Postpacking Sweet Cherry Stem and Fruit Quality Attributes Influenced by Cultivar

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Keywords. **Bing, Black Pearl, Chelan, modified atmosphere, *Prunus avium*, Regina, Skeena, sweet cherry**

Abstract. **Sweet cherries (*Prunus avium*) destined for traveling to export markets must retain fruit and stem quality for 2 to 5 weeks postharvest. This 2-year study evaluated commercially sorted and packed sweet cherry cultivars (Chelan, Black Pearl, Bing, Regina, Skeena) fruit and stem quality outcomes following 4 weeks of storage at −0.6 ± 0.5 °C or 4.4 ± 0.5 °C in modified atmosphere (MA) bags. Cultivar-specific influences on physiochemical quality outcomes included pedicel fruit retention force, fruit firmness, color, soluble solids content, and titratable acidity at 4 weeks postharvest. A comparison of quality attribute changes within each lot between the initial evaluation and 4 weeks postharvest indicated that color and firmness changed with regard to cultivar, with Skeena having the least change in firmness and Bing undergoing the most darkening. Many visual attributes, including stem weight-to-length ratio (an indicator of thickness or desiccation), stem retention, fruit cracking, pitting, and pebbling, were not statistically influenced by cultivar, indicating that in a commercial setting, lot-to-lot differences in horticultural, harvest, and packing management influence stem and fruit quality outcomes as much as cultivar. Stems with the distal end removed by packinghouses' cluster-cutter had lower stem weight-to-length ratios than those of stems that did not have their ends removed, indicating that this aspect of packing leads to desiccation of cut stems. Packinghouse (four in 2023 and five in 2024) did not statistically influence fruit or stem quality. Respiration rates differed among cultivars, with Black Pearl exhibiting the lowest and Regina exhibiting the highest; overall respiration rates were higher at 4.4 °C. There were significant ($P < 0.05$) but weak (approximately Spearman $r^2 = 0.50$) correlations between respiration rates at 1 week and fruit quality attributes at 4 weeks postharvest [increased loss of stems, decrease in pitting and pebbling incidence, and a change in a* (red/green fruit color component derived from colorimeter instrumentation)]. In a multivariate analysis, 'Black Pearl' and 'Chelan' lots stored at −0.6 °C typically were closest to an "ideal" lot of sweet cherries. Understanding cultivar-specific quality attributes as well as the impact of management decisions can aid in new planting choices, strategic planning in packinghouses, and proactive treatment to mitigate quality loss.**

In the United States, the sweet cherry export value can exceed $500 million annually (US Department of Agriculture – Economic Reporting Service 2024), and approximately one-third of the Pacific Northwest crop is destined for foreign markets (Northwest Horticultural Council 2024). Most cherries transported to distant markets are frequently in storage and transportation for more than 3 weeks (Wang and Long 2014). Although some fruit are exported via ground transportation or airplane, allowing transport to retail within a matter of days, a portion of the crop is transported via long-distance ocean shipping, which requires up to 5 weeks. In 2017 in the United States, Washington produced 262,550 tons of sweet cherries (US Department of Agriculture – National Agricultural Statistics Service 2018). Approximately 30% (78,765 tons) of the crop is exported to foreign markets, with an estimated 1575 tons being shipped by sea (Washington State University 2024). Because of the economic importance of sweet cherry export and the potential cost of shipment rejection, relative suitability of sweet cherry cultivars for export is a stakeholder priority (Washington State Tree Fruit Research Commission 2023).

Industry criteria for "export-quality" red cherries include the following: large size (>12 g; row size, 8 or 9); firm (>400 g·mm^{-1}); and dark red colored fruit with good stem quality (industry communication 2023). Formal information regarding supply chain preferences and product factors that influence retail purchase decisions for sweet cherry is limited. A study by Gallardo et al. (2014) indicated that the potential for a longer shelf life influences decision makers in the supply chain, but defining the attributes of "shelf life" was beyond the scope of that study. Research often emphasizes fruit eating attributes, including flavor (Kappel et al. 1996; Ye 2023; Zheng et al. 2016), which leaves knowledge gaps regarding visual factors that influence purchase decisions. There is limited consumer and stakeholder preference information about the importance of stem appearance or quality, yet stem quality is an important physiological indicator of sweet cherry freshness (Linke et al. 2010). Stem quality can more quickly become affected by mismanagement in postharvest handling than fruit (Golding et al. 2017; Wang et al. 2015; Zhi et al. 2023).

Northwest sweet cherries are a high-value crop exported all over the world. The relative importance of cultivar in the context of standard commercial handling practices is unknown because few studies use fruit after commercial packing. The goals of this research were to determine cultivar-specific differences in fruit and stem quality after commercial sorting and packing and after storage simulating ocean liner export transit. This study emphasized the retention of visual quality and firmness of red sweet cherry cultivars as well as physical and physiological characteristics that could influence the longevity of these qualities.

Materials and methods

This 2-year project (2023 and 2024) evaluated five sweet cherry cultivars to determine storage longevity, cultivar-specific resilience to higher-than-optimal storage temperatures, and related physiological quality indicators.

Sweet cherry lots were obtained soon after packing from commercial packinghouses in Washington and Oregon (Table 1). Fruit were "export-quality" and packed accordingly. Within 24 h of receipt, fruit were transferred from packinghouse-specific materials

Table 1. Sweet cherry cultivars evaluated, typical harvest timing, and receipt date of sweet cherry lots from commercial packinghouses in Oregon and Washington, USA, 2023–24.

		Commercial packinghouse[i]				
Cultivar	Harvest timing[ii]	1	2	3	4	5
Chelan	−11			27 Jun 2023	28 Jun 2023	
		12 Jun 2024	27 Jun 2024		10 Jun 2024	
Black Pearl	−8		22 Jun 2023	27 Jun 2023		26 Jun 2023
			19 Jun 2024	19 Jun 2024	19 Jun 2024	
Bing	0		5 Jul 2023	5 Jul 2023	12 Jul 2023	
			1 Jul 2024		19 Jun 2024	2 Jul 2024
Regina	+11		14 Jul 2023	19 Jul 2023		
		9 Jul 2024	12 Jul 2024	3 Jul 2024		
Skeena	+10			19 Jun 2023	12 Jun 2023	
		9 Jul 2024	3 Jul 2024	3 Jul 2024		

[i] Packinghouse names are withheld to maintain confidentiality.
[ii] Days relative to 'Bing' according to Long et al. (2021).

to modified atmosphere (MA) bags according to the manufacturer's specifications (LifeSpan; Amcor Inc., Zurich, Switzerland). Storage conditions were 4 weeks in MA bags at optimal temperature (−0.6 °C) and higher-than-optimal temperature (4.4 °C), with the latter simulating an extended cold chain break during transport.

Within 24 h of fruit receipt (initial evaluation) and 4 weeks poststorage, sweet cherry fruit and stem quality were destructively evaluated (Table 2); 30 fruit were evaluated per lot to collect continuous variable data and 100 fruit were evaluated per lot to collect binary data of each treatment combination. Stem presence was determined by randomly selecting 100 fruit per lot and counting the number of fruit with a stem. Pedicel length (mm) was measured with a digital caliper, and weight (g) was determined using an analytical balance accurate to ±0.0001 g (XSR104; Mettler-Toledo Ltd., Columbus, OH, USA). Stem weight-to-length ratio was determined by dividing the weight (g) by the length (mm). Pedicel fruit retention force (PFRF) (Toivonen and Manganaris 2020) was measured using a mechanical force gauge (Imada DPS-11; Imada Co., Northbrook, IL, USA) fitted with a polyvinyl chloride (PVC) guide to facilitate separation of the fruit from the stem. "Stem doublet" refers to the percentage of fruit (n = 100 per lot) that had two stems (e.g., the fruit's own stem attached to another stem, usually with no fruit attached to the second stem). "Cut stems" refers to the number of fruits with stems that were sliced short with the cluster-cutter (e.g., missing the fat rounded distal end of the stem).

Fruit quality evaluations included the assessment of cracking, pitting, pebbling, weight, color, firmness, soluble solids content (SSC; %), and titratable acidity (TA; %). Cracking, pitting, and pebbling were initially collected using the following criteria: 0 = no defect; 1 = slight defect but marketable; and 2 = unmarketable scale. Only binary (presence/absence) data are presented because of inconsistencies in personnel's opinion of "marketable." "Pebbling" refers to the presence of small dimples covering the fruit surface and is a result of desiccation (Toivonen and Managanaris 2020). Fruit surface color was measured using a colorimeter (Konica-Minolta, Tokyo, Japan) in the middle of the nonseam side of the fruit and expressed as L*, a*, b* (McGuire 1992); a color figure based on the hexademical color code approximation of L* a* b* was generated using software (MS Excel; Microsoft Corporation, Redmond, WA, USA). The SSC (%) was collected from 10-mL fruit juice samples expressed from 10 fruit (excluding the pit) using a juicer (Champion Classic 2000 Juicer; Plastaket Manufacturing Inc., Lodi, CA, USA) with a handheld digital refractometer (HI 96822; HANNA Instruments, Smithfield, RI, USA). Then, 10 mL of the remaining juice was diluted 1:1 with distilled water and the pH and TA were determined using a potentiometric titrator (T5; Mettler-Toledo, Ltd.) equipped with an autosampler (InMotion Pro; Mettler-Toledo Ltd.) and a pH electrode (InLab Cool; Mettler-Toledo Ltd.). Samples were titrated to a pH of 8.2 with 0.1 M potassium hydroxide, typically made fresh weekly. Results are expressed as % volume/volume malic acid of initial (undiluted) juice. Malic acid was selected because it is the predominant organic acid in cherries. Cherry juice samples were titrated with potassium hydroxide (KOH) to a pH of 8.2. The ratio of SSC to TA was calculated because this value can be an indicator of flavor of stone fruit, with higher values preferred for peach (Crisosto and Crisosto 2005); to our knowledge, consumer preference for this value in sweet cherry has not been established. Fruit firmness, diameter, and row size were measured on one side of each fruit, with the thickest part of the fruit oriented vertically toward instrument plunger and midway between the pedicel and calyx using a nondestructive instrument (FirmTech-2, software version 1.2; BioWorks Inc., Stillwater, OK, USA).

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Table 2. Sweet cherry characteristics evaluated.

Visual quality		Indirect sensory	Physiological
Stem length and width	Pitting	Firmness	Respiration
Stem presence	Pebbling	Soluble solids content	(CO_2 production,
Stem quality	Cracking	Titratable acidity	O_2 consumption)
Cut stems	Rot	Pedicel fruit retention force	Bag atmosphere
Stem doublets	Weight		(CO_2, O_2)
Color (lightness, hue, chroma)			

CO_2 = carbon dioxide; O_2 = oxygen.

Respiration rates and bag atmosphere of a subset of fruit stored in polyethylene bags (opening MA bags would alter the atmosphere) were evaluated periodically. To evaluate respiration, 30 fruit in three technical replications of 10 fruit each were analyzed. Carbon dioxide (CO_2) production and oxygen consumption were determined using the static headspace method detailed by Kays and Paull (2004). For CO_2, 0.5-cm^3 (1 cc = 1 mL) gas samples were injected in a gas chromatograph-flame ionization detector (model 8890; Agilent Technologies, Santa Clara, CA, USA) equipped with a multimode inlet (Agilent Technologies), Porabond Q column (Agilent CP7350; 10 m × 320 µm × 5 µm) connected in series to a thermal conductivity detector, and flame ionization detector. The sample run method was based on information in a technical document for large-sample volume injection (Agilent G3510-90020, 2009), with modifications because the sample is gas, not liquid. The front inlet heater temperature mode was solvent vent, with an initial pressure of 5 psi and postinjection pressure of 8 psi until 0.15 min into the sample run. The liner volume was 0.87 mL (Agilent 5190-2295). Inlet and oven temperatures were 50 °C. The thermal conductivity detector heater was set at 200 °C in negative polarity mode with reference flow of 7.5 mL·min^{-1}. The flame ionization detector was set at 250 °C with airflow of 300 mL·min^{-1}. The hydrogen fuel flow was 30 mL·min^{-1}, and the make-up nitrogen flow was 18 mL·min^{-1}. Oxygen was pumped (Gas Sampling Sensor Micro Pump kit; GasLab.com, Ormond Beach, FL, USA) from a static headspace through an oxygen sensor (LOX-O2-F coupled MX300 chip; GasLab.com) and reported to software (Gaslab 2.1; Gaslab.com) to obtain oxygen measurements. Gas was returned to the static headspace via a return line after measurement.

Before the statistical analysis, data for each fruit and stem quality attribute were averaged within each lot and treatment combination; technical replications for respiration rates were also averaged. The percent change between the initial samples at harvest and poststorage samples was calculated; because stem and fruit were destructively measured at each evaluation, change between the initial evaluation and 4 weeks poststorage was not consistent with simple subtraction. Analyses were performed using statistical software (SAS; SAS Institute Inc, Cary, NC, USA) and PROC GLM (continuous data), PROC FREQ/PROC LOGISTIC (binary data), or PROC CORR (Spearman's r) for correlations. Because cultivars and packinghouses were not fully crossed, (i.e., representative lots for each cultivar could not be obtained from all packinghouses each year), the influence of the packinghouse (numbered 1 through 5 to maintain anonymity) on stem and fruit quality attributes was analyzed separately using a one-way analysis of variance (ANOVA). A *post hoc* power analysis was performed using freeware (G*power 3.1.9.7) (Faul et al. 2007). A principal components analysis (PCA), which is an unsupervised type of multivariate analysis (e.g., component differentiation was not directed by any of the experimental factors), was also performed using freeware (Hammer et al. 2001). Before the PCA, an "ideal" sweet cherry lot was constructed with values representing optimal postharvest outcomes; for example, the highest average firmness of any lot, lowest percentage of pitted fruit, and so forth, with the exclusion of L*, a*, b*, because optimal consumer preference values for each color component for sweet cherry were not readily available.

Results

During the initial evaluation upon fruit receipt, the influence of the packinghouse was not statistically significant for the stem and fruit attributes evaluated (Table 3). Based on a *post hoc* power analysis with an α of 0.05 and a large effect size of 0.40 (suitable for studies with results that have practical significance), the study was slightly underpowered (1 – β probability of 0.73; a minimum of 0.80 is preferred). A potential outcome of low statistical power is failure to detect differences in stem and fruit quality outcomes according to the packinghouse when, in fact, there are packinghouse-specific differences.

Initial stem and fruit quality. The initial stem weight-to-length ratio, which is an indirect indicator of stem thickness, differed among cultivars, with Chelan, Regina, and Skeena having the thickest stems, and Black Pearl and Bing having the thinnest stems (Supplemental Table 1). Stem presence did not differ much according to cultivar, but it did differ by year; overall stem retention was higher in 2024 (Supplemental Table 1). The force required to separate fruit from the stem (PFRF) also differed among cultivars, with Regina having the highest PFRF. 'Regina' had longer stems than those of 'Chelan' and 'Skeena'; 'Bing' and 'Black Pearl' had a mid-range stem length and did not differ statistically from either shorter or longer stemmed cultivars (Supplemental Table 1). The average stem length of 'Regina' sweet cherries was noticeably longer, at 52 mm, when compared with that of other cultivars in this trial. Fruit firmness of 'Regina' was lowest; however, firmness did not differ significantly among the other cultivars (Supplemental Table 2). Lightness (L*), which is a colorimeter parameter previously reported for sweet cherries (Wang and Long 2014), did not differ among cultivars, but parameter a* (red-green) did, with Bing having the highest, followed by Skeena, Regina, Chelan, and Black Pearl, which had the lowest. Color component b* (blue-yellow) also differed

Table 3. Stem and fruit quality upon receipt and summary of the packinghouse influence. Some cultivars were not available from all packinghouses (data were not fully crossed for packinghouse × cultivar interactions). The influence of packinghouse on cultivar attributes at pickup was analyzed separately for each cultivar and summarized in the bottom row.

Cultivar	Stem presence (% with stems)	Stem wt:length (g:mm)	PFRF (kg force)[i]	Cut stems (%)	Stem doublet (% with doublets)[ii]	Firmness (mm·g^{-1})	Cracking incidence (% with cracking)	Pitting incidence (% with pitting)	Pebbling incidence (% with pebbling)	SSC (%)[iii]	TA (% malic acid equivalent)[iv]	SSC:TA
Chelan	94	3.1	0.88	38	13	293	19	64	80	19	0.75	26
Black Pearl	87	2.8	0.88	38	13	296	13	49	41	20	0.80	26
Bing	89	2.9	0.74	33	17	290	16	46	38	20	0.80	26
Regina	77	2.8	0.42	35	15	255	28	42	43	20	0.76	27
Skeena	85	2.5	0.68	27	9	325	13	59	54	22	0.89	25
Statistical significance[v]	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

[i] Pedicel fruit retention force (PFRF).
[ii] A single cherry with two stems (stems remained connected at the distal end of fruit).
[iii] Soluble solids content (SSC).
[iv] Titratable acidity (TA), 1 g·L^{-1} = 0.1% malic acid equivalent.
[v] There were no significant (*ns*) differences at $P < 0.05$; data include both years.

among cultivars, with Bing separating into its own category. Visualization of fruit color is shown in Fig. 1. Cracking incidence, pitting, and pebbling incidence were not statistically significant with either cultivar or year for the initial evaluation. The SSC was maximal for 'Bing' and minimal for 'Chelan'. The SSC of 'Black Pearl', 'Chelan', 'Regina', and 'Skeena' did not differ statistically (Supplemental Table 2). The TA was highest for 'Bing' and 'Chelan' and lowest for 'Black Pearl'. The TA of 'Black Peal' was lower than that of the other cultivars. The SSC (%):acidity (% malic acid equivalents) ratio was significantly higher and statistically different for 'Black Pearl', followed by 'Regina' and 'Skeena'; however, it was lowest for 'Chelan' (Supplemental Table 2).

Poststorage stem and fruit quality. At 4 weeks postharvest, the stem weight-to-length ratio did not differ statistically according to any of the experimental factors (Supplemental Table 3). The PFRF did differ according to cultivar, with Black Pearl and Chelan having the highest PFRF, succeeded by Regina and Bing; Skeena had the lowest (Fig. 2, Supplemental Table 3). Change in PFRF between the initial samples and those at 4 weeks did not differ statistically. Percent stem retention and change in stem retention were also not statistically significant. Firmness was highest for 'Black Pearl' and 'Chelan', midrange for 'Bing' and 'Skeena', and lowest for 'Regina', and it was lower when stored at higher temperatures. According to the firmness testing device, fruit typically gained firmness between pickup and 4 weeks poststorage; Skeena was the only cultivar with statistically less gain (Fig. 2). Increases were lower at 4.4 °C (Supplemental Table 4b). Colorimeter value L* (lightness color component) and its change from pickup to 4 weeks was not statistically significant (Supplemental Table 4a), while a* (red/green color component) was influenced by temperature and b* (blue/yellow color component) was influenced by both cultivar and temperature (Fig. 2, Supplemental Table 4a). The change in b* between pickup and harvest differed slightly among cultivars, with Bing having the greatest change, followed by Chelan and Regina; Black Pearl and Skeena had the least change. Change was greater at higher temperatures. Color comparisons and relative changes are

Cultivar	Initial Evaluation	Stored at -0.6 °C	Stored at 4.4 °C
Bing	#5E3537	#563435	#503737
Black Pearl	#4F3838	#493635	#443735
Chelan	#503637	#4B3736	#473837
Regina	#523637	#4D3636	#4B3736
Skeena	#573537	#523536	#4D3737

Fig. 1. Sweet cherry color at the initial evaluation and after 4 weeks of storage in modified atmosphere bags at either −0.6 or 4.4 °C. Colorimeter values L*, a*, b* were converted to the hexadecimal code for visualization.

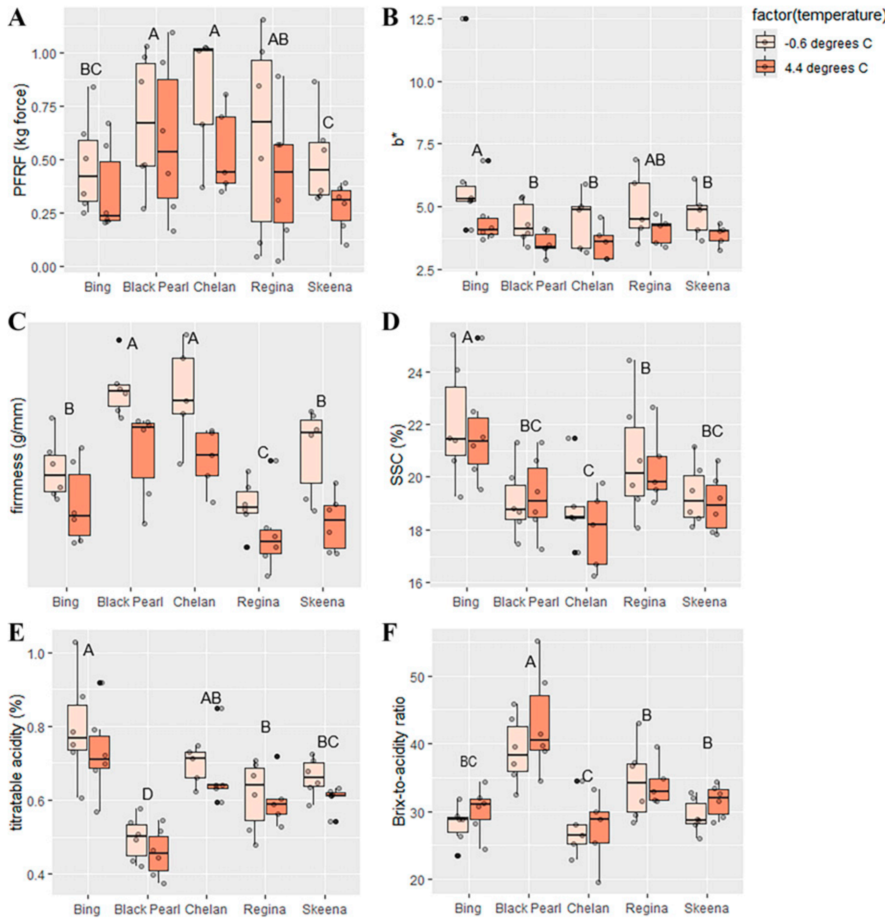

Fig. 2. Differing stem and fruit quality attributes according to cultivar after 4 weeks of storage in modified atmosphere bags at either −0.6 or 4.4 °C include pedicel fruit retention force (PFRF) (A), color component b* (B), fruit firmness (C), soluble solids content (SSC) (D), titratable acidity (TA) (E), and SSC:TA ratio (F). Each data point represents the mean of 30 stems or fruit (taken from the same packed box). Complete tables of stem and fruit quality attributes are provided in the Supplemental Materials (Supplemental Tables 3, 4a, and 4b).

visually summarized in Fig. 1. The SSC was highest for 'Bing' and lowest for 'Chelan'. The SSC of 'Black Pearl', 'Regina', and 'Skeena' did not differ statistically (Supplemental Table 4b). Change in SSC did not differ statistically. The TA was highest for 'Bing' and 'Chelan' and lowest for 'Black Pearl'. Loss of acidity did not differ statistically. The SSC:TA ratio was highest for 'Black Pearl' and lowest for 'Chelan' poststorage. Changes in SSC:TA between the initial evaluation and 4 weeks postharvest were not statistically significant.

Cut stems. Stems with distal ends that were mechanically removed by the cluster-cutter, which is ubiquitous equipment in commercial cherry packinghouses, had lower a stem-length-to-weight ratio at 4 weeks postharvest, suggesting that this aspect of packing leads to desiccation of cut stems (Fig. 3).

Respiration rate. At 1 week postharvest, 'Chelan' and 'Regina' had the highest CO_2 respiration rates, irrespective of temperature (Table 4). 'Black Pearl' had the lowest CO_2 respiration rate. The respiration rate was higher at 4.4 °C than at −0.6 °C, but the interaction of cultivar × temperature was not statistically significant (e.g., temperature did not have a uniform influence on the cultivar respiration rate). There were weak ($r^2 \leq 0.50$) statistically significant positive correlations between the 1-week respiration rate (CO_2 production) and 4-week quality outcomes, including the percent of stems lost and color component b*, and there was a negative correlation between pitting incidence and respiration (Fig. 4, Supplemental Table 5).

The ideal sweet cherry cultivar. A PCA (Fig. 5) indicated that the combined attributes of 'Black Pearl' and 'Chelan' lots were closest to the "ideal" sweet cherry lot. Principal component 1 (89% of variability) indicated that firmness, PFRF, and stem presence are among the top sweet cherry lot-separating quality attributes, and principal component 2 (6% of variability) indicated that respiration rate (CO_2 production; oxygen consumption) were additional consequential cultivar attributes that influenced lot separation.

Bag atmosphere. Average oxygen and CO_2 levels in MA bags were higher for fruit held at higher temperatures and increased with storage duration (Supplemental Table 6).

Discussion

The use of commercially grown fruit postcommercial packing imposed the experimental challenge that preharvest management and postharvest handling (e.g., production, picking, cooling, selection, grading, packaging) (Valero 2015) could not be uniformly set and controlled for statistical purposes. While this does lend limitations to cultivar-focused comparisons, it provides a pragmatic lens into the extent of preharvest management and postharvest handling influence on fruit quality outcomes. In the present study, the use of fruit postcommercial packing led to both sufficiently variable and physiologically consequential outcomes such that the cultivar-specific influences of many quality attributes were below detection in traditional univariate statistics. When fruit are handled uniformly

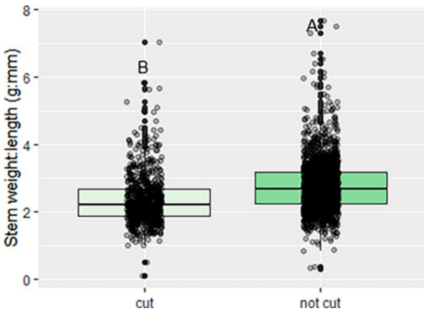

Fig. 3. Sweet cherry stems with the distal portion removed with a commercial cluster-cutter had lower stem weight-to-length ratios, indicating stem desiccation. Box plots capped by differing letters indicate statistical separation at $P < 0.0001$. Each point represents a single stem. Data include all cultivars, all lots, both timepoints (initial and 4 weeks postharvest), and both temperatures postharvest (−0.6 and 4.4 °C).

(Kappel et al. 2002), more cultivar-specific separation in quality attributes is apparent, but the present study indicated that optimizing every aspect of production and postharvest management is as important as cultivar selection in terms of poststorage stem and fruit quality outcomes.

Combining data from 2023 and 2024 for fruit commercially sized and packed, no single cultivar outperformed all other cultivars in all fruit and stem characteristics at the initial evaluation (soon after packing) and after a 4-week hold in MA bags at either −0.6 ± 0.5 °C or 4.4 ± 0.5 °C. However, a multivariate analysis indicated that 'Black Pearl' and 'Chelan' lots stored at −0.6 °C ± 0.5 °C typically were closest to an "ideal" lot of sweet cherries; for this "ideal" lot, attributes were artificially set to what is currently understood to be preferred, such as high firmness, high SSC, high TA, a high percentage of fruit with stems, high stem weight-to-length ratio, low percentage of fruits with defects (cracking, pitting, and pebbling), and optimal physiologically (low respiration rate). Color (L*, a*, b*) was excluded from the multivariate analysis because color vectors for preferred "dark" fruit are not defined. Fruit firmness, PFRF, and stem presence were the main three dependent data attributes that influenced cultivar separation in the multivariate analysis, indicating that, in general, 'Black Pearl' and 'Chelan', which were closest to the "ideal' in the loadings plot, had higher firmness, PFRF, and stem presence, consistent with the results of univariate analyses. High temperatures during storage (4.4 ± 0.5 °C) most clearly negatively affected PFRF, color, fruit firmness, and TA; these results are in line with those of Toivonen (2014). Cultivar-specific differences 4 weeks poststorage were most definitive for PFRF, color, fruit firmness, SSC, and TA. A value judgment was definitively defined only for SSC, firmness, and TA. Consumers typically prefer firmer, sweeter, and more acidic fruit (Turner et al. 2007).

Stem quality is an important visual attribute of cherry fruit quality that can rapidly deteriorate in suboptimal postharvest conditions, specifically low humidity and high ambient temperature (Golding et al. 2017; Linke et al. 2010), as well as methyl bromide application (Drake et al. 1991). Stems can contribute to water loss from the fruit as well (Linke et al. 2010). In the present study, there were no differences in the stem weight-to-length ratio (an indication of stem thickness and desiccation) (Linke et al. 2010). Additionally, relative losses from pickup to 4 weeks poststorage were not statistically significant according to experimental factors, suggesting additional unevaluated factors that influence outcomes (e.g., potentially a lagged effect of postharvest handling). In the present study, humidity was near saturation in the tightly closed MA bags for the duration of the experiment. The PFRF (force required to separate stem from fruit) was the only stem attribute measured poststorage that differed according to cultivar and was also affected by the postpickup storage temperature (with higher temperatures leading to more loss in PFRF). Research has demonstrated that PFRF can vary each year (Zhao et al. 2013). Stem retention (stem presence) differed between years during the initial evaluation but was not statistically significant postharvest, although a multivariate analysis indicated that this attribute is third in contributing to lot separation in the multivariate analysis, with the first two being fruit firmness and PFRF.

Pitting, cracking, and pebbling (the latter is a fruit surface defect indicating desiccation) (Toivonen and Manganaris 2020) did not vary among cultivars in the univariate analysis; the presented results summarize the incidence only, which did not indicate that affected fruit were necessarily in unmarketable condition. Discussions of marketability informally suggested consequential technician variability in willingness to accept defects and also that their view of marketability would be influenced by price. Changes in pitting

Table 4. Respiration rate at 1 week postharvest (fruit stored in perforated polyethylene bags until evaluation).

Temp	Cultivar	mg $CO_2 \cdot kg^{-1} \cdot h^{-1}$ [i]	mg $O_2 \cdot kg^{-1} \cdot h^{-1}$
−0.6 ± 0.5 °C	Bing	26.9 B	21.6 BC
	Black Pearl	21.6 C	23.1 ABC
	Chelan	32.2 A	26.4 A
	Regina	33.4 A	26.1 AB
	Skeena	30.8 AB	20.4 C
4.4 ± 0.5 °C	Bing	28.3 B	24.2 BC
	Black Pearl	24.3 C	24.1 ABC
	Chelan	33.3 A	29.3 A
	Regina	37.0 A	27.0 AB
	Skeena	32.2 AB	22.4 C
	−0.6 ± 0.5 °C	27.0 B	21.6 B
	4.4 ± 0.5 °C	31.0 A	25.4 A
	2023	18.2 B	22.1 B
	2024	39.8 A	25.0 A
	Pr < F	<0.0001	0.0037
	Cultivar	<0.0001	0.0253
	Year	<0.0001	0.0368
	Temperature	0.0044	0.0083
	Cultivar × temperature	0.7527	0.8532
	Cultivar × year × temperature	0.0030	0.0509

[i] Values in a column followed by differing letters are statistically different at $P < 0.05$.

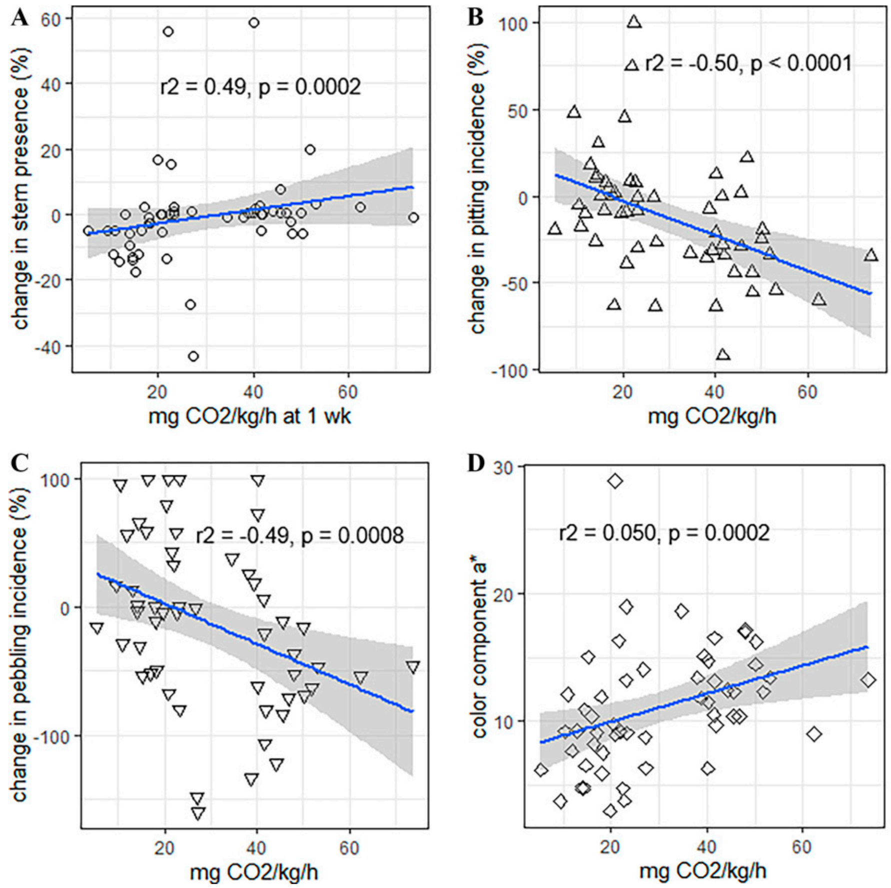

Fig. 4. Spearman's correlations between fruit carbon dioxide production (respiration) at 1 week postharvest and stem or fruit quality at 4 weeks postharvest. Changes in stem presence (A), pitting (B), and pebbling (C) were calculated as the percent of initial lot-by-lot [(initial – final)/initial × 100]. Sampling was destructive. To determine stem presence, pitting, and pebbling, 100 fruit from each lot initially and from each treatment postharvest were evaluated. Color (D) of 30 fruit for each timepoint and treatment was evaluated.

incidence between pickup and 4 weeks poststorage were too variable in each lot to be statistically significant, likely because of factors that can influence pitting incidence, including fruit maturity temperature of handling, and packing line configuration (Grant and Thompson 1997). Pitting incidence is lower when fruit are handled at higher temperatures (Crisosto et al. 1993), which is at odds with the need to cool fruit rapidly and completely to preserve other aspects of quality. Fruit maturity as well as dry matter, which can vary year-to-year (Lidster et al. 1980), also affect pitting outcomes; recent studies also indicated that cultivar-specific metabolic composition (which could be considered a more detailed assessment of dry matter) also influences pitting (Fuentealba et al. 2021). Toivonen (2014) indicated that pitting incidence is higher with storage at lower temperatures. In agreement with this outcome, the incidence of pitting decreased with higher respiration rates (provoked by higher temperature storage). A similar decrease in pebbling was also observed, suggesting potential recovery from this defect in storage. Cracking also did not differ among cultivars and, because fruit were commercially sorted and graded before receipt, varying rates of cracking may have occurred postpacking. Fruit firmness was affected by both cultivar and post-pickup storage temperature, with colder storage ($-0.6 \pm 0.5\,°C$) being optimal. Fruit gained firmness in storage at $-0.6 \pm 0.5\,°C$ in MA bags. Gaining firmness in storage has been previously documented (Toivonen 2014). Because fruit were commercially managed preharvest, gibberellic acid was probably applied to most fruit. The effects of gibberellic acid can be variable according to cultivar and application timing (Einhorn et al. 2013). Color component b* (blue-to-yellow) was the only color component significantly different postharvest and was affected by temperature. Dark color is preferred by consumers (Turner et al. 2008), but the exact contribution of b* to "dark color" is unclear. The TA influences flavor retention and has potential as an indicator of general physiological resilience (Dong 2018; Mattheis et al. 1997; Wang and Long 2014). The TA differed among cultivars both during the initial evaluation and at 4 weeks postharvest, with relative differences among cultivars remaining consistent. 'Black Pearl' had low levels of acidity throughout, but other fruit characteristics of 'Black Pearl' were not relatively lower. All SSC levels were in acceptable ranges for cultivars at harvest (maturity guidelines detailed in Long et al. 2021). The SSC lost between pickup and 4 weeks poststorage differed among cultivars, potentially suggesting cultivar-specific postharvest respiratory substrate utilization rates.

Postharvest respiration rates differed among cultivars (measured at 1 week and 4 weeks into storage). Respiration rates (CO_2 production) varied with lot and over the course of storage, and they were higher at higher temperatures. Although a multivariate analysis in which 'Black Pearl' and 'Chelan' were closest to ideal indicated that respiration rates contribute to sweet cherry lot variability, the present study did not provide statistically backed evidence of cultivar-specific differences in response to temperature. The respiratory phenotype (e.g., pattern over time and temperature) has been considered previously in a PCA (Toivonen 2014). 'Black Pearl' had the lowest and 'Regina' the highest respiration at both temperatures. The production of CO_2 was slightly higher than that reported previously at similar temperatures (Crisosto et al. 1993) but similar to that reported by Wang and Long (2014). In addition to comparisons of respiration at 1 week (present study) and at the initial harvest, 4 weeks postharvest, or 6 weeks postharvest (Wang and Long 2014) or within 24 h of harvest (Cristoso 1993), technology for measuring CO_2 and oxygen (O_2)

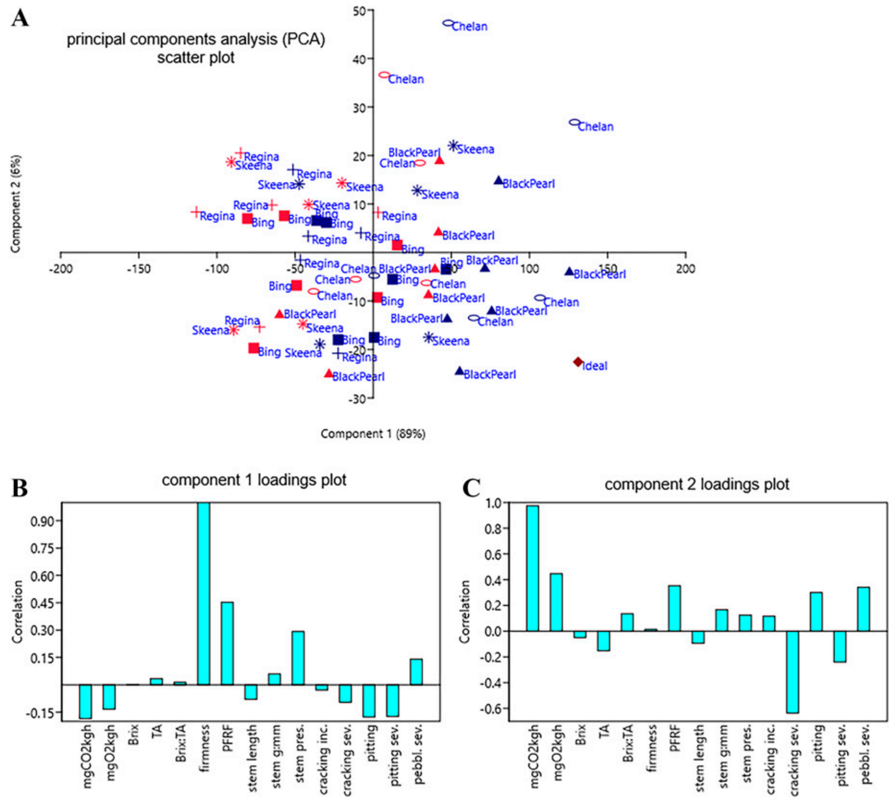

Fig. 5. Principal component analysis of sweet cherry lots poststorage. Red symbols indicate that fruit were stored at 4.4 °C; blue indicates that fruit were stored at −0.6 °C. An "ideal" lot is indicated by a diamond. 'Bing' is indicated by squares, 'Black Pearl' is indicated by inverted triangles, 'Chelan' is indicated by ovals, 'Skeena' is indicated by stars, and 'Regina' is indicated by pluses (A). Firmness, pedicel fruit retention force (PFRF), and stem presence contributed most to cultivar separation in component 1 (B), while respiration (mg CO_2 kg·h^{-1}) and cracking severity contributed most to cultivar separation in component 2 (C).

differed as follows: gas chromatography for CO_2 and fluorescence quenching sensor for O_2 vs. nondispersive infrared and an unspecified chemical sensor for O_2 (Wang and Long 2014), and infrared (Cristoso 1993) measured 1 week into storage vs. immediately after harvest. A statistical correlation analysis of all lots and all cultivars showed that stem loss at 4 weeks and color component a* had the highest correlation (near $r^2 = 0.50$) with respiration rate, whereas pitting incidence had a negative relationship ($r^2 = -0.50$) with respiration.

According to the results of Wang and Long (2014), in the present study CO_2 and O_2 levels were too low and too high, respectively, in MA bags to impede flavor loss. Flavor was not specifically assessed. The MA bags prolonged stem and fruit quality longevity irrespective of cultivar or temperature and, in high-temperature storage (e.g., cold chain breaks), retained quality better than non-MA bags (data from 2023, not shown).

The packinghouse (which was inclusive of all aspects of preharvest and postharvest management) did not typically have a statistically significant influence on fruit and stem quality outcomes. This appeared to be an effect of high variability in lot-to-lot preharvest management, whether innate to the lot or as a result of handling.

Conclusion

This report details cultivar-specific sweet cherry characteristics after long-term storage to provide guidance for decisions involving export or orchard planning. During this 2-year study including multiple lots from multiple years for each cultivar (and data averaged within-lot to impose a more stringent comparison), the overall results suggest that 'Black Pearl' and 'Chelan' are among optimal cultivars for export. The results further indicate that firmness, PFRF, SSC, TA, and respiration are more readily influenced by cultivar, whereas others, including visual defects such as stem weight-to-length ratio (desiccation), fruit pitting, pebbling, and cracking, are apparently more greatly affected by management factors. Knowledge of specific quality attributes more sensitive to postharvest management practices, whether cultivar-specific or general challenges, can enable proactive planning or treatment to mitigate potential problems.

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