HortScience 51(12):1503–1510. 2016. doi: 10.21273/HORTSCI11323-16

Mechanical Harvesting and Postharvest Storage of Two Southern Highbush Blueberry Cultivars Grafted onto *Vaccinium arboreum* Rootstocks

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Additional index words. grafting, sparkleberry, *Vaccinium corymbosum* interspecific hybrid, yield, packout efficiency, fruit quality

Abstract*. The profitability of the fresh market blueberry industry in many areas is constrained by the extensive use and cost of soil amendments, high labor requirements for hand harvesting, and the inefficiencies of mechanical harvesters. *Vaccinium arboreum* Marsh is a wild species that has wide soil adaptation and monopodial growth habit. It has the potential to be used as a blueberry rootstock, expanding blueberry production to marginal soil and improving the mechanical harvesting efficiency of cultivated blueberry. The objectives of this research were to compare yield, berry quality, and postharvest fruit storage of own-rooted vs. grafted southern highbush blueberry (SHB) cultivars (Farthing and Meadowlark) grown on amended vs. nonamended soil and either hand or mechanical harvested. Yields of hand-harvested SHB during the first two fruiting years were generally greater in own-rooted plants grown on amended soil compared with own-rooted plants on nonamended soil or grafted plants on either soil treatment. However, by the second fruiting year, hand-harvest yields of grafted SHB were ≈80% greater than own-rooted plants when grown in nonamended soil. Yields of mechanical-harvested SHB grafted on *V. arboreum* and grown in either soil treatment were similar to yields of mechanical-harvested own-rooted plants in amended soil the second fruiting year, and greater than yields of own-rooted plants in non-amended soil. In general, mechanical harvesting reduced marketable yield ≈40% compared with hand harvesting. However, grafted plants reduced ground losses during harvest by ≈35% compared with own-rooted plants for both cultivars. Mechanical-harvested berries had a greater total soluble solids:total titratable acidity ratio (TSS:TTA) than hand-harvested berries, and berries harvested toward the end of the harvest season had a greater TSS:TTA than those from early-season harvests. As postharvest storage time increased, berry appearance ratings decreased and berry softness and shriveling increased, particularly in mechanical-harvested compared with hand-harvested berries. Firmness of mechanical-harvested berries decreased during storage, whereas firmness of hand-harvested berries remained relatively stable. However, fruit quality at harvest and during postharvest storage was unaffected by *V. arboreum* rootstocks or lack of pine bark amendment. This study suggests that using *V. arboreum* as a rootstock in an alternative blueberry production system has the potential to decrease the use of soil amendments and increase mechanical harvesting efficiency.

Highbush blueberries grown for fresh market are typically hand harvested; however, hand harvesting is labor intensive and costly, resulting in low production efficiency and profitability (Takeda et al., 2008, 2013). In addition, unpredictable labor supplies affect a large number of specialty crops, and are becoming a major issue in blueberry production (Zhang and Wilhelm, 2011). To decrease harvesting costs in blueberry production, mechanical harvesters have been developed, tested, and manufactured since the late 1950s (Hedden et al., 1959; Peterson and Brown, 1996; Takeda et al., 2008, 2013; van Dalfsen and Gaye, 1999), but have been primarily used to harvest berries for processing or at the end of the harvest season (Williamson et al., 2012; Yu et al., 2012). However, growers' concerns about hand-harvesting costs and labor availability have increased interest in adopting mechanical harvesters for fresh market blueberries. Brown et al. (1996) reported an increase of ≈60-fold in labor efficiency and a cost reduction of ≈85% when using over-the-row mechanical blueberry harvesters. However, mechanical harvesting causes excessive fruit bruising (Sargent et al., 2013) and harvest losses. Bruising occurs when berries hit canes, other fruits, and interior surfaces of the harvester or catch plates while falling through the bush after detachment (Takeda et al., 2008), and as fruit moves from the catch plates to the lugs (Yu et al., 2012). Harvest losses may occur due to harvesting of unripe or damaged berries, reducing packout efficiency by 4% to 30% (Peterson and Brown, 1996; Takeda et al., 2013; van Dalfsen and Gaye, 1999). Harvest losses may also occur due to the design of the machine, which allows berries to fall to the ground because the catch plates do not fit closely around the multicaned crown of the bush. Estimates of ground losses from mechanical harvesting range from 10% to 50% of the total fruit harvested (Brown et al., 1996; Peterson and Brown, 1996).

Blueberries are very perishable (Vicente et al., 2007), thus, adequate and efficient harvesting methods (Sargent et al., 2013), handling and packing (Jackson et al., 1999), and postharvest storage strategies (Schotsmans et al., 2007) are needed to increase the storage and shelf life of fresh blueberries. Several studies have compared fruit quality of mechanical- vs. hand-harvested blueberry fruit immediately after harvest and during postharvest storage. The increased fruit bruising associated with mechanical harvest reduces berry firmness compared with hand harvest (Li et al., 2011). During postharvest storage, mechanical-harvested berries exhibit a decrease in overall appearance, fresh weight, and firmness, and an increase in shriveling (Sargent et al., 2013) and respiration (Nunez-Barrios et al., 2005) compared with hand-harvested berries. Efficient harvesting systems are needed to reduce fruit losses during harvest and maintain good fruit quality during postharvest storage, since fresh-market berries must maintain acceptable fruit quality for 2 or 3 weeks after harvest (Sargent et al., 2013).

Vaccinium arboreum is a wild species native to the southeastern United States that exhibits a single-trunk growth habit (Brooks and Lyrene, 1998). If used as a rootstock for cultivated *Vaccinium*, the monopodial tree-like architecture of *V. arboreum* could improve mechanical harvesting efficiency of blueberries. A blueberry plant with a single trunk could eliminate much of the yield losses that occur with multicaned plants, as well as reduce the need to prune the bushes to fit the harvest machines. Along with the desired characteristics for mechanical harvesting, *V. arboreum* tolerates high pH (above 6.0) and low organic matter soils (below 2.0%) (Brooks and Lyrene, 1998), conditions that cultivated *V. corymbosum* tolerates poorly. Thus, it may be useful in reducing use of soil amendments that are necessary for successful blueberry production in many areas.

Received for publication 2 Sept. 2016. Accepted for publication 22 Sept. 2016.
This material is based on work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2009-51181-06021 and by the Florida Department of Agriculture and Consumer Services award number 00120479.
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Although there is currently research investigating mechanical vs. hand harvesting of blueberry, there are no reports of studies comparing grafted vs. own-rooted plants to assess yield losses due to mechanical harvesting. Further, there are no other reports examining the potential of using *V. arboreum* as a rootstock to reduce or eliminate soil amendments while maintaining yield and postharvest fruit quality in blueberry.

The hypotheses tested in the present research are that 1) yield and fruit quality at harvest and during postharvest storage of hand- or mechanical-harvested grafted SHB are greater compared with own-rooted SHB and 2) fruit ground losses during harvest are decreased in grafted plants that are mechanical harvested compared with mechanical-harvested own-rooted plants. The specific objectives were to evaluate the effects of root (own rooted vs. grafted), soil (amended vs. nonamended), and harvest method (hand vs. mechanical) treatments on marketable fruit yield, berry weight, harvest losses, and berry quality at harvest and during postharvest storage.

Materials and Methods

The research was located at Straughn Farms, LLC in Archer, FL (29°32′ 56″ N, 82°29′ 11″ W) using 'Meadowlark' and 'Farthing' SHB. Both cultivars have potential for mechanical harvesting (Williamson et al., 2014); however, they exhibit different plant architectures. 'Farthing' is bushy with numerous lateral shoots (Lyrene, 2008), whereas 'Meadowlark' is tall with upright shoots (Lyrene, 2010).

Four scion/rootstock combinations were tested: 1) own-rooted 'Farthing', 2) 'Farthing' grafted onto *V. arboreum*, 3) own-rooted 'Meadowlark', and 4) 'Meadowlark' grafted onto *V. arboreum*. Scions and rootstocks were propagated as previously described by Casamali et al. (2016). Briefly, own-rooted plants were propagated by stem cuttings at a commercial nursery in Summer 2010. *Vaccinium arboreum* seedlings used as rootstocks for grafted plants were germinated from open-pollinated seeds of native *V. arboreum* plants in northeast Florida, and from ≈1-year-old seedlings purchased from a native plant nursery (Ornamental Plants and Trees, Inc., Hawthorne, FL).

For grafted plants, scions were veneer grafted onto *V. arboreum* seedling rootstocks in Summer 2010. Own-rooted plants and their grafted counterparts were field planted in May 2011. Plant spacing was 0.9 m in the row and 3.3 m between rows. The soil is a well-drained, typically dry, Arredondo sand, pH 5.5–6.0, with very low organic matter. Each scion/rootstock combination was grown in two different soil treatments 1) pine bark amended soil and 2) nonamended soil. The amended soil consisted of a mixture of pine bark (primarily *Pinus elliottii*) and native soil, where a 10-cm layer of pine bark was rototilled into the top 20 cm of the native soil. Nonamended soil consisted of native soil. Planting occurred in rows ≈90 cm wide. All treatment combinations were either hand or mechanical harvested (see Materials and Methods).

Treatments were arranged in a strip-split-plot design with soil treatment (amended vs. nonamended) and harvesting method (hand vs. mechanical) as main plots, and the scion/rootstock combination as subplots. Main plots were replicated four times in 2013 and six times in 2014. Each subplot consisted of eight plants in which six were guard plants and two were data plants. For the postharvest storage experiments, treatments were arranged in a completely randomized split design, with each scion/rootstock × soil × harvest method combination as plots composed of six clamshells, which were split between two storage durations (7 and 14 d, with three clamshells for each duration). Fruit quality after 7 and 14 d of storage was compared with fruit quality of the nonstored control (day 0), as described in the Materials and Methods.

Irrigation and fertilization through drip irrigation, and pest management followed the recommended guidelines for blueberry production in Florida (Williamson and Lyrene, 1995, 2013). Plants received an annual rate of 178N–24P–75K $kg \cdot ha^{-1}$ and 1290 L of irrigation water per plant, and had overhead irrigation for frost protection. About 34% of the annual rate of fertilizer and water was applied from January to June, 54% from June to October, and 12% applied from October to December. Foliar Fe (Dissolvine® E-Fe-13; AkzoNobel, Amsterdam, NL) was applied at a rate of 0.17 $kg \cdot ha^{-1}$ in Oct. 2013. Soil pH was kept between 5.0 and 6.0, using 38% sulfuric acid injected through the irrigation system. From February to July 2013, soil pH increased to 6.3 due to problems with the acid injector. The most basal branches of all plants were removed in the winter to avoid contact with the ground, and rootstock suckers were removed in the summer and fall of 2013 and 2014. In June of 2014, plants were top-pruned using a handheld hedger (PP2822; Poulan PRO, Charlotte, NC), reducing the maximum plant height to ≈150 cm.

Hand-harvested plants were harvested twice a week throughout the season—simulating commercial practice—to avoid overripe berries and fruit losses. Fruit yield was determined and mean berry weight was estimated for each harvest day by weighing a random subsample of 25 berries. At the end of the harvest season, cumulative yield was determined. Mechanical-harvested plants were harvested two or three times during the season using a handheld shaker (Model H; BEI, South Haven, MI), as shown in Fig. 1A.

When the mechanical harvesting was performed, hand-harvested plants were picked at the same time for comparison of fruit quality and postharvest attributes (described in the Materials and Methods). In addition, hand-harvested plants were harvested only once a week during the times when mechanical harvests were performed. Immediately before and after mechanical harvesting, ground berries were collected from around each bush and weighed to determine preharvest losses and ground losses during mechanical harvest. The first mechanical harvest occurred at ≈30% ripe fruit, the second harvest occurred 14 d later, and the third harvest, if necessary, occurred 14 d after the second harvest. For mechanical harvesting, individual fruiting canes were shaken for ≈3 s (≈5100 Hz) and the berries were collected in catch frames (142 cm long × 112 cm wide plastic netting held by a metal frame, with rear skids and height adjustable front wheels) placed under the plants, as shown in Fig. 1B. Berries from each mechanical- and hand-harvested subplot were placed in clamshells (Model H232–907g; Highland Packaging Solutions, Plant City, FL), transported from the field to cold storage within 5 h after harvest, and stored overnight at ≈6 °C before fruit quality analysis and set up of the storage tests. At the end of the harvest season, all remaining fruit on both hand- and mechanical-harvested plants were picked to determine yield of berries left on the plant after the final harvest. Maximum potential yield of mechanical-harvested plants was determined by adding yields of harvested berries, ground losses before and during harvest, and berries left on the plant after harvest. Hand-harvested berries were observed to have no losses due to ground drops and a nonsignificant amount of unripe or damaged berries (≈3% across cultivars and years).

The day following harvest, hand- and mechanical-harvested berries were removed from the cooler, brought to room temperature, sorted into marketable fruit, red, green, and damaged berries for each scion/rootstock × soil × harvest method combination, and weighed. Red, green, and damaged berries were combined and designated as packout losses. Following this, 25 marketable berries per replication for each treatment combination were randomly selected and mean berry weight was determined. For the seasonal berry weight of hand-harvested berries, the harvest season was divided into three periods, according to the mechanical harvesting dates. The harvest dates of each period were combined to generate the mean berry weight of that period. The seasonal berry weight was then calculated using a weighted average according to the fruit yield of each period. For the seasonal berry weight of mechanical-harvested berries, the mean berry weight of each mechanical harvest day was used, and the seasonal berry weight was then calculated using a weighted average according to the fruit yield of each mechanical harvest.

Berry firmness was measured on the 25 berries previously selected using a fruit firmness tester (Model Firmtech 2; BioWorks, Wamego, KS). The 25 berry sample was then frozen at –30 °C until analysis for TSS and TTA (protocol described in the Materials and Methods). A second subsample of 30 berries (10 berries per each of 3 replications) was selected and analyzed for appearance, softness, shriveling, and decay (protocol described below). These first fruit quality analyses were used as the

Fig. 1. (**A**) Handheld shaker used to mechanical harvest blueberry plants. (**B**) Catch frames placed under the plants to collect berries detached during mechanical harvesting.

nonstored control (day 0) for the storage experiment.

Storage experiments were performed only when the mechanical harvest occurred. After sorting the berries, the marketable fruit of each scion/rootstock × soil × harvest method treatment were combined and three commercial blueberry clamshells (Model H144–125g; Highland Packaging Solutions) were filled for each treatment combination and storage period (7 and 14 d). Clamshells were stored at 1 °C and 80% relative humidity. Berries from each treatment were analyzed initially (as described in the Materials and Methods for the nonstored control) and at 7 and 14 d of storage for appearance, softness, shriveling, decay, firmness, TSS, and TTA. Clamshells were weighed before storage and again when removed from storage at day 7 and 14 to determine weight loss throughout the experiment. For appearance, each clamshell was graded between 1 and 5, according to the scale: 1 = fully damaged, nonedible; 2 = extreme shriveling and/or decay; 3 = moderate shriveling (minimum acceptable quality); 4 = slight dullness and/or shriveling; and 5 = field fresh, turgid, bright color, no damage. For softness, 10 berries from each clamshell were randomly chosen and evaluated individually by touching to detect soft berries. The number of soft berries (ranging from 0 to 10) was counted. Shriveling and decay were quantified similarly. Eight berries from each of three clamshells in the first season (2013) and 10 from each clamshell in the second season (2014) were collected at days 7 and 14 to quantify firmness with the fruit firmness tester. Clamshells with berries were then frozen at –30 °C until berry TSS and TTA analysis.

TSS and TTA were determined after selecting 25 berries from each clamshell. Berries were thawed, macerated inside a plastic bag, centrifuged at 14,636 g_n for 20 min (Model Sorvall Legend XTR; Thermo Scientific, Waltham, MA), and the supernatant was filtered through cheese cloth to extract the juice. TSS were estimated using a refractometer (Model AR200 or Model R^2I300; Reichert, Depew, NY) and expressed as °Brix. TTA (as % citric acid) was assessed using an automated titrator (Model 719 S Tritino or Model 901 Titrando; Metrohm, Riverview, FL), titrating 6 mL of juice diluted in 50 mL of deionized water with 0.1 N NaOH to an endpoint of pH 8.2. Berry ripeness was determined by the TSS:TTA ratio.

Data were collected during the 2013 and 2014 harvest seasons. With the exception of fruit yield and berry weight, years were analyzed together since there were no year effects on fruit quality. Each cultivar was evaluated separately because of the different growth habit. SAS 9.2 (SAS Institute Inc., Cary, NC) was used to compare treatment means and interactions, using PROC GLIMMIX. Means were separated using Tukey's honestly significant difference test at $P \leq 0.05$. For the presentation of results, P values smaller than 0.001 were rounded to 0.001.

Results

Fruit yield and losses. For hand harvest in 2013, yield of own-rooted plants in amended soil was greater than own-rooted plants in nonamended soil or grafted plants in either soil treatment for both cultivars (Table 1). In 2014, hand harvest yields of own-rooted and grafted 'Farthing' in amended soil were similar. Grafted plants in both soil treatments had similar yields, which were greater than yields of own-rooted plants in nonamended soil. Hand-harvested 'Meadowlark' own-rooted plants in amended soil had greater yield in 2014 than grafted plants in either soil treatment, which were generally greater than own-rooted plants in nonamended soil (Table 1).

For mechanical harvest in 2013, 'Farthing' own-rooted plants in amended soil had greater yield than own-rooted plants in nonamended soil or grafted plants in either soil treatment (Table 1). For 'Meadowlark', the interaction between soil and root treatments was not significant; however, plants in amended soil had greater yield (1257 g) than plants in nonamended soil (885 g) (Table 1; $P = 0.048$). Similarly, in 2014, 'Farthing' plants in amended soil had greater yield (2280 g) than plants in nonamended soil (1397 g) (Table 1; $P = 0.003$), whereas 'Meadowlark' own-rooted plants in amended soil or grafted plants in either soil treatment had greater yield than own-rooted plants in nonamended soil.

In general, hand-harvested plants had greater yield than mechanical-harvested plants, with the exception of own-rooted 'Farthing' or 'Meadowlark' plants in nonamended soil and grafted 'Meadowlark' plants in amended soil in 2013, and own-rooted 'Meadowlark' plants in nonamended soil in 2014, where yields were similar for both harvest methods (Table 1).

In 2013, root and soil treatments did not affect mean berry weight of hand-harvested 'Farthing' (Table 2); however, mean berry

Table 1. Effects of the root and soil treatments and harvest method on total yield of 'Farthing' and 'Meadowlark' SHB in 2013 and 2014.

	Farthing		Meadowlark	
	HH	MH	HH	MH
	Total yield (g/plant)			
Treatment[z]	2013			
Own rooted/amended	5,192 aA[y]	2,572 aB	3,323 aA	1,601 B
Own rooted/nonamended	1,980 bA	1,329 bA	1,418 bA	889 A
Grafted/amended	2,568 bA	1,699 bB	1,281 bA	913 A
Grafted/nonamended	2,009 bA	1,291 bB	1,679 bA	880 B
P values				
Root[x]	0.001	0.015	0.014	0.062
Soil	0.007	0.002	0.071	0.048
Root × soil	0.001	0.022	0.004	0.068
	2014			
Own rooted/amended	4,943 aA	2,257 B	5,036 aA	2,384 aB
Own rooted/nonamended	1,927 cA	1,132 B	1,715 cA	914 bA
Grafted/amended	4,298 abA	2,302 B	2,792 bcA	1,904 aB
Grafted/nonamended	3,263 bA	1,661 B	3,323 bA	1,807 aB
P values				
Root	0.254	0.075	0.347	0.002
Soil	0.001	0.003	0.001	0.335
Root × soil	0.003	0.125	0.001	0.005

HH = hand harvest; MH = mechanical harvest; SHB = southern highbush blueberry.

[z]Own rooted = cultivars grown on their own roots; grafted = cultivars grafted onto *Vaccinium arboreum* rootstock; amended = pine bark amended soil; nonamended = native soil.

[y]Means represent the root × soil interaction. Means followed by the same lowercase letter within a column and year, or by the same uppercase letter within a row and cultivar, are not significantly different by Tukey's honestly significant difference test, $P \leq 0.05$. Means without lowercase letters indicate the root × soil interaction was not significant.

[x]Main effect means for root (own rooted vs. grafted) and soil (amended vs. nonamended) are not given, but *P* values indicate significance.

Table 2. Effects of the root and soil treatments and harvest method on seasonal mean berry weight of 'Farthing' and 'Meadowlark' SHB in 2013 and 2014.

	Farthing		Meadowlark	
	HH	MH	HH	MH
	Mean berry wt (g)			
Treatment[z]	2013			
Own rooted/amended	1.93 B	2.36 bA[y]	2.50 A	2.71 A
Own rooted/nonamended	1.67 B	2.05 cA	1.91 B	2.40 A
Grafted/amended	1.90 B	2.68 aA	2.43 B	3.11 A
Grafted/nonamended	1.89 B	2.51 abA	2.35 B	2.87 A
P values				
Root[x]	0.421	0.001	0.209	0.001
Soil	0.267	0.029	0.036	0.007
Root × soil	0.328	0.026	0.099	0.676
	2014			
Own rooted/amended	2.00 bB	2.55 A	1.77 B	2.36 A
Own rooted/nonamended	1.76 cB	2.49 A	1.52 B	2.12 A
Grafted/amended	2.22 aB	2.56 A	2.35 A	2.22 A
Grafted/nonamended	2.24 aA	2.35 A	2.06 A	2.24 A
P values				
Root	0.001	0.585	0.001	0.938
Soil	0.158	0.258	0.001	0.386
Root × soil	0.031	0.503	0.731	0.328

HH = hand harvest; MH = mechanical harvest; SHB = southern highbush blueberry.

[z]Own rooted = cultivars grown on their own roots; grafted = cultivars grafted onto *Vaccinium arboreum* rootstock; amended = pine bark amended soil; nonamended = native soil.

[y]Means represent the root × soil interaction. Means followed by the same lowercase letter within a column and year, or by the same uppercase letter within a row and cultivar, are not significantly different by Tukey's honestly significant difference test, $P \leq 0.05$. Means without lowercase letters indicate the root × soil interaction was not significant.

[x]Main effect means for root (own rooted vs. grafted) and soil (amended vs. nonamended) are not given, but *P* values indicate significance.

weight of hand-harvested 'Meadowlark' was greater in amended (2.47 g) than nonamended (2.13 g) soil (P = 0.036). In 2014, berry weight of 'Farthing' hand-harvested fruit was greatest in grafted plants in either soil, followed by own rooted in amended soil, which was greater than own rooted in nonamended soil (Table 2). Hand-harvested grafted 'Meadowlark' plants had greater berry weight (2.21 g) than own-rooted plants (1.65 g) in 2014 (P = 0.001), and plants in amended soil had greater berry weight (2.06 g) than plants in nonamended soil (1.79 g) (Table 2; P = 0.001).

For the 2013 mechanical harvest, berry weight of grafted 'Farthing' plants in either soil treatment was greater compared with own-rooted plants in nonamended soil, whereas berry weight of grafted plants in amended soil was greater than berry weight of own-rooted plants in amended soil (Table 2). For mechanical-harvested 'Meadowlark' in 2013, there was no significant root × soil interaction. Plants in amended soil had greater berry weight (2.91 g) than plants in nonamended soil (2.64 g) (Table 2; P = 0.007), and grafted plants had greater berry weight (2.99 g) than own-rooted plants (2.56 g). In 2014, there were no effects of root or soil treatments on mean berry weight of mechanical-harvested fruit for either cultivar (Table 2). Berry weight of mechanical-harvested 'Farthing' plants was greater compared with hand-harvested berries in both years, with the exception of grafted plants in nonamended soil in 2014 (Table 2). For 'Meadowlark', mechanical-harvested plants also generally had greater berry weight than hand-harvested plants in both years, with exception of own-rooted plants in amended soil in 2013, and grafted plants in both soil treatments in 2014.

Following mechanical harvest, grafted 'Farthing' plants had greater percent marketable yield and smaller percent ground losses during harvest, but greater percent packout losses compared with own-rooted plants (Table 3). Preharvest ground losses of 'Farthing' were unaffected by root or soil treatments (≈17.5%). 'Farthing' plants in amended soil had greater packout losses than plants in nonamended soil. 'Meadowlark' grafted plants also had smaller percent ground loss during harvest compared with own-rooted plants, but had greater percent preharvest ground losses than own-rooted plants. Percent marketable yield, packout losses, and berries left on the plant after the final harvest were unaffected by root or soil treatments (Table 3).

Storage experiment. Root, soil, and postharvest storage times did not affect TSS, TTA, or the TSS:TTA ratio, therefore, means were averaged across these treatments. Generally, early-season berries of both cultivars had lower TSS but higher TTA and a smaller TSS:TTA ratio compared with berries from mid or late season, regardless of harvest method (Table 4).

Mechanical-harvested 'Farthing' berries had higher TSS than hand-harvested berries in early season; however, TSS was not different between hand- and mechanical-harvested berries from mid- or late-season harvest. Hand-harvested berries of both cultivars had higher TTA than mechanical-harvested berries throughout the harvest season (Table 4). 'Meadowlark' mechanical-harvested berries had higher TSS than hand-harvested berries throughout the season. TSS:TTA ratio of mechanical-harvested berries was greater than hand-harvested berries for both cultivars throughout the season.

Berry appearance ratings, soft fruit, shrivel, and weight loss were unaffected by

Table 3. Effects of root and soil treatments on marketable yield, preharvest, and during harvest ground losses, packout losses, and berries left on the plant after harvest in mechanical-harvested 'Farthing' and 'Meadowlark' SHB.

Treatment[z]	MY (%)	PHGL (%)	DHGL (%)	PL (%)	BLP (%)
			Farthing		
Root					
Own rooted	55.0[y]	18.4	9.2*	14.9	2.4
Grafted	58.4*	16.6	6.0	17.1*	1.8
Soil					
Amended	55.4	16.8	7.8	17.2*	2.7*
Nonamended	58.0	18.2	7.4	14.8	1.5
P values					
Root × soil	0.346	0.764	0.689	0.627	0.006
			Meadowlark		
Root					
Own rooted	62.6	8.8	10.6*	13.5	4.5
Grafted	63.6	11.5*	6.6	13.8	4.3
Soil					
Amended	61.7	11.4	9.0	13.8	4.0
Nonamended	64.5	9.0	8.2	13.5	4.8
P values					
Root × soil	0.565	0.785	0.619	0.502	0.915

MY = marketable yield; PHGL = preharvest ground losses; DHGL = during harvest ground losses; PL = packout losses; BLP = berries left on the plant after the final harvest; SHB = southern highbush blueberry.
[z]Own rooted = cultivars grown on their own roots; grafted = cultivars grafted onto *Vaccinium arboreum* rootstock; amended = pine bark amended soil; nonamended = native soil.
[y]Means are percentages of the potential total yield for each treatment and were averaged across years.
*Indicates significant differences between root or soil treatments by Tukey's honestly significant difference test, $P \leq 0.05$.

Table 4. Effects of harvest season and method on TSS, TTA, and TSS:TTA ratio of 'Farthing' and 'Meadowlark' SHB fruit.

		TSS (°Brix)		TTA (% citric acid)		TSS:TTA ratio	
Cultivar	Season	HH	MH	HH	MH	HH	MH
Farthing	Early[z]	10.8 cB[y]	11.5 bA	0.59 aA	0.34 aB	19 bB	35 cA
	Mid	11.4 bA	11.5 bA	0.51 bA	0.26 bB	23 abB	48 bA
	Late	14.6 aA	14.1 aA	0.54 abA	0.24 bB	28 aB	60 aA
Meadowlark	Early–mid	9.9 bB	10.5 bA	0.30 aA	0.18 aB	35 bB	61 bA
	Mid–late	11.5 aB	12.0 aA	0.27 bA	0.12 bB	46 aB	104 aA

HH = hand harvesting; MH = mechanical harvesting; TSS = total soluble solids; TTA = total titratable acidity; SHB = southern highbush blueberry.
[z]Early or early-midseason was from 25 Mar. to 17 Apr. in 2013 and 11 to 22 Apr. in 2014; mid or mid-late season was from 18 Apr. to 1 May in 2013 and from 23 Apr. to 7 May in 2014; late season was from 2 to 15 May in 2013 and 8 to 21 May in 2014.
[y]Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter within a row and quality trait, are not significantly different by Tukey's honestly significant difference test, $P \leq 0.05$. Means were averaged across years, root, soil, and storage period treatments.

time of fruit harvest, root, or soil treatments, thus, means were averaged across these treatments. Berries from day 0 had a higher appearance rating than berries stored for 7 or 14 d for both cultivars and harvest methods (Table 5). The storage period did not affect the percentage of soft fruit in hand-harvested 'Farthing'; however, the percent of soft fruit increased significantly in hand-harvested 'Meadowlark' berries stored for 14 d compared with 0 or 7 d of storage. When berries were mechanical harvested, there was a significant increase in percent of soft fruit at days 7 and14 compared with day 0 for both cultivars (Table 5). After 14 d of storage, berries had a greater percentage of shriveling than berries from 0 or 7 d of storage for both cultivars, regardless of harvest method (Table 5).

Appearance ratings were higher and percent of shriveled berries was less in hand harvested compared with mechanical-harvested berries at 7 and 14 d of storage for both cultivars (Table 5). Percent of soft fruit was similar between hand- and mechanical-harvested berries of 'Farthing' immediately after harvest (day 0); however, percent softness was greater immediately after harvest in mechanical-harvested compared with hand-harvested 'Meadowlark'. By 7 and 14 d of storage, berries from mechanical harvested had greater percentage of soft fruit than hand-harvested berries for both cultivars (Table 5). No decay was observed (data not shown).

Fruit weight loss was greater at 14 d of storage (ranging from 2.2% to 2.6%) compared with 7 d (ranging from 1.0% to 1.3%) for both cultivars. There was no effect of harvest method, time of fruit harvest, root, or soil treatments on fruit weight loss during storage (data not shown).

Berry firmness of hand-harvested berries was similar throughout the storage period for both cultivars and root treatments (Table 6). The exception was berries from hand-harvested grafted 'Farthing', which were softer by day 14 of storage compared with 0 or 7 d of storage (Table 6). However, mechanical-harvested berries of both cultivars were softer by 14 d of storage for both root treatments. Hand-harvested berries were firmer than mechanical-harvested berries for both cultivars, regardless of root treatment or storage period. In general, berries of own-rooted 'Farthing' were firmer than berries of grafted 'Farthing', regardless of harvest method or storage time. However, root treatments did not significantly affect berry firmness of 'Meadowlark'.

Discussion

Fruit yield. Hand harvest yields of grafted plants were generally less than own-rooted plants when both were grown in amended soils, with the exception of 'Farthing' in 2014. The decrease in yield of hand-harvested grafted plants is in contrast to work by Ballington (1998), who reported increased yields of grafted blueberry compared with own-rooted blueberry during the first 3 years in the field. Yield differences between our work and the work by Ballington (1998) may be due to differences in plant age; in Ballington's study, grafted plants were older when they were first evaluated for yield. This is supported by the similar yields of own-rooted and grafted 'Farthing' in 2014 in our work, suggesting that as plants age, yields of grafted plants and own-rooted plants may be similar.

In contrast to hand-harvested yields in amended soils, positive effects on yield were observed when grafted plants were grown in nonamended soils. Although hand-harvest yields were similar in grafted and own-rooted blueberry grown in nonamended soils the first year, yields of grafted plants grown in nonamended soil were greater the 2nd year (2014) compared with own-rooted plants. This is likely due to the ability of *V. arboreum* rootstock to tolerate the low organic matter (Brooks and Lyrene, 1998) in the nonamended soils once the rootstock was established. Although *V. arboreum* rootstock use had a positive effect on yields in nonamended soils, the yields were lower than those of own-rooted plants in amended soils. Thus, *V. arboreum* rootstock was unable to completely compensate for lack of soil amendments in hand-harvested plants through the first two fruiting years. Yields of grafted plants in nonamended soil may reach yields of own-rooted plants in amended soils as plants mature; however additional research is needed to determine this.

For mechanical-harvested plants, yields in 2014 were similar between own-rooted plants in amended soil and grafted plants in either soil treatment. This suggests that using *V. arboreum* as a rootstock for SHB blueberry production may be feasible in nonamended soils where fruit are mechanical harvested.

No consistent differences between root or soil treatments were found for mean berry weight; however, there was a trend toward greater mean berry weight in grafted compared

Table 5. Effects of storage period and harvest method on appearance, softness, and shriveling ratings of 'Farthing' and 'Meadowlark' SHB fruit for both seasons.

		Appearance (1–5 scale)[z]		Soft fruit (%)		Shrivel (%)	
Cultivar	Storage period (d)	HH	MH	HH	MH	HH	MH
Farthing	0	5.0 aA[y]	5.0 aA	0 aA	3 cA	0 bA	0 cA
	7	4.5 bA	4.0 bB	3 aB	24 bA	3 bB	14 bA
	14	4.1 cA	3.4 cB	8 aB	40 aA	23 aB	41 aA
Meadowlark	0	5.0 aA	5.0 aA	1 bB	7 bA	0 bA	3 cA
	7	4.5 bA	3.7 bB	1 bB	26 aA	6 bB	35 bA
	14	3.8 cA	3.1 cB	13 aB	34 aA	49 aB	69 aA

HH = hand harvest; MH = mechanical harvest; SHB = southern highbush blueberry.

[z]Appearance rating scale: 1 = fully damaged, nonedible; 2 = extreme shriveling and/or decay; 3 = moderate shriveling (minimum acceptable quality); 4 = slight dullness and/or shriveling; 5 = field fresh, turgid, bright color, and no damage.

[y]Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter within a row and quality trait, are not significantly different by Tukey's honestly significant difference test, $P \leq 0.05$. Means were averaged across years, root, soil, and harvest season treatments.

Table 6. Effect of storage period, root system, and harvest method on berry firmness of 'Farthing' and 'Meadowlark' SHB.

		Firmness (g·mm^{-1})					
		Own rooted		Grafted		*P* values root[z]	
Cultivar	Storage period (d)	HH	MH	HH	MH	HH	MH
Farthing	0	233 aA[y]	217 aB	222 aA	203 aB	0.052	0.019
	7	234 aA	212 aB	222 aA	195 abB	0.033	0.004
	14	223 aA	199 bB	209 bA	180 bB	0.020	0.002
Meadowlark	0	246 aA	227 aB	232 aA	216 aB	0.079	0.170
	7	254 aA	221 abB	244 aA	207 abB	0.209	0.067
	14	254 aA	210 bB	239 aA	197 bB	0.070	0.109

HH = hand harvest; MH = mechanical harvest; SHB = southern highbush blueberry.

[z]*P* values $\leq$ 0.05 indicate significant differences between root treatments (own rooted vs. grafted) for a given harvest method and cultivar for the indicated storage period.

[y]Means followed by the same lowercase letter within a column and cultivar, or by the same uppercase letter within a row and root treatment, are not significantly different by Tukey's honestly significant difference test, $P \leq 0.05$. Means were averaged across years, soil, and harvest season treatments.

with own-rooted plants. Similar results were found by Ballington (1998), who reported greater mean berry weight of 'Premier' blueberry grafted onto *V. arboreum* compared with own-rooted 'Premier'. This may be due to improved plant water status resulting from the drought-tolerant root system of *V. arboreum* (Ballington, 1998; Hancock et al., 2008) compared with own-rooted plants.

Fruit from mechanical-harvested plants generally had greater mean berry weight than those from hand-harvested plants for both cultivars and years evaluated. Berries from mechanical harvesting treatments remained attached to the plants longer compared with the hand harvesting treatments, due to the different harvest intervals. The longer period of attachment between mechanical harvests likely allowed for further expansion of cell size, resulting in larger berries.

Overall, mechanical-harvested plants had a 40% decrease in marketable yield compared with hand-harvested plants for both cultivars and years due to fruit losses. The first source of loss was the preharvest ground losses (≈14% of the potential yield averaged across cultivars and years), which comprised the berries that dropped between harvest days. The 14-d harvest interval between mechanical harvests resulted in significant abscission of ripe berries between harvests, regardless of treatment, indicating that more frequent harvests are needed to avoid abscission of ripe berries, potentially reducing losses. The interval between mechanical harvests is not well established for SHB, and is influenced by berry ripeness stage, weather conditions, and cultivar characteristics. Previous studies on mechanical harvest of blueberry used harvest intervals from 7 to 18 d (Takeda et al., 2008; van Dalfsen and Gaye, 1999).

Another source of loss due to mechanical harvesting was the harvest of unripe or damaged berries, indicated as packout losses. These losses accounted for nearly 15% of the potential yield averaged across cultivars and years. The final important source of loss was the ground losses during harvest. Ground loss of berries during harvest was decreased significantly (≈35%) in grafted compared with own-rooted plants, likely because the catch frames fit closer around the single trunk structure of the grafted plants compared with the multicaned structure of own-rooted plants. This ground loss could be further reduced if the graft union was higher. In our research, the graft union averaged 18 cm above the soil line; however, visual observations indicate that a graft union at least 30 cm above the soil line would allow better fit of the catch frames, potentially resulting in minimal ground loss during harvest and further improving mechanical harvesting efficiency.

Similar results documenting reductions in marketable yield due to mechanical harvesting have been reported previously with own-rooted blueberry. Takeda et al. (2008) reported ≈98% marketable yield for hand-harvested blueberry vs. 62% to 81% for mechanical-harvested plants. Yield reductions in the mechanical-harvested plants were due to harvest of nonmarketable berries. Ground losses were not quantified. Brown et al. (1996), testing hand harvesting vs. three mechanical harvesters, reported ≈45% yield loss for mechanical harvesting compared with hand harvesting. Ground losses during harvest accounted for ≈35% of the loss, whereas harvest of nonmarketable berries accounted for ≈10% loss. Peterson and Brown (1996) reported that mechanical harvesting of blueberry decreased marketable yields by ≈36% compared with hand harvesting, with nonmarketable berries accounting for ≈20% loss and ground loss during harvest accounting for ≈16% loss. Preharvest ground losses were not quantified for any research cited.

Although mechanical harvesting of grafted blueberry in our research did not reduce preharvest fruit losses or decrease the percent of unripe or damaged berries that were harvested compared with mechanical harvesting of own-rooted plants, ground losses during harvest were significantly reduced in grafted vs. own-rooted blueberry. In mechanical harvesting of conventional blueberry plantings, ground losses range from 10% to 50% of the potential yield (Brown et al., 1996; Peterson and Brown, 1996). Thus, grafted plants have potential to significantly decrease yield loss of mechanical harvested berries by decreasing ground losses during harvest. This would increase marketable yield if mechanical harvest intervals are frequent enough to avoid excessive preharvest fruit losses.

Other strategies have been tested to reduce ground losses during mechanical harvest of blueberry. Strik and Buller (2002) found that a blueberry trellis system reduced ground losses during mechanical harvest compared with no trellis. Takeda et al. (2013) reported that a crown-restricted blueberry production system or crown-restricted plus a T-post trellis system reduced ground loss during mechanical harvest compared with a conventional blueberry production system. Although both studies reported reduced ground losses during harvest, production systems based on trellising or crown restriction potentially increase establishment costs (Julian et al., 2012), and may require extra labor to maintain the training system required for these production systems. *Vaccinium arboreum* rootstocks also add a significant cost to establishment; however, it has the potential to reduce the use of soil amendments, which could reduce the total establishment costs by up to 15% (J.W. Julian, personal communication). Blueberry production based on grafting onto *V. arboreum* rootstock has the potential to reduce ground losses during mechanical harvest, as well as increase soil adaptation, and may be a viable alternative to reduce production costs.

Storage experiment. Rootstock did not affect, TSS, TTA, or TSS:TTA ratio, supporting previous work by Ballington (1998) and Xu et al. (2014). The length of the postharvest storage period had no effect on these fruit quality traits, again supporting previous work in blueberry (Chiabrando et al., 2009; Sargent et al., 2013). Thus, *V. arboreum* rootstock had no negative effects on internal fruit quality or postharvest storage ability of these SHB cultivars.

As the harvest season progressed, fruit ripeness (TSS:TTA) increased, supporting work by Lobos et al. (2014). This increase was particularly true for mechanical-harvested berries, which always had greater values than hand-harvested berries. The long interval between mechanical harvests (14 d) allowed the fruit to ripen to a more advanced stage compared with hand-harvested treatments, which were harvested twice a week. Another possible reason for the advanced stage of ripeness of mechanical- vs. hand-harvested berries is a result of the harvesting process directly. For mechanical harvesting, the harvest machine tends to remove berries that have the abscission layer formed. For hand harvesting, the picker potentially removes berries that are not completely ripe, likely due to the ease of berry detachment even when the abscission zone is not completely formed. Rohrbach et al. (2004) described the relationship between TSS:TTA ratio and ripeness in blueberry, indicating that just-ripe berries have an average TSS: TTA ratio nearly 25, ripe berries nearly 50, and overripe berries nearly 90. By the end of the harvest season (late season) in the present study, the TSS:TTA ratio was over 50 for mechanical-harvested fruit of both cultivars ($\approx$82 across cultivars), significantly higher than what was observed in the hand-harvested fruit ($\approx$37 across cultivars). Thus, under our conditions, mechanical harvesting should be done more often than every 14 d to decrease harvest of overripe fruit and maintain better fruit quality at harvest and during postharvest storage.

Qualitative traits of berry appearance, softness, and shriveling were unaffected by root or soil treatments, or harvest season; however, storage period significantly influenced these traits. Berry quality, as determined by these qualitative traits, decreased during storage and the reduction was more pronounced in mechanical-harvested compared with hand-harvested berries. Similar results were found by Sargent et al. (2013), who reported that berries from hand-harvested SHB tended to have greater appearance rating and lower percentages of soft or shriveled fruit compared with mechanical-harvested berries during 14 d of storage. The loss of fruit quality during storage may be correlated with the degree of ripeness at harvest, which was greater for mechanical- vs. hand-harvested plants, and the damage caused by the mechanical harvest, which elevates ethylene production rates, potentially accelerating berry deterioration (Fonseca et al., 2002). Overall, grafting SHB onto *V. arboreum* rootstocks did not negatively impact fruit quality or postharvest storage compared with own-rooted SHB.

Although berry weight loss is often correlated with berry firmness (Paniagua et al., 2013), firmness of hand-harvested berries did not change during storage, even though weight loss increased. This agrees with results of Li et al. (2011) and Nunez-Barrios et al. (2005), who found no significant differences in berry firmness of hand-harvested blueberries during storage up to 21 d. On the other hand, berry firmness of mechanical-harvested plants decreased during storage, agreeing with results by Takeda et al. (2013). The reduction in firmness in mechanical-harvested berries during storage is likely due to internal tissue damage caused by the mechanical harvesting (Takeda et al., 2008). Damage may not impact firmness at harvest. However, as the storage period increases, damaged tissues can activate and release enzymes (Takeda et al., 2013) responsible for degradation of the cell wall and middle lamella, causing berry softening (Chiabrando et al., 2009). Although grafted 'Farthing' plants generally had reduced berry firmness compared with own-rooted plants, the firmness values were within the acceptable range for SHB (greater than 160 $g\cdot mm^{-1}$) (Ehlenfeldt and Martin, 2002). Additional work is needed to better understand the influences of *V. arboreum* rootstock on berry firmness of SHB.

By the second fruiting year in the field (2014), yields of SHB grafted on *V. arboreum* rootstock and grown in either soil treatment were generally greater for hand- and mechanical-harvested plants compared with own-rooted plants in nonamended soil. Further, yields of mechanical-harvested SHB grafted on *V. arboreum* and grown in either soil treatment were similar to yields of mechanical-harvested own-rooted plants in amended soil. Fruit quality at harvest and during postharvest storage was not negatively affected by *V. arboreum* rootstocks or lack of pine bark amendment. Thus, grafting SHB cultivars on *V. arboreum* rootstocks may ultimately result in an alternative production system, with reduced use of soil amendments, and better adaptation to mechanical harvesting. The economic viability of such a system over the lifetime of a planting remains to be determined.

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