harvested fruit may either go to the fresh or processed market depending on the cultivar and condition of the fruit. To reduce labor costs, blueberry growers in Florida, in other production areas across the United States and in major blueberry producing countries (e.g., Australia, Canada, Chile, and Poland), are increasingly showing interest in adopting mechanical harvesting for the fresh market from machine manufacturers such as Oxbo International Corp. (pers. comm).

Mechanical harvesters have been used to pick northern highbush blueberries (NHB) since the 1960s [3], primarily for fruit destined for processed products. However, mechanically harvesting blueberries for fresh-market and with good shelf life has been a challenge due to plant architecture, excessive ground loss, and rapid fruit softening incurred from mechanical impact damage [3–5]. Peterson et al. [6] demonstrated the superiority of the experimental V45 over-the-row (OTR) harvester to harvest NHB compared to a commercial harvester used at that time. Takeda et al. [4] continued trials with the V45 harvester on partially pruned rabbiteye (*V. virgatum* (syn. *V. ashei*) and SHB cultivars so that V45's diagonally oriented shaker drums would not cause excessive damage to blueberry plants. Although pruning increased the number of marketable fruit, the selective removal of blue fruit remained a challenge. Studies with 'Meadowlark' and 'Farthing', two SHB cultivars from the University of Florida blueberry breeding program, have shown the potential for repeated harvests by commercial harvesters instead of hand harvest [5,7,8].

The use of harvest aids such as handheld shakers is a low-cost option compared to more costly OTR harvesters, and handheld shakers were shown to reduce labor costs by increasing blueberry harvest efficiency [9,10]. Takeda et al. [11] found that harvesting blueberries with handheld shakers in conjunction with a portable, soft catch surface frame resulted in less bruise damage than commercial OTR harvesters. However, the ergonomics of using unsupported, handheld shakers while standing on the ground was a concern as the weight, vibration and extended use could lead to musculoskeletal disorders and, without any mechanical fruit conveyance system on the portable harvesting frame, the overall harvest efficiency did not improve over hand harvesting [11,12].

In 2017, further tests were conducted in Florida, California, Oregon, and Washington to harvest blueberries with an OTR harvester (Oxbo 7240, Oxbo International, Lynden, WA USA) with several key modifications: (1) a platform with two heights was installed on each side of the OTR harvester between the front and rear wheel wells for human operators to stand on and work the shaker while looking down at the bush, (2) the handheld shakers were suspended from the overhead frame of the OTR harvester. The shaker to be operated from the higher platforms had a 1-m-long handle and the shaker to be operated from the lower platforms had a 0.5-m-long handle, (3) the hard polycarbonate catch plates were replaced with soft fruit catch plates [13] on one side of the harvester by the harvester manufacturer, and (4) intermediate soft sheets were installed over the rigid conveyor as described in a recent companion article by DeVetter et al. [14]. The first two modifications were intended to increase harvest efficiency while reducing worker fatigue. The latter two modifications were installed to eliminate the falling fruit from directly landing on the hard conveyor belt. The goal of this research was to determine SHB fruit quality and storage life after harvest with an OTR harvester fitted with handheld, semi-mechanical fruit shakers and soft fruit catching surfaces compared to hand-harvested fruit.

2. Materials and Methods

2.1. Field Conditions and Modified Mechanical Harvester Description

In spring 2017, two commercially grown, SHB cultivars were harvested in Waldo, Florida. Previous harvests determined that the fruit from 'Meadowlark' and 'Farthing' cultivars were sufficiently firm to withstand mechanical harvesting; these conclusions were based on harvesting one plant at a time with an electric, handheld shaker and collecting the fruit in a portable catch frame placed around the base of the bush [9]. The blueberry plants used for the current study were five years old and mechanically top-hedged in previous seasons. In February 2017, preharvest pruning was performed to remove several upright or cross-arching, stiff branches from the middle of each plant essentially creating a divided canopy (Figure 1). For each cultivar, the rows were divided into four field blocks of 17 bushes each. 'Meadowlark' was harvested on 19 and 25 April 2019 and 'Farthing' was harvested on 20 and 27 April and 2 May 2019 with a modified OTR harvester (Model 7240; Oxbo International Corporation, Lynden, WA). The rotary drum shakers were removed, and on each side of the harvester tunnel openings were made to accommodate a platform work station for two workers (Figure 2). Two pneumatic olive shakers (Campagnola S.R.L.; Bologna, Italy) were attached to suspended tool balancers at each work station and fruit catching surfaces were installed on each side of the harvester tunnel.

Figure 1. 'Meadowlark' (**a**,**b**) and 'Farthing' (**c**,**d**) southern highbush blueberries (SHB) blueberry plants before and after selective branch removal performed prior to mechanical harvest in February 2017. 'Meadowlark' and 'Farthing' plants were, respectively, ~1.8 m and 1.5 m tall. The branches of 'Meadowlark' tend to grow upright while 'Farthing' produces a canopy with more branched limbs. Note the pruning removed some of the mature, stiff branches in the interior of the plant canopy. These photos also show where the branches were top-hedged (e.g., large diameter light-colored branches at bottom-half of the bush. The flower-bearing, one-year-old branches (e.g., small-diameter, brown-colored, 0.4-m-long) are located on top half of the plant with typically as many as 12 fruit clusters, each with a few to ten fruit on.

On each side of the harvester tunnel, an inclined frame was affixed over each hard conveyor belt. Modification No. 1 consisted of installing canvas fabric over the frame on one side, leaving the original hard-polycarbonate catch plates (Figure 3, left) [13]. Modification No. 2 consisted of installing a thin, stretchable neoprene sheet over the frames on the other side of the harvester tunnel and the hard polycarbonate catch plates were replaced with soft catch plates (Figure 3, left). The soft catch plates were fabricated by modifying a commercial, hard polycarbonate catch plate (6.1 mm thick) whose middle was cut out leaving a 2.5 cm-wide ring (Figure 3, right). A 6.1 mm-thick neoprene sheet with approximate dimensions of the polycarbonate catch plate was placed on top of the hollowed-out catch plate. A 2 mm-thick by 2.4-cm wide stainless steel ring, with the same perimeter dimensions as the hollowed-out catch plate, was placed on top of the neoprene sheet, and the three components were fastened together with screws. On each side, the respective materials used to cover the conveyor belt were installed at inclined plane partially up the hard side panel (Figure 3).

Figure 2. Left: Front view of modified over-the-row (OTR) harvester during harvest. **Right**: Side view showing platform work station openings on each side of the structure between the front and rear wheel housings. Each work station has two platform heights to permit one worker to harvest lower fruit and the other worker to harvest higher fruit on the bush.

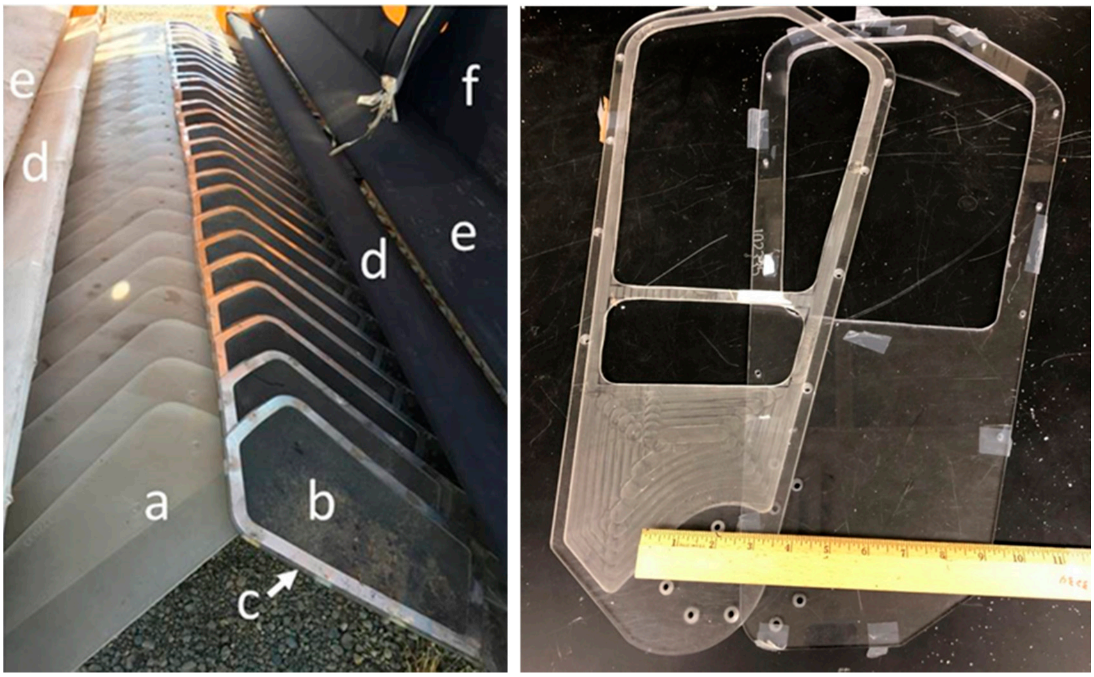

Figure 3. Left: Front view of the harvester tunnel showing catch plates and covered conveyor configuration. Commercial, rigid plates (**a**), soft catch plates (**b**) with stainless-steel fastening ring (**c**). On both sides, intermediate, soft surfaces covered the conveyor belts (**d,e**) and partially visible side wall (**f**). **Right:** Detail of modified, rigid catch surface plates shown with one plate overlapping an adjacent plate. A 6.0 mm neoprene sheet in the dimensions of the catch plate was fabricated and sandwiched between the catch plate and a 2.4-cm-wide stainless steel ring.

2.2. Blueberry Harvesting Operation with Handheld, Pneumatic Shaker

The tines on the shakers had lateral displacement of 7.5 cm and a reciprocal action of 7 Hz. In order to maximize the transmission of vibration amplitude from the tines to the fruit, the tines engaged almost the entire length of each one-year-old branch, causing the branches to move laterally. The worker operating from the higher platform used a shaker with a 1.0-m-long handle and engaged the branches on the distal side of the plant by placing the tines on one-year-old branches while at the same time pushing the branches outward, away from the middle of the plant (Figure 4). The operators on the lower platform used a shaker with a 0.5-m-long handle and engaged the tines of the shaker on proximal branches on the lower half of the plant. The workers were instructed to use a push-pull action on the suspended shaker while at the same time changing the vertical angle of the shaker to engage a 0.4-m section from bottom. The shaker was angled upward until most if not all blue fruit were detached from branches in a 30-cm swath. This process was quickly repeated on the next set of branches as the OTR moved forward down the row with a ground speed of 0.3 km/h. The push action of the shaker forced the branches on the top-half of the plant to be displaced away from the crown to maximize detached fruit falling onto the catching surfaces. When one of the shaker operators noted all fruiting branches were not being engaged in his assigned sector, he pushed a button to stop the forward movement of the OTR harvester to complete the shaking before the harvester resumed moving forward.

Figure 4. Left: Rear view showing workers operating the shakers from both sides of the OTR harvester. **Right:** Top view of a worker standing on the platform and operating the handheld pneumatic shaker (**a**).

2.3. Harvest, Sorting and Packing

An analysis of the fruit conveyance process in the modified OTR harvester was conducted by visually observing the movement of fruit from detachment from the plant to dropping into the field lug. The harvested fruit were transported over four transition points:

*Point 1: Harvested fruit landed on the respective catching surface (e.g., intermediate catching surfaces or catch plate) and either rolled or bounced onto the conveyor belt (Figure 3). The conveyor belt was positioned ~7.5 cm below the midsection of the catch plate. The conveyor belt moved the fruit to the rear of the harvester.

*Point 2: Fruit on the conveyor belt dropped 20 cm into a moving canvas-made bucket of the vertical bucket elevator which lifted the fruit to the top level of the harvester (Figure 5).

Figure 5. Rear view of a rigid conveyor without the soft surface covering, (**a**) transferring fruit to elevator lift in horizontal position (**b**), prior to elevating to the top level of the harvester.

*Point 3: At the top of the harvester, the bucket elevator dumped the fruit 30 cm onto a horizontal, hard plastic conveyor belt (Figure 6a,b) which moved under a trash removing suction blower (Figure 6c).

Figure 6. Rear-facing view of the top level of the OTR harvester showing the separate conveyor systems (**a**,**b**) for fruit collection from the respective side of the catch plates below. The fruit were lifted to the top level of the harvester and dropped onto a short conveyor belt which moved the fruit under an air classifier (**c**) to separate leaves and other debris before dropping into a lug (**d**).

*Point 4: Fruit dropped from the conveyor belt into lugs (Figure 6d). Filled lugs were stacked on a pallet on the top platform for later off-loading. The drop from the conveyor belt to the bottom of the lug was 30 cm.

At each harvest, fruit from the same cultivars were hand-harvested (HH) from an adjacent row and placed into lugs for later comparison to mechanically harvested fruit. Within two hours of harvest into field lugs, 'Meadowlark' fruit were transported in an air-conditioned vehicle to the Postharvest Horticulture Laboratory at the University of Florida in Gainesville; mechanically harvested fruit were hand-sorted by color (green, red, blue) and culls (soft, shriveled and chaff). Blue (ripe, marketable) fruit (mechanically harvested and HH) were then packed into 125 g (4.4 oz) clamshells (H144, Highland Packaging Solutions, Plant City FL). 'Farthing' fruit were collected on both sides of the harvester at Transition Points 2 and 4 for a single harvest and fruit firmness and bruise damage was determined. 'Farthing' fruit were palletized in the field and quickly transported to the nearby packinghouse where they were partially forced-air cooled to 10 °C. That same day, lugs from each treatment (n = 4) were transferred onto a commercial packing line where samples were taken at four points: (1) inline color sorter (removed green and red fruit), (2) soft fruit sorter (Woodside Electronics Corp., Woodland, CA), (3) culls (hand-sorted to remove soft, shriveled fruit) and (4) after packing into 170 g clamshell containers. HH 'Farthing' fruit were packed directly into clamshell containers after harvest and not run over the packing line. Fruit from each sample point were weighed and percent distribution calculated from the total amount for that lug. Following sorting, samples for initial fruit quality were held at room temperature (22 °C) overnight to allow for bruise development; remaining samples for storage were immediately placed at 1 °C (91% relative humidity, RH). Fruit quality was determined for 'Meadowlark' after 7 days and for 'Farthing' after 7 and 14 days.

2.4. Firmness

Firmness of individual blueberries (n = 25) was measured at the equator using a FirmTech 2 texture analyzer (BioWorks, Inc., Wamego, KS, USA). After firmness measurement, each fruit was sliced through the equatorial plane and the cut surfaces imaged by a color camera, and then frozen at −30 °C for later compositional analysis. The images of sliced fruit were later rated for bruise severity by estimating the area of internal discoloration on the cut surface of each fruit (n = 25) using a scale from 0 (no bruising) to 100 (entire surface bruised) [3]. Previous studies showed that northern highbush and rabbiteye fruit with less than 25% bruising maintained acceptable quality for several weeks in storage [3,6]. For this study with SHB, individual fruit were considered marketable when <20% bruising was apparent on the cut surface.

2.5. Soluble Solids Content (SSC) and Total Titratable Acidity (TTA)

To determine blueberry composition, samples were thawed, homogenized, and centrifuged at 17,600× g for 20 min. The blueberry juice supernatant was filtered through cheesecloth and was used to determine soluble solids content (SSC), total titratable acidity (TTA) and pH. SSC was determined with a digital benchtop refractometer (model r2i300, Reichert Technologies, Depew, NY, USA) and expressed as °Brix. TTA and pH were determined using an automatic titrimeter (model 905 Titrando; Metrohm Ion Analysis, Switzerland). Blueberry juice (3 ml) was diluted with 50 mL deionized water and TTA was determined by titration with 0.1 N sodium hydroxide (NaOH) to an end point of pH 8.2. TTA was expressed as percent citric acid.

2.6. Statistical Analysis

The tests were set up using a Completely Randomized Design and analyzed by cultivar (SAS 9.4; SAS Institute Inc., Cary, NC, USA). Means were separated using Tukey's honestly significant difference test at $p \leq 0.05$.

3. Results

3.1. Fruit Quality

There was no significant effect of harvest time on the variables measured; therefore, results by harvest time were combined for each cultivar. Marketable packout after mechanical harvest was high for both 'Meadowlark' (87%) and for 'Farthing' (91%) (Table 1). However, packout distribution (blue [ripe, marketable], color [green/red], and culls) by catch surface was only significantly different for 'Farthing', where fruit collected from the side with the hard catch plates (HCP) had 2.7% higher packout than those from the side with the soft catch plates (SCP). 'Meadowlark' was more difficult to selectively harvest blue fruit, having two-to-three times more color defects than 'Farthing' (Table 1). However, in contrast, 'Farthing' was much more sensitive to mechanical harvest, in that the number of culls was 3% to 4% higher than for 'Meadowlark'. Only 'Farthing' was sorted on the commercial packing line with the automated soft berry sorter; the amount of soft fruit removed was negligible (<0.5%) and there was no difference due to catch surface.

Table 1. Packout distribution day of harvest for 'Meadowlark' (manually sorted) and 'Farthing' (commercially sorted) blueberries after mechanical harvest onto soft or hard catch plates.

Cultivar	Treatment	Marketable (%)	Defect ^{z} (%)		
			Color	Cull	Soft
'Meadowlark'	SCP ^{y}	86.49 a ^{x}	12.17 a	1.34 a	-
	HCP	88.37 a	10.82 a	0.81 a	-
'Farthing'	SCP	89.41 b	5.64 a	4.50 a	0.46 a
	HCP	92.11 a	4.19 a	3.32 b	0.38 a

^{z} Color (green, red); cull (soft, shriveled); soft (automatic sorter on packing line, 'Farthing' only). ^{y} SCP = soft catch plates; HCP = hard catch plates. ^{x} Means followed by the same lowercase letter within a column and by cultivar are not significantly different according to Tukey's honestly significant different test, $p \leq 0.05$. Data represent the mean (n = 4 clamshell containers) averaged across harvest times for each cultivar.

3.2. Firmness

Mechanically harvested 'Meadowlark' and Farthing' fruit were initially softer (overall mean = 218 g/mm) than those that were hand-harvested (244 g/mm) (Table 2), and HCP fruit were slightly softer (213.9 g/mm) than SCP (223.1 g/mm). After 7 days of cold storage at 1 °C, 'Meadowlark' firmness remained constant for SCP and HCP, while for unknown reasons HH firmness was actually higher than that for the initial samples. For 'Farthing', fruit from all treatments softened after 7 and 14 days of storage, and fruit that impacted the SCP were slightly firmer than those that impacted the HCP (Table 2). However, fruit sampled at Transition Points 2 and 4 showed no significant differences in firmness due to catch surface or number of transition points.

3.3. Bruising

Mechanically harvested fruit had more initial severe bruising (>20% of cut-fruit surface area) than HH fruit and remained higher during storage; there was no difference due to catch plate type. 'Farthing' had higher severe bruising after harvest (8.5%) than 'Meadowlark' (2.8%) (Table 3). After 7 days at 1 °C, bruising for mechanically harvested fruit increased to similar levels, approximately five-to-seven times for 'Meadowlark' and approximately two times for 'Farthing'. Bruising in 'Farthing' remained unchanged after 14 days storage. Catch plate type did not affect bruising throughout storage.

Table 2. Fruit firmness of 'Meadowlark' and 'Farthing' blueberries, after hand or mechanical harvest onto soft or hard catch plates, at harvest (24 hr at 22 °C) and during storage at 1 °C. (At each sampling time n = 25; means were averaged across harvest times for each cultivar.)

Firmness (g/mm)				
Cultivar	**Storage (d)**	**HH [z]**	**SCP**	**HCP**
'Meadowlark'	1	245.0 bA [y]	221.8 aB	214.6 aB
	7	262.3 aA	221.4 aB	213.1 aB
'Farthing'	1	243.3 aA	223.1 aB	213.9 aC
	7	236.6 bA	207.1 bB	196.9 bC
	14	227.6 cA	193.2 cB	184.4 cC

[z] HH = hand harvest; SCP = soft catch plates; HCP = hard catch plates. [y] Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter in a row, are not significantly different according to Tukey's honestly significant different test, $p \leq 0.05$.

Table 3. Internal bruise severity for 'Meadowlark' and 'Farthing' blueberries at harvest (24 hr at 22 °C) and during storage at 1 °C. Unmarketable fruit: >20% cut surface discoloration. (At each sampling time n = 25; means were averaged across harvest times for each cultivar).

Unmarketable Fruit Due to Severe Bruising (%)				
Cultivar	**Storage (d)**	**HH [z]**	**SCP**	**HCP**
'Meadowlark'	1	0.0 bA [y]	3.0 bA	2.5 bA
	7	2.0 aB	22.0 aA	12.0 aAB
'Farthing'	1	0.0 aB	8.7 bA	8.3 bA
	7	0.7 aB	19.1 aA	18.3 aA
	14	0.7 aB	19.7 aA	16.0 abA

[z] HH = hand harvest; SCP = soft catch plates; HCP = hard catch plates. [y] Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter in a row, are not significantly different according to Tukey's honestly significant different test, $p \leq 0.05$.

3.4. SSC and TTA

Neither catch plate type nor storage period affected SSC or TTA within cultivar, with the minor exceptions in TTA for HH and HCP for 'Meadowlark'. 'Meadowlark' had slightly lower overall means for SSC (12.1 °Brix) compared to 'Farthing' (13.5 °Brix). TTA for 'Meadowlark' was roughly 1/3 lower (0.33%) than that for 'Farthing' (0.47%); the SSC/TTA value for 'Meadowlark' was somewhat higher than that for 'Farthing', indicating possibly sweeter flavor (Table 4).

3.5. Modified OTR Harvester Limitations

These initial harvesting trials with the prototype fruit catching surface design and handheld shakers revealed several limitations in harvesting SHB cultivars.

1. Soft catch plates were not sufficiently slanted such that fruit accumulated on the neoprene insert (Figure 7). In addition, the catch plates were angled too high from the front edge to the back edge, creating sufficient space for fruit to roll between adjacent catch plates and become lodged and damaged.

2. Catch plates did not easily slide over and under adjacent plates, so that when they were pushed back by the blueberry plant, some plates did not spring back to their original position. This created large gaps between the fruit catching plates, allowing many fruit to fall to the ground.

Table 4. Soluble solids content (SSC), total titratable acidity (TTA) and SSC:TTA ratio for 'Meadowlark' and 'Farthing' blueberries, after mechanical harvest onto soft or hard catch plates, after harvest (24 hr at 22 °C) and during storage at 1 °C. (At each sampling time n=25; means were averaged across harvest times for each cultivar).

Cultivar	Storage (d)	SSC (°Brix)			TTA (%)			SSC:TTA Ratio		
		HH [z]	SCP	HCP	HH	SCP	HCP	HH	SCP	HCP
Meadowlark	1	11.95 aB [y]	12.31 aA	12.08 aAB	0.38 aA	0.31 aA	0.27 bA	38.26 bA	42.16 aA	46.59 aA
	7	12.36 aA	11.94 aA	11.94 aA	0.24 bB	0.37 aAB	0.4 aA	52.58 aA	36.41 aB	31.76 bB
Farthing	1	13.98 aA	13.48 aB	13.08 aC	0.49 aA	0.49 aA	0.49 aA	28.97 aA	27.57 aA	27.6 aA
	7	14.03 aA	13.78 aA	13.43 aA	0.45 aA	0.44 aA	0.45 aA	31.27 aA	32.18 aA	30.42 aA
	14	13.96 aA	13.46 aB	13.57 aAB	0.48 aA	0.48 aA	0.44 aA	29.56 aA	28.06 aA	31.87 aA

[z] HH = hand harvest; SCP = soft catch plates; HCP = hard catch plates; SSC = soluble solids content; TTA = total titratable acidity (% citric acid). [y] Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter in a row for each parameter, are not significantly different according to Tukey's honestly significant different test, $p \leq 0.05$.

3. The white canvas-like sheet was not tightly stretched and the resultant sag prevented detached blueberries from rolling onto the conveyor belt underneath. Wherever fruit pooling occurred, the harvester had to be stopped and the fruit manually pushed onto the conveyor belt.

4. It was difficult to selectively remove ripe fruit with the handheld shakers. If the vibration frequency to the abscission zone was too low, no fruit detached. However, if the vibration frequency was excessive, there was no selectivity and fruit of all ripeness stages (green, red, blue) detached.

5. The catch plate modifications did not create an entirely soft surface. The modified catch plate had a 2.4-cm wide stainless steel ring around its perimeter. The plates were mounted onto the harvester such that one plate covered ~50% of the plate that was positioned behind it and covered by the plate that was positioned in front of it (Figure 3).

6. There was the possibility that the soft catch plate design and catch plate movements contributed to quality loss. Each catch plate had a rod attached near its base (Figure 3). The rod was inserted into receptacle placed at a specified distance on a rail which is bolted onto the harvester frame. At the base of the catch plate, a strong spring was attached between the plate and the rail on which the plates were mounted. As the OTR harvester moved forward, the catch plates sequentially contacted branches, and sprung back at the speed of 11 cm/sec as the branch passed. It was observed that when the detached blueberries did not quickly roll off the catch plate (Figure 7), the back edge of the plate impacted the fruit due to the rapid spring-back motion.

Figure 7. Front view of the OTR harvester tunnel after harvest of SHB fruit. **Left**: The disorganization of the soft catch plates allowed pooling of harvested fruit on the soft material insert (arrow). **Right**: The harvested fruit accumulated on the loose intermediate soft-catching surface located above the conveyor belt (arrow).

4. Discussion

Widespread adoption of mechanically harvest of SHB cultivars destined for fresh market is a challenge for growers due to bruising, excessive ground loss, removal of immature fruit, and other types of injuries incurred during the harvest operation. Previously in 2009 and 2010, 'Meadowlark' and 'Farthing' were harvested two or three times with a commercial harvester (Korvan 8000, Oxbo International, Lynden, Washington, USA). Fruit quality was not affected by harvest time (early, mid, and late season). However, after two weeks of storage at 1 °C fruit quality decreased, where mechanically harvested fruit had lower appearance and firmness ratings, and higher shriveling than hand-harvested fruit [7]. In separate tests during those same seasons, Takeda et al. [5] used the same Korvan 8000 harvester and reported an acceptable packout for 'Farthing' (87%) compared to hand-harvested fruit (94%), but as in the previously cited work, mechanically harvested blueberries softened to a greater extent and had more bruising than hand-harvested fruit after 7 days storage at 2.2 °C.

Controlled impact tests that simulated mechanical harvest of currently grown SHB cultivars found cultivar differences in susceptibility to bruising; 'Farthing' (used in the present study) was moderately susceptible to bruising from single impacts of 60 or 120 cm onto a hard surface, while impacts onto a cushioning pad reduced bruise incidence by about 2/3 for both drop heights [8]. Other factors reported to contribute to higher packout rates include specialized pruning practices, and availability of cultivars with firmer fruit and with longer pedicels that facilitate better contact with the harvester (reducing the amount of red and green fruit removed during harvest) [11,15]. Two previous studies demonstrated the critical role of soft catch surfaces in reducing bruising in SHB blueberries [9,11]. Handheld, pneumatic shakers were used to harvest blueberries that were collected in a portable frame (W = 1.0 m by L = 1.5 m) with a net fabric or neoprene sheet fabric stretched across the frame. With this harvest method, the potential of harvested blueberries dropping onto a hard surface was minimal to nonexistent. In the current study, much of the hard fruit catching surfaces were covered with softer neoprene or canvas-like sheet material. However, a closer analysis of the modified fruit catching surface revealed that 27% of the catching surface was actually covered with stainless steel rings. In addition, the soft fabric material for the inclined surface over the conveyor belts was wrapped around the metal frame on two sides which resulted in 22% of the inclined surfaces to be hard. Blueberries falling onto these hard surfaces during harvesting would most likely be bruised.

Manually graded 'Meadowlark' fruit had more than twice the percent of unripe fruit than commercially graded 'Farthing' fruit (Table 1). It is possible that our grading in the laboratory was more severe to that obtained by the electronic and optical sorting equipment and commercial packing labor. Fruit firmness for 'Meadowlark' and 'Farthing' following harvest (Table 2) was comparable to that reported by Takeda et al. [5] for these same cultivars harvested with unmodified, commercial harvesters. Firmness for 'Draper', a NHB cultivar also harvested with handheld shakers, was similar (239 g/mm) to the SHB cultivars harvested in the present study. However, these SHB cultivars were firmer than NHB cultivars 'Legacy' and 'Liberty' (178 and 152 g/mm, respectively) [11]. In another study that harvested NHB cultivars with handheld shakers, 'Elliott' and 'Aurora' were also softer (155 and 172 g/mm, respectively) than the SHB cultivars in this study [16]. In these reports, there were minimal differences in bruising due to catch surface type. Most likely, the lack of difference in bruising was due to suspension of soft catch surfaces over the rigid conveyors on both sides of the harvester, protecting the majority of blueberries from directly striking the hard catch surface. As evidenced with 'Farthing' during storage, bruise development did not progress further after 7 days at 1 °C (Table 3).

The cultivar differences in SSC and TTA in this study (Table 4) followed similar trends to those reported in a previous study using a handheld shaker, in which 'Meadowlark' also had significantly lower TTA than 'Farthing' [9]. The authors found that MH fruit had consistently lower TTA and greater mean fruit weight than HH fruit following harvest, irrespective of time of harvest (early, mid or late season). They attributed these differences to the 14-day interval between mechanical harvests, whereas HH occurred twice weekly, the commercial standard. Thus, at a given harvest, a greater proportion of riper blueberries (with lower TTA) would have been harvested mechanically. It is also likely that fruit that turned blue just prior to harvest would have had higher TTA and be firmer than those fruit that turned blue 7 to 10 days earlier.

It is less likely that harvest impacts reduced blueberry TTA; blueberries at 30 °C were dropped once from 60 cm (simulating commercial mechanical harvest) had up to four times higher respiration rate and greater than twice the ethylene production than undropped fruit at the same temperature without a resultant effect on TTA [17]. Impacted fruit did not have lower TTA than HH in another study by Casamali, et al. [9] nor in the present study.

Fruit detachment force was determined over several years for 'Meadowlark' and 'Farthing' fruit at green, red and blue color stages [18]. The technique involved securing the branch with one hand, placing a double-pronged probe over the pedicel and slowly pulling the individual fruit straight from the pedicel until detachment. A force gauge attached to the probe registered the detachment force in Newtons. Green fruit typically required a higher detachment force than blue fruit for both cultivars.

Although blueberries weren't tagged so as to determine length of time blue fruit remained on the bushes, field managers at Straughn Farms indicated that significantly more blue fruit fall to the ground when the hand harvest interval is delayed more than three days.

A recent report determined the effect of canopy shaker vibration on hedgerow olive trees harvested with a "straddle harvester" [19]. Tri-axial accelerometers were suspended in the trees to determine the correlation between vibration time and acceleration range. Although this automated system was not directly comparable to the hand shakers used in the present study, the authors concluded that there was a significant damping effect of the tree branches on the shaker vibration time as the harvester passed down the row and that the vibration time /acceleration range correlation was found to be a critical factor for optimizing olive fruit quality at harvest. Previously, Takeda et al. (11), used a tri-axial accelerometer to record vibration amplitude generated by a handheld olive shaker. The accelerometer was attached at different distances from the shaker engagement point near the base of an approximately 1-m long blueberry branch. The data recorded by the accelerometer revealed that vibration amplitude was highest near the engagement point, gradually decreasing to 30% at the top section of the branch. It was also observed that larger diameter branches registered much lower levels of vibration at all measurement sites. Other studies with commercial OTR blueberry harvesters [4,5] indicated that 50 to 70% of blue-colored fruit can be easily removed while less than 10% of green/red/immature berries were removed from the bush.

Although green and blue fruit were segregated based on fruit removal force, further tests revealed that this method did not accurately reflect the manner in which the handheld shaker removed the fruit. A slow-motion video analysis was made of the tines on a handheld shaker engaging fruit-bearing branches. The video revealed that blueberries detached in two ways: (1) When the tines were placed around the branch, the vibration traveled up the branch causing one or more fruit in loose clusters to sway perpendicular to the axis of the pedicel. As vibrational frequency increased, the lateral displacement of the fruit became sufficiently high to cause the fruit to separate from the abscission layer of the pedicel. However, on tight clusters individual fruit did not sway independently; in this case the entire cluster could detach with excessive vibration. (2) When the vibrating tines were placed against the side of the branch with sufficient force, the branch was quickly displaced laterally. In the case of fruit positioned parallel to the direction of the branch displacement, their displacement was momentarily delayed because of its mass. When the quick pull-away motion exceeded the binding force of the abscission layers at either end of the pedicel (fruit or subtending branch), fruit detached.

5. Conclusions

Adoption of mechanical harvest for SHB requires the coordination of many factors, from cultivar selection to cultural practices to harvester design and operation. As increasing numbers of SHB growers replace large manual-harvest crews with fully mechanized OTR harvesters, the development of mechanical OTR harvesting systems capable of harvesting high quality fruit has become more critical.

This study focused on two components of OTR mechanical harvesting system: (1) detachment of blueberries with a semi-mechanical harvesting system which consisted of workers positioned on a mobile platform (e.g., modified OTR harvester) and detaching blueberries with handheld pneumatic shakers and, (2) addition of an experimental fruit catching surface that was affixed to modified catch plates on one side of the harvester. Small-sized blueberry farms would be economically challenged to purchase OTR harvesters. A semi-mechanical harvesting system could be an option for the small-sized blueberry farms facing labor shortages. However this semi-mechanical harvesting system is not practical for large-scale blueberry growers who make up the majority of blueberry acreage in the United States. Operators of handheld shakers encountered repetitive motion, awkward and/or sustained postures, prolonged standing and vibration which can cause fatigue and various risks to their upper limbs [12].

Past research demonstrated the potential of using soft catch surfaces on a modified OTR harvester to improve packout similar to those achieved by hand harvest. In particular, the work of Peterson et al. [6]

with the V45 blueberry harvester is noteworthy in that the V45 harvester had a unique design feature that positioned the fruit-bearing branches within 30 cm of padded catch plates. The combination of soft fruit catch surface and decreased fruit drop height contributed to reducing bruise damage. In the current study, upright blueberry plants harvested with handheld shakers allowed fruit to drop up to 1 m onto the catching surface. The modifications incorporated into the experimental harvester were not sufficient to reduce impact on blueberries that had fallen >60 cm.

This study identified several key limitations of OTR blueberry harvesters, specifically those related to the fruit catch surface design: (a) modified catch plates must be installed on the OTR harvester so that detached blueberries that land on the surface are transferred quickly onto the conveyor belt, and (b) catch plates must be installed on the rail system so that when catch plates slide over adjacent catch plate there is no gap to prevent the possibility of blueberries getting sandwiched between them. With catch plates rapidly sliding over one another there is the potential of a detached fruit resting or rolling on one catch plate can be impacted from the side by the adjacent catch plate moving across over the plate. Mechanically harvested blueberries are satisfactory for fresh consumption when consumed up to two weeks after harvest. However, the likelihood of shipping blueberries harvested by the conventional harvesters to distant domestic and foreign markets is still problematic. Researchers and manufacturers must work cooperatively to foster changes in machine designs and harvesting methods and processes to develop a harvesting system that will not cause damage that contributes to rapid deterioration of quality while the fruit is in cold storage or transit.

To date, machine manufacturers have designed harvesters with increasingly higher fruit handling and loading capacity, and with shaker mechanisms designed to be more gentle to blueberry fruit and with greater fruit removal selectivity settings. However, additional harvester design changes are necessary to further reduce bruise damage and maintain higher fruit firmness. Improving selectivity of fruit detachment is critical, but additional modifications should focus on the fruit catching surface design and material, and on reducing the number of transfer points and their corresponding drop heights. The manufacturer involved in our research is addressing these issues. Future research will use a next-generation OTR harvester that has undergone further design improvements in catch plate design and changes to transition points that reduce impact force on falling fruit and compare the effects of these harvester modifications on blueberry fruit quality compared to fruit harvested conventional, non-modified OTR harvesters.

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