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Respiration and Quality Responses of Sweet Cherry to Different Atmospheres during Cold Storage and Shipping

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Abstract

Most sweet cherries produced in the US Pacific Northwest and shipped to distant markets are often in storage and transit for over 3 weeks. The objectives of this research were to study the effects of sweet cherry storage O_2 and CO_2 concentrations on the respiratory physiology and the efficacy of modified atmosphere packaging (MAP) on extending shelf life. Oxygen depletion and CO_2 formation by 'Bing' and 'Sweetheart' cherry fruit were measured. While respiration rate was inhibited linearly by reduced O_2 concentration from 21% to 3-4% at 20 °C, it was affected very little from 21% to ~10% but declined logarithmically from ~10% to ~1% at 0 °C. Estimated fermentation induction points determined by a specific increased respiratory quotient were less than 1% and 3-4% O_2 for both cultivars at 0 and 20 °C, respectively. 'Bing' and 'Sweetheart' cherry fruit were packaged (~8 kg/box) in 5 different commercial MAP box liners and a standard macro-perforated polyethylene box liner (as control) and stored at 0 °C for 6 weeks. MAP liners that equilibrated with atmospheres of 1.8-8.0% O_2 + 7.3-10.3% CO_2 reduced fruit respiration rate, maintained higher titratable acidity (TA) and flavor compared to control fruit after 4 and 6 weeks of cold storage. In contrast, MAP liners that equilibrated with atmospheres of 9.9-14.4% O_2 + 5.7-12.9% CO_2 had little effect on inhibiting respiration rate and TA loss and maintaining flavor during cold storage. All five MAP liners maintained higher fruit firmness (FF) compared to control fruit after 6 weeks of cold storage. In conclusion, storage atmospheres of 1.8-14.4% O_2 + 5.7-12.9% CO_2 generated by commercial MAP, maintained higher FF, but only the MAP with lower O_2 permeability (i.e., equilibrated at 1.8-8.0% O_2) maintained flavor of sweet cherries compared to the standard macro-perforated liners at 0 °C. MAP with appropriate gas permeability (i.e., equilibrated at 5-8% O_2 at 0 °C) may be suitable for

commercial application to maintain flavor without damaging the fruit through fermentation, even if temperature fluctuations, common in commercial storage and shipping, do occur.

Keywords: *Prunus avium* L., respiration rate, respiratory quotient, fermentation induction point, modified atmosphere packaging, flavor loss

1. Introduction

Due to a high respiratory activity, minimal reserve carbohydrate, and high susceptibility to mechanical damage, sweet cherries (*Prunus avium* L.) are highly perishable and have a shelf life of only about 2 weeks under cold chain management that includes rapid elimination of field heat after harvest and low temperature control during storage and shipping (Kupferman and Sanderson, 2001). Their shelf life is often shortened due to loss of flavor, darkening of fruit skin color, pedicel browning, and decay development (industry communication).

The combination of controlled atmosphere (CA) with low temperature could be used to further extend storage and shipping life of sweet cherries (Kader, 1997). High levels of CO_2 (10 or 20%) help to reduce decay and retain firmness, acidity, and fruit color (Chen et al., 1981; Patterson, 1982). Low O_2 (0.5-2%) also maintained fruit firmness, brighter color, higher acidity and green pedicels in 'Bing' cherries stored at -1.1 °C (Chen at al., 1981). The storage life of 'Sweetheart' cherries was extended to 6 weeks at 1 °C under CA conditions (5% O_2 and 2% CO_2) and the fruit maintained higher acidity and firmness and brighter color (Remon et al., 2003). In general, O_2 at 3-10% delayed fruit softening and CO_2 at 10-20% limited decay and maintained flesh appearance (Crisosto et al., 2009). However, O_2 concentrations below 1% may induce skin pitting and off-flavor while CO_2 higher than 30% has been associated with brown skin discoloration of 'Bing' cherries (Kader, 1997).

Previous studies have examined the potential of modified atmosphere packaging (MAP) for extending storage and shipping life of sweet cherries with promising results. Meheriuk et al (1995, 1997) reported a postharvest storage life of 6 weeks for 'Lapins' cherries with equilibrium atmospheres of 0.8% O_2 + 4.5% CO_2 and 4 weeks for 'Sweetheart' cherries with atmospheres of 4.6-6.6% O_2 + 3.5-10% CO_2 when stored in consumer sized polyethylene bags (500-750 g).

MAP box liners effectively maintained better acidity, firmness, color, and stem quality of 'Bing' cherries in cold storage (Crisosto et al., 2009; Lurie and Aharoni, 1997; Mattheis and Reed, 1994). Storage quality of 'Hedelfingen' and 'Lapins' cherries was improved by using MAP box liners that had equilibrated atmospheres of 4-5% O_2 + 7-8% CO_2 and 9-10% O_2 + 7-8% CO_2, respectively (Padilla-Zahour et al., 2004). MAP box liners with equilibrated atmospheres of 1-3% O_2 + 9-12% CO_2 prolonged storage life of 'Burlat' cherries (Remon et al., 2000). The storage life of 'Regina' cherries packed in MAP liners was extended to 5 weeks with improved fruit firmness, skin color, ascorbic acid content, and flavor (Harb et al., 2006). While storage life of some cultivars could be prolonged, the flavor, texture and stem quality of others may be negatively affected by the same MAP box liners (Kahlke et al., 2009) indicating that package selection is highly cultivar dependent. Petracek et al. (2002) found that modified O_2 and CO_2 in MAP atmospheres had no apparent benefit to the shelf life of 'Sam' sweet cherries with respect to respiration and mold control.

More than 1/3 of US Pacific Northwest (PNW) sweet cherries are exported each year. Most of the cherries are shipped to distant markets with storage and transit often requiring over 3 weeks (industry communication). Extending storage and shipping life and assuring good arrival quality of sweet cherries are requisites for satisfying consumers and keeping the PNW cherry industry profitable. Commercial use of MAP for cherries has developed rapidly in the PNW allowing delivery of cherries to distant markets by boat instead of air freight thereby reducing costs (Kupferman and Sanderson, 2001). A number of box liners with differing gas diffusion rates have become available, however, detailed evaluations under similar conditions are lacking. The altered gas atmosphere surrounding the commodity in MAP is created by the respiration of the product and the polymeric film's resistance to O_2 and CO_2 diffusion (Mir and Beaudry, 2004).

115 A good understanding of product respiration dynamics as affected by cultivar, temperature, O_2
116 and CO_2 concentrations, maturity, and production environment is essential for optimizing MAP
117 efficacy. Sweet cherries have moderate to high respiration rates (expressed as production rate of
118 CO_2) with significant differences among cultivars (e.g., from 7.2 μg kg^{-1} s^{-1} of 'Hedelfingen' to
119 36 μg kg^{-1} s^{-1} of 'Emperor Francis' at 20 °C and others in between) reported in the literature
120 (Blanpied, 1972; Crisosto et al., 1993; Sekse, 1988; Toivonien et al., 2004). The influence of O_2
121 and CO_2 concentrations on respiration rates of PNW cultivars under storage and shipping
122 conditions is poorly understood.

123 Respiration rate measurements are commonly made as CO_2 evolution in a flow through
124 system (Kays, 2004). Respiration dynamics, as a function of O_2 and CO_2 concentrations, are
125 most conveniently done in a hermetically sealed chamber in a single experiment (Beveridge and
126 Day, 1991; Jaime et al., 2001). Data collected in sealed chambers has been demonstrated to be
127 adequate for determining the gas compositions inside sealed packages of respiring commodities
128 (Deily and Rizvi, 1981).

129 The objectives of this study were to (1) assess the effect of O_2 and CO_2 concentrations
130 and temperature on the respiration rate of cherry fruit using a closed system; (2) evaluate the
131 effects of different gas atmospheres generated by various commercial MAP liners on fruit quality
132 during storage and shipping of the two major cultivars ('Bing' and 'Sweetheart') grown in the
133 PNW (Long et al., 2007).

134 **2. Materials and methods**

135 *2.1 Fruit materials*

136 Commercially packed 'Bing' and 'Sweetheart' cherries, 20 boxes (~8 kg/box) of each
137 cultivar (row size 10 = 26.6 mm diameter), were obtained from Orchard View Farms (OVF)

(The Dalles, OR) and transported to Mid-Columbia Agricultural Research and Extension Center (Hood River, OR). The fruit were harvested at commercial maturity of color grade 4-5 according to the color comparator developed by CTIFL (Centre Technique Interprofessionnel des Fruit et Legumes, Paris, France), in which 1 = light pink and 7 = dark mahogany. Harvested fruit were hydrocooled and packed (fruit pulp temperature at 0-2 °C) the same day by OVF using standard industry procedures for both cultivars. The respiration experiments and MAP trial described below were started the second day after harvest.

2.2. Closed system respiration experiments

Two boxes of each cultivar were used for respiration experiments. Thirty sound fruit with pedicels were weighed and then placed inside each of the air-tight glass containers (960 mL) equipped with 2 rubber self-sealing sampling ports, and equilibrated at 0, 10, and 20 °C for at least 4 h prior to the experiment. A thin layer of Vaseline® was incorporated into the gap between lid and jar to ensure a hermetic seal for all the containers. To determine the influence of CO_2 on respiration activity, 5 mL of 20% KOH solution in a glass beaker was placed between fruit in selected containers for absorption of CO_2 from the air.

Headspace O_2 and CO_2 concentrations were periodically monitored using an O_2/CO_2 analyzer with an accuracy of ± 0.2% (Model 900161, Bridge Analyzers Inc., Alameda, CA, USA). The analyzer was manufactured with a configuration that recirculated headspace gases. The entrance and exit ports of the analyzer were connected to the entrance and exit ports of the glass containers, and therefore the air sample was flowing continuously between the glass container and the analyzer. Headspace sampling was stopped when the O_2 level inside the container reached < 0.1%. The rates of O_2 uptake (R_{O2}) and CO_2 production (R_{CO2}) and respiratory quotient (RQ) were calculated using equations: 1, 2, and 3, respectively,

$$R_{O2} = dO_2\% \times V_f \div W \div dt \div 100 \quad (1)$$

$$R_{CO2} = dCO_2\% \times V_f \div W \div dt \div 100 \quad (2)$$

$$RQ = R_{CO2}/R_{O2} \quad (3)$$

where V_f is the free volume inside the glass jar (μL), W is the total weight of the product (kg), and time unit is s. R_{O2}, R_{CO2}, and RQ were plotted against the decreasing O_2 concentration as a function of holding period.

2.3. MAP trial

Ten fruit were randomly selected from each box of each cultivar (18 boxes/cultivar) for initial quality evaluations of fruit firmness (FF), soluble solid content (SSC), titratable acidity (TA), and sensory quality. The remaining fruit were immediately packed at 0 °C into 5 different MAP liners and a standard macro-perforated polyethylene box liner as the control (~8 kg/box, 3 boxes/liner). The 5 sweet cherry MAP box liners were ViewFresh® (61954, OVF, The Dalles, OR), Xtend® (815-CH57/14, StePac, Tefen, Israel), LifeSpan® (L504, Amcor, Victoria, Australia), Breatheway® (363-106-A, Apio Inc. Guadalupe, CA), and Primpro® (PP118, Chantler Packaging Inc., Ontario, Canada) and were designated as MAP1 through MAP5, respectively. The characteristics of each MAP liner are proprietary. The MAP and macro-perforated box liners were sealed using a "twist-and-tie" and an elastic band applied to hold the folded twist intact. After 4 and 6 weeks of storage at 0 °C, 50 fruit were randomly sampled from each box for respiration rate and fruit quality evaluations and 50 for sensory evaluations. After opening for sampling at 4 weeks of storage, box liners were resealed immediately and stored at 0 °C for two more weeks.

2.3.1. Fruit weight loss and atmospheric determination inside the packages

The boxes of fruit were weighed initially and before and after sampling at each evaluation date. Weight loss was expressed as percentage loss of original weight. The concentrations of O_2 and CO_2 in the box liners were determined using the O_2 and CO_2 analyzer every day during the first week then every week until at the end of the experiment. A silicon septum was glued to each MAP liner to prevent gas leakage at the sampling site.

2.3.2. Fruit respiration rate and quality determinations

Fifty fruit were randomly selected from each box after 4 and 6 weeks of storage. Of these, 30 sound fruit were equilibrated in air for 2-3 h before placed in hermetically sealed glass containers (960 mL) equipped with 2 rubber sampling ports at 0 °C. After 1 h incubation, headspace CO_2 concentrations were determined using the O_2/CO_2 analyzer (as described in 2.2). Fruit respiration rate was expressed as CO_2 production rate expressed as $\mu g\ kg^{-1}\ s^{-1}$.

After the respiration measurements, the 50 fruit from each box were held in the laboratory at 20 °C for 4-5 h (until condensation on fruit surface was gone) before quality evaluations. Fruit firmness was measured on 25 fruit per box using a FirmTech 2 Fruit Firmness instrument (BioWorks Inc., Stillwater, OK) and expressed as Newton (N). After FF determinations, fruit juice was prepared for SSC and TA measurements using a juicer (Acme Model 6001, Acme Juicer Manufacturing Co., Sierra Madre, CA) equipped with a uniform strip of milk filter (Schwartz Manufacturing Co., Two Rivers, WI). SSC was determined using a refractometer (Model N1, Atago, Tokyo, Japan). TA was determined by titrating 10 mL juice plus 40 mL distilled water to pH 8.1 using 0.1 N NaOH using a commercial titration system (Model T80/20, Schott-Gerate, Hofheim, Germany) and expressed as the equivalent percentage of malic acid.

2.3.3. Sensory evaluations

Fifty fruit were randomly selected from each box after 4 and 6 weeks of storage and brought to 20 °C in the laboratory. Sensory quality evaluations of flavor and texture were conducted using an experienced three-member panel (the senior author and two experienced technicians) and a nine-point hedonic scale: flavor (9 = characteristic sweet cherry flavor at harvest, 5 = acceptable, 1 = bland or fermented) and texture (9 = characteristic crunchy texture at harvest, 5 = acceptable, 1 = soft). Each assessor tasted 5 fruit per replicate. The procedures for sensory evaluation of horticultural crops described by Heintz and Kader (1983) were utilized by the panelists.

2.4. Statistical Analyses

Experimental replicated units were individual glass container (for closed system respiration experiments) or box (for MAP trial) with three replications per treatment at each evaluation period. The experimental design was completely randomized and the data were subjected to analysis of variance (ANOVA) using StatSoft® Statistica version 6 (StatSoft, Tulsa, OK). When appropriate, means were separated by Fisher's Protected LSD test at $P < 0.05$.

3. Results and discussion

The initial quality parameters were: FF = 2.66 N, SSC = 19.2%, and TA = 0.95% for 'Bing'; FF = 3.16 N, SSC = 22.5%, and TA = 0.97% for 'Sweetheart'.

3.1. Closed system respiration experiments

3.1.1. Effect of temperature on respiration activity

The mid-season cultivar ('Bing) had a higher respiration rate than the late season cultivar ("Sweetheart') (Table 1). The initial R_{O2} and R_{CO2} at 20 °C were 17.8 and 12.4 μg kg^{-1} s^{-1} for 'Bing' and 12.1 and 8.3 μg kg^{-1} s^{-1} for 'Sweetheart', respectively and were similar to those reported by Crisosto et al. (1993) and Toivonien et al. (2004). Compared to 20 °C, the initial R_{O2}

and R_{CO2} were reduced significantly at 0 °C to 2.8 and 1.8 μg kg^{-1} s^{-1} for 'Bing' and 2.2 and 1.6 μg kg^{-1} s^{-1} for 'Sweetheart', respectively. The temperature coefficient (Q_{10}) for R_{CO2} was 3.3 and 2.1 for 'Bing', and 2.8 and 1.9 for 'Sweetheart' at 0-10 °C and 10-20 °C, respectively, which were greater than most commodities (Kays, 2004). This implies that a strict temperature control is extremely important for reducing catabolic activity and maintaining quality of sweet cherries during storage and shipping.

3.1.2. Effect of O_2 and CO_2 concentrations on respiration rate at 0 and 20 °C

At 20 °C, R_{O2} and R_{CO2} of 'Bing' and 'Sweetheart' cherry fruit were inhibited linearly by reduced O_2 from 21% to 3-4%. The linear portions were fitted by linear regression equations: $R_{O2} = 1.38\ O_2\% + 9.09$ ($R^2 = 0.99$) and $R_{CO2} = 0.96\ O_2\% + 6.40$ ($R^2 = 0.99$) for 'Bing'; and $R_{O2} = 0.96\ O_2\% + 5.78$ ($R^2 = 0.99$) and $R_{CO2} = 0.67\ O_2\% + 3.81$ ($R^2 = 0.99$) for 'Sweetheart'. At O_2 levels below 3-4%, R_{O2} fell rapidly to near zero at ~0.1% O_2. In some instances, R_{CO2} at O_2 levels lower than 3-4% has slowed slightly until ~1% and then increased significantly (Fig. 1A&B). A similar response was reported for 'Van' sweet cherries (Beveridge and Day, 1991) and peaches (Deily and Rizvi, 1981). The estimated minimum critical O_2 concentrations for the linear portion of the respiratory curves for 'Van' cherries and peaches were 4-5% and 5.5%, respectively.

At 0 °C, R_{O2} and R_{CO2} were affected very little by O_2 concentration from 21% to ~10%, but declined in a logarithmic manner from ~10% to ~1% (Fig. 1C&D). The logarithmic portions were characterized using regression equations: $R_{O2} = 1.36\ Ln(O_2\%) + 0.87$ ($R^2 = 0.97$) and $R_{CO2} = 0.76\ Ln(O_2\%) + 0.65$ ($R^2 = 0.98$) for 'Bing'; $R_{O2} = 1.18\ Ln(O_2\%) + 0.80$ ($R^2 = 0.97$) and $R_{CO2} = 0.64\ Ln(O_2\%) + 0.55$ ($R^2 = 0.98$) for 'Sweetheart'. At O_2 levels below ~1%, R_{O2} fell rapidly to near zero at ~0.1% O_2, but R_{CO2} declined slowly and began to increase at O_2 levels lower than

~0.5%. The respiration rate in response to O_2 concentration at 0 °C implies that the gas permeability of the commercial MAP should ideally equilibrate at an O_2 concentration lower than ~10% to efficiently reduce sweet cherry catabolic activity during storage/shipping. Jaime et al. (2001) reported that respiration rate was inhibited slightly when the O_2 concentration was reduced from 21 to ~10% and dramatically below ~10% for three cultivars ('Burlat', 'Sunburst', and 'Sweetheart') at 2, 5, and 20 °C. However, the respiration rate of 'Sam' cherries was not affected by aerobic O_2 concentrations and decreased at lower O_2 levels until anaerobic respiration was stimulated (Petracek et al., 2002); the oxygen concentration at which this occurred was temperature dependent (i.e., 0-20 °C).

CO_2 accumulation in the closed containers reached ~18% and ~16% at 20 and 0 °C, respectively, by the end of the measurement period for both cultivars. Inclusion of KOH in the closed container reduced the CO_2 concentration to nearly zero, but did not significantly affect R_{O2} at 20 °C (Fig. 2) or 0 °C (data not shown). These results are similar to those found for other sweet cherry cultivars (Jaime et al., 2001; Petracek et al., 2002), raspberries (Joles et al., 1994), and strawberries (Hertog et al., 1999). Thus, CO_2 accumulation in commercial MAP does not seem to inhibit R_{O2} in sweet cherries.

3.1.3. Effect of O_2 concentration on RQ

The RQ represents the ratio of CO_2 produced to O_2 consumed and is determined by the substrate utilized from the composition of a commodity for respiration (Kays, 2004). RQ was maintained at 0.70 and 0.68 between 21% to 3-4% O_2 for 'Bing' and 'Sweetheart', respectively, and increased rapidly after the O_2 concentration fell below 3-4% at 20 °C (Table 1; Fig. 1A&B). At 0 °C, RQ was constant at 0.62 for 'Bing' and 0.60 for 'Sweetheart' between O_2 concentration of 21% to ~1% and began to increase at O_2 concentrations below ~1% (Table 1; Fig. 1C&D).

Since a rapid rise in RQ is known to be a characteristic of anaerobic respiration in plant materials (Kader and Saltveit, 2003; Kays, 2004), the fermentation induction point (FIP) for "Bing' and 'Sweetheart' appears to be below ~1% and 3-4% O_2 at 0 and 20 °C, respectively. The FIP of 'Sam' sweet cherries was estimated based on RQ values 0.2% and 2.5% O_2 at 0 and 20 °C, respectively (Petracek et al, 2002).

The most frequent RQ values reported for various types of fresh produce ranged from 0.7 to 1.3 and was influenced by cultivar, temperature, storage time, and other factors (Kader and Saltveit, 2003). The RQ for 'Sam' sweet cherries was reported to be 1.6 under aerobic conditions between 0 and 25 °C (Petracek, 2002). The RQ values of 'Bing' and 'Sweetheart' determined in this study were close to those of 'Lambert', Stella', and 'Van' (Beveride and Day, 1991). An RQ value near 1 indicates that carbohydrates are the primary respiratory substrate under aerobic conditions while an RQ < 1 indicates lipids and an RQ > 1 organic acids (Kader and Saltveit, 2003; Kays, 2004). Beaudry et al. (1992) explained the high RQ (1.3) value for blueberries was due to their high sugar (12-15 %) and acid (0.3-1.3%) content. However, it is difficult to attribute the low RQ for 'Bing' and 'Sweetheart' cherries to their chemical compositions. Our data also showed that RQ values for both cultivars were reduced by reducing storage temperatures from 20 to 0 °C (e.g., from 0.70 to 0.62 for 'Bing' and from 0.68 to 0.60 for 'Sweetheart') (Table 1). This reduction in RQ is most likely due to the increasing solubility of CO_2 in aqueous environment of the fruit tissue with decreasing temperature, which would lower the apparent CO_2 concentration in the closed container thereby giving lower RQ values (Beveridge and Day, 1991).

3.2. MAP trial

3.2.1. Weight loss, and O_2 and CO_2 concentrations in MAP

297 Cumulative weight losses were less than 1% and there was no difference in weight loss
298 among the different MAP treatments and the control ($P < 0.05$) for 'Bing' and 'Sweetheart' after
299 6 weeks at 0 °C (data not shown). Therefore, any differences in respiration rate and fruit quality
300 among MAP and control fruit should be mainly attributed to differences in the atmospheres
301 within the box liners.

302 The concentrations of O_2 and CO_2 in each of the 5 MAP liners for 'Bing' and
303 'Sweetheart' reached an equilibrium after the first week and remained relatively stable
304 throughout the remaining 5 weeks at 0 °C (Fig. 3). The 5 MAP liners resulted in differing
305 equilibrium O_2 and CO_2 concentrations for each cultivar. O_2 ranged from 1.8 to 13.0% for 'Bing'
306 and 2.2 to 14.4% for 'Sweetheart'. CO_2 ranged from 7.3 to 12.9% for 'Bing' and 5.7 to 10.1%
307 for 'Sweetheart'. There was no accumulation of CO_2 or reduction of O_2 in the macro-perforated
308 liners (control). The equilibrium O_2 and CO_2 concentrations for each of the MAP liners for
309 'Bing' were: MAP1 (13.0%, 7.3%), MAP2 (11.1%, 12.9%), MAP3 (9.9%, 7.8%), MAP4 (7.4%,
310 8.8%), MAP5 (1.8%, 10.3%); and 'Sweetheart': MAP1 (14.4%, 5.7%), MAP2 (12.2%, 10.1%),
311 MAP3 (11.2%, 6.5%), MAP4 (8.0%, 7.3%), MAP5 (2.2%, 8.1%).

312 *3.2.2. Effect of different MAP on fruit respiration rate*

313 After 6 weeks of storage in box liners, 'Sweetheart' fruit had a lower respiration rate than
314 'Bing' at 0 °C regardless of treatment (Fig.4). For both cultivars, fruit packed in MAP5 had an
315 equilibrium O_2 concentration of ~2.0%. The next lowest respiration rate was in MAP4 with an
316 equilibrium O_2 concentration of ~7.7% and MAP1-3 with an equilibrium O_2 concentration of
317 ~10%. MAP1-3 did not reduce the respiration rates of 'Bing' and 'Sweetheart' fruit ($P < 0.05$)
318 compared to control. It was reported that CA conditions with lower O_2 and elevated CO_2

inhibited the respiration rate of ‘Regina’ cherries during low temperature storage, and the inhibition persisted even after 36 h at room temperature (Harb et al., 2003).

3.2.3. Effect of different MAP on fruit texture

Fruit firmness is an important quality attribute in cherries that affects consumer acceptance, fruit storage potential, and resistance to mechanical damage (Brown and Bourne, 1988). The results demonstrated that firmness of both cultivars increased dramatically when the fruit were held in cold storage in MAP liners and control after 4 or 6 weeks (Fig. 5A&B). While there was no difference in FF among MAP and control fruit after 4 weeks, after 6 weeks of storage FF was higher in MAP than in control for both cultivars. Panelists could not differentiate texture differences in either ‘Bing’ or ‘Sweetheart’ among MAP and control fruit after 6 weeks of storage at 0 °C (data not shown). One possible reason is that all fruit in either MAP or control had relatively high FF after cold storage and the difference of FF among MAP and control was not high enough to be assessed by panelists. After 6 weeks at 0 °C, firmness increased 31 and ~42% (‘Bing’) and 15 and ~21% (‘Sweetheart’) in control and MAP fruit, respectively. An increase in cherry FF in air, MAP, or CA storage has been reported by others for different cultivars (Chen et al., 1981; Drake and Fellmann 1987; Kappel et al., 2002; Remon et al., 2000; Sekse et al., 2009). Our FF results are in agreement with Kappel et al. (2002), who found that different cherry cultivars packed in MAP had higher firmness scores after cold storage than at harvest or when stored in air. Chen et al. (1981) reported that lowering the temperature enhanced ‘Bing’ cherry firmness independently of controlled atmosphere (CA) conditions. However, Remon et al (2003) reported that increased firmness of ‘Sweetheart’ cherry was only related to CA and did not occur in samples stored in air at the same temperature (1 °C). In contrast, different cultivars, including ‘Bing’ and ‘Sweetheart’, were reported to decrease in firmness

342 during cold storage in air (Bai et al., 2011; Clayton et al., 2003; Kappel et al., 2002). It is known
343 that firmness development at cold storage is a function of cultivars (Toivonen and Kappel, 2012).
344 Factors determining cherry firmness development during storage and shipping warrant further
345 research.
346 *3.2.4. Effect of different MAP on flavor*
347 The loss of flavor due to a decline in fruit acid content shortens the potential storage and
348 shipping life of sweet cherries; therefore, reducing the rate of acidity loss is a critical objective
349 for extending the potential marketing period (Mattheis et al., 1997). Although TA content was
350 reduced in all MAP treatments and control, MAP4&5 (equilibrated at ~7.7% and ~2.0% O_2,
351 respectively) maintained a higher TA than control fruit for both cultivars after 4 and 6 weeks of
352 storage (Fig. 5C&D). In contrast, MAP1-3 with O_2 equilibrium concentrations higher than ~10%
353 did not affect TA compared to control fruit at each of the evaluation times. There was no
354 difference in TA of each cultivar between MAP4 and MAP5 after 4 weeks, however, after 6
355 weeks of cold storage, fruit in MAP5 had higher TA than in MAP4 ($P < 0.05$). After 6 weeks of
356 storage, TA had declined by 21, 20, 20, 19, 15, and 11% ('Bing") and 26, 25, 25, 26, 21, and
357 14% ('Sweetheart') in control and MAP1-5 treatments, respectively. TA content of each cultivar
358 after 6 weeks of storage was negatively correlated with the equilibrated O_2 concentrations (Fig.
359 6A&B). The reduction of TA degradation by low O_2 is most likely through the inhibition of fruit
360 respiration, based on the positive relationship between respiration rate and O_2 concentration in
361 different MAP liners (Fig. 6C&D). A negative correlation between respiration rate and content
362 of organic acids during cold storage was found in different sweet cherry cultivars (Wei et al.,
363 2011). Both low O_2 and high CO_2 were reported to retard TA loss of 'Bing' cherries during CA
364 storage (Chen et al., 1981; Mattheis et al., 1997). Low O_2 and/or high CO_2 have a negative and

cumulative impact on respiration rate and retarded acid loss in 'Regina' sweet cherries (Harb et al., 2003). Our data indicates that it is the low O_2 (lower than ~10%) rather than the elevated CO_2 that retards the rate of TA loss that occurs due to the reduced respiration rate in MAP storage.

'Bing' fruit packed in MAP4&5 had better flavor than in MAP1-3 and control after 4 and 6 weeks of storage at 0 °C (Fig. 5E). Flavor of 'Sweetheart' was not affected by MAP after 4 weeks, but was better in MAP4&5 than in MAP1-3 and control after 6 weeks of storage at 0 °C (Fig. 5F). There was no difference in flavor between MAP1-3 and control for both cultivars after storage. Sweet cherry flavor is largely determined by a balance between sugar and acid content (Crisosto et al., 2003; Kappel et al., 1996), but not aroma (Mattheis et al., 1994, 1997). SSC did not change ($P < 0.05$) in either cultivar during 4 or 6 weeks of storage (data not shown). Therefore, the superior fruit flavor in MAP4&5 was probably due to the higher TA that was maintained by lower O_2 concentrations (e.g., < ~8%) in the two liners.

Anaerobic fermentation flavor was not determined in fruit packed in MAP5 (i.e., equilibrated O_2 at 1.8% for 'Bing' and 2.2% for 'Sweetheart') after 4 or 6 weeks of storage at 0 °C, which is consistent with the fact that FIP for both 'Bing' and 'Sweetheart' are lower than 1% O_2 at 0 °C (Fig. 1). However, temperature fluctuations during shipping will often affect the respiration rate of cherries, and therefore may change O_2 and CO_2 concentrations in MAP. There may be a risk in causing anaerobic fermentation of cherry fruit in MAP5 in a commercial application due to temperature fluctuations. Further research is warranted on studying simulated temperature fluctuations during commercial shipping on the O_2 and CO_2 concentrations in the MAP liners and their effects on fruit quality, especially flavor among sweet cherry cultivars.

4. Conclusions

Results of the present study indicated that 'Bing and 'Sweetheart' cherries have moderate to high respiration rates, and have a relatively high Q_{10} compared to other fresh commodities. At 0 °C, the respiration rates were little affected by O_2 from 21% to ~10%, but declined logarithmically and significantly from ~10 to ~ 1%. FIP based on a specific increase of RQ was estimated to be <1% O_2 for both cultivars at 0 °C. Elevated CO_2 did not affect respiration rate of either cultivar.

The MAP box liners designed for sweet cherry and assessed in this study generated varied equilibrium O_2 (1.8-14.4%) and CO_2 (5.7-12.9%) concentrations for 'Bing' and 'Sweetheart' at 0 °C. While all five of the MAP liners maintained higher FF than macro-perforated polyethylene box liners, they had different efficacy on maintaining fruit flavor after 4 and 6 weeks of cold storage. Only the MAP with equilibrium O_2 concentration of 1.8-8.0% effectively reduced the rate of respiration and acid loss while maintaining fruit flavor.

Sweet cherry flavor loss is one of the major arrival issues at long-distance markets. The results of this study indicate that MAP liners with the right gas permeability that equilibrate at 2-8% O_2 and >7% CO_2 maintained flavor by retarding acid loss without creating anaerobic fermentation during cold storage and shipping at 0 °C. Due to potential temperature fluctuations during commercial postharvest operations, MAP liners with very low gas permeability (i.e., MAP5) may risk causing anaerobic fermentation of sweet cherries. MAP liners with appropriate gas permeability (i.e., 5-8% O_2 at 0 °C) may be suitable for commercial application to maintain flavor without damaging sweet cherries through fermentation, even at temperature fluctuations common in commercial storage and shipping.

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Fig. 1. Effect of O_2 concentrations on O_2 consumption rate (R_{O2}), CO_2 production rate (R_{CO2}), and respiratory quotient (RQ) of 'Bing' and 'Sweetheart' cherries in a closed system at 20 and 0 °C. Vertical bars represent standard deviations (5% level).

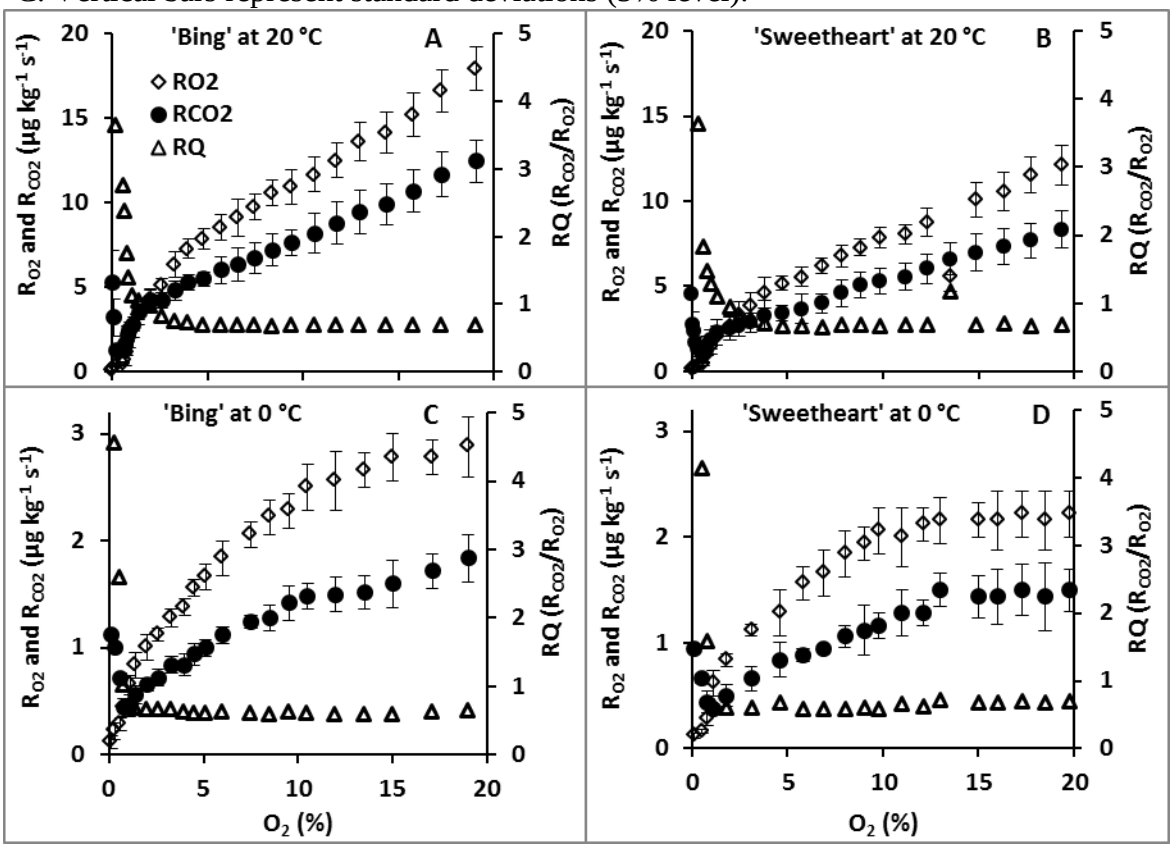

Fig. 2. Effect of CO_2 concentrations on O_2 consumption rate (R_{O2}) of 'Bing' and 'Sweetheart' cherries in a closed system in the presence and the absence of KOH at 20 °C. Vertical bars represent standard deviations (5% level).

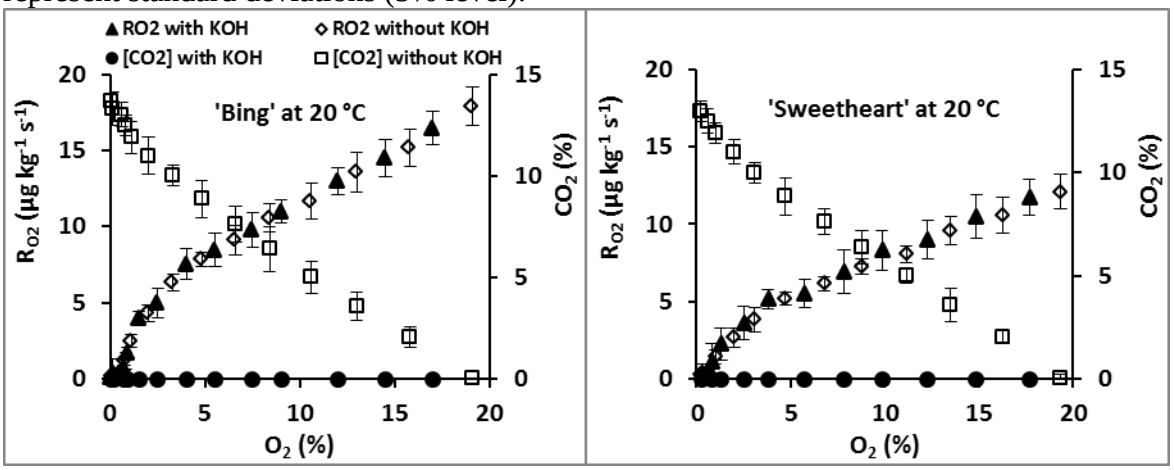

Fig. 3. O_2 and CO_2 concentrations in five different modified atmosphere packages (MAP1-5) and a macro-perforated polyethylene liner (control) containing 'Bing' and 'Sweetheart' cherries stored at 0 °C. Vertical bars represent standard deviations (5% level).

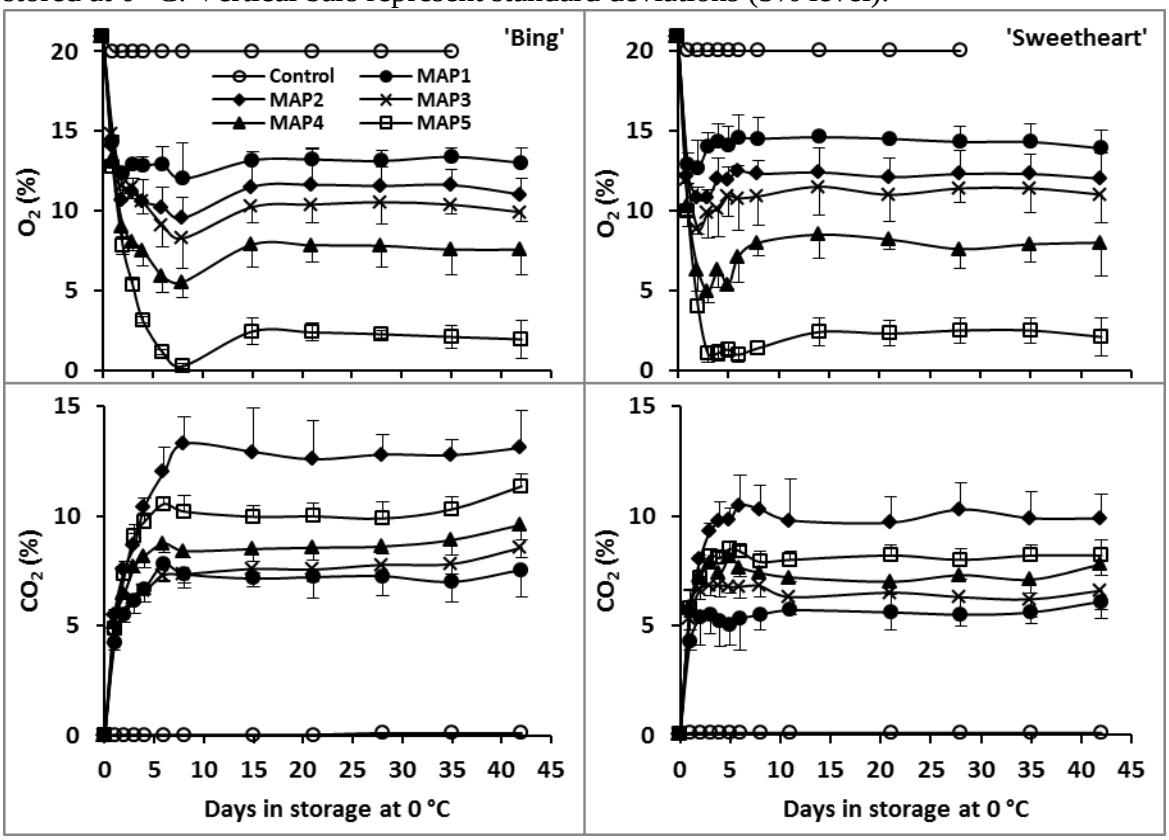

Fig. 4. Respiration rates of 'Bing' and 'Sweetheart' cherries in 5 different modified atmosphere packages (MAP1-5) and a macro-perforated polyethylene liner (control) after storage at 0 °C for 4 or 6 weeks. Vertical bars represent standard deviations (5% level). Different letters indicate significant differences between treatments according to Fisher's protected LSD test at $P < 0.05$.

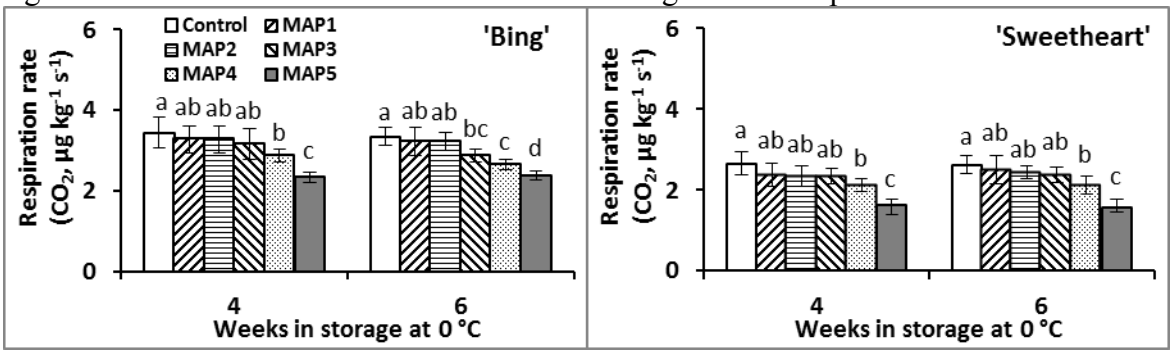

Fig. 5. Effects of 5 different modified atmosphere packages (MAP1-5) and a macro-perforated polyethylene liner (control) on fruit firmness (FF) (A&B), titratable acidity (TA) (C&D), and flavor (E&F) of 'Bing' and 'Sweetheart' cherries after 4 or 6 weeks of storage at 0 °C. Vertical bars represent standard deviations (5% level). Different letters indicate significant differences between treatments according to Fisher's protected LSD test at $P < 0.05$.

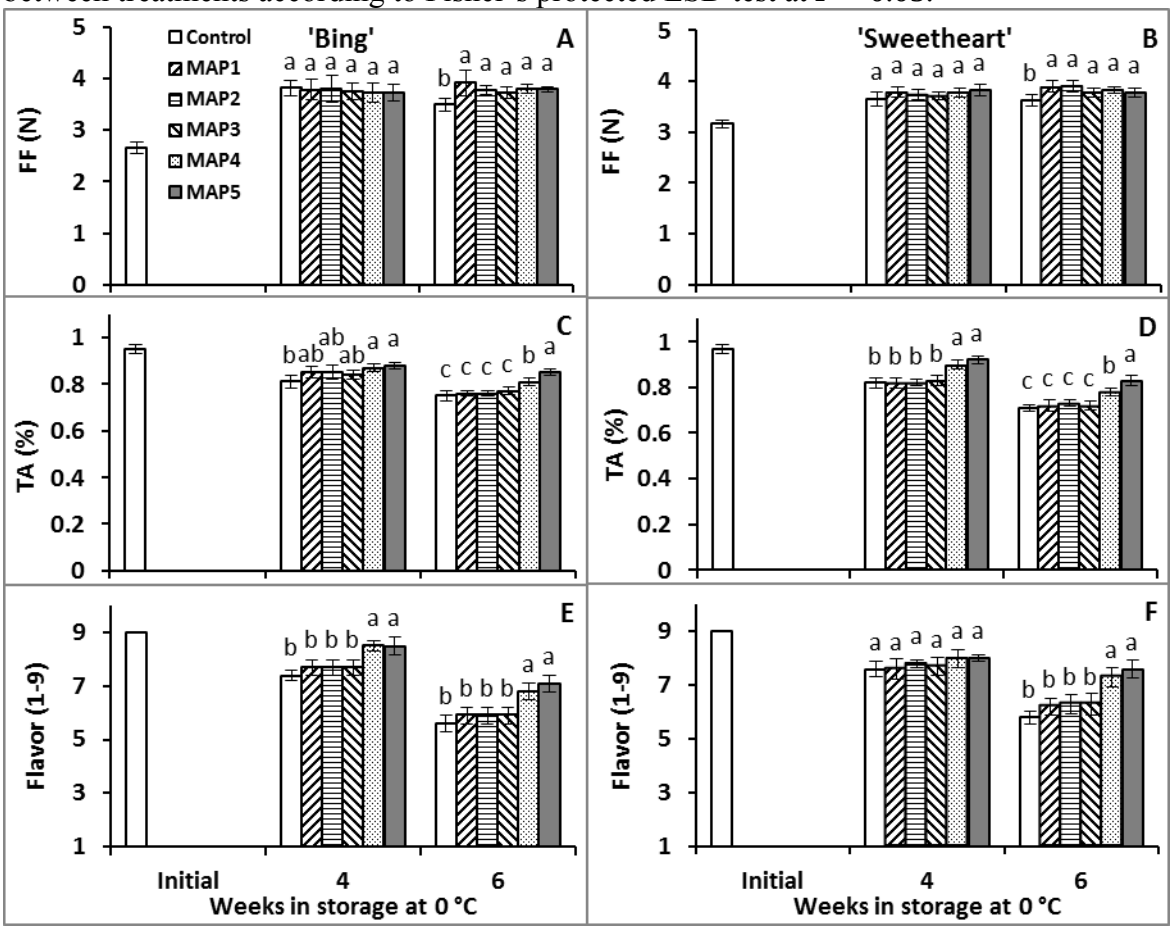

Fig. 6. The relationships between titratable acidity (TA) and equilibrium O_2 concentration (A&B) and respiration rate and equilibrium O_2 concentration (C&D) of 'Bing' and 'Sweetheart' cherries stored in 5 different modified atmosphere packages (MAP) and a macro-perforated polyethylene liner stored for 6 weeks at 0 °C. Vertical bars represent standard deviations (5% level).

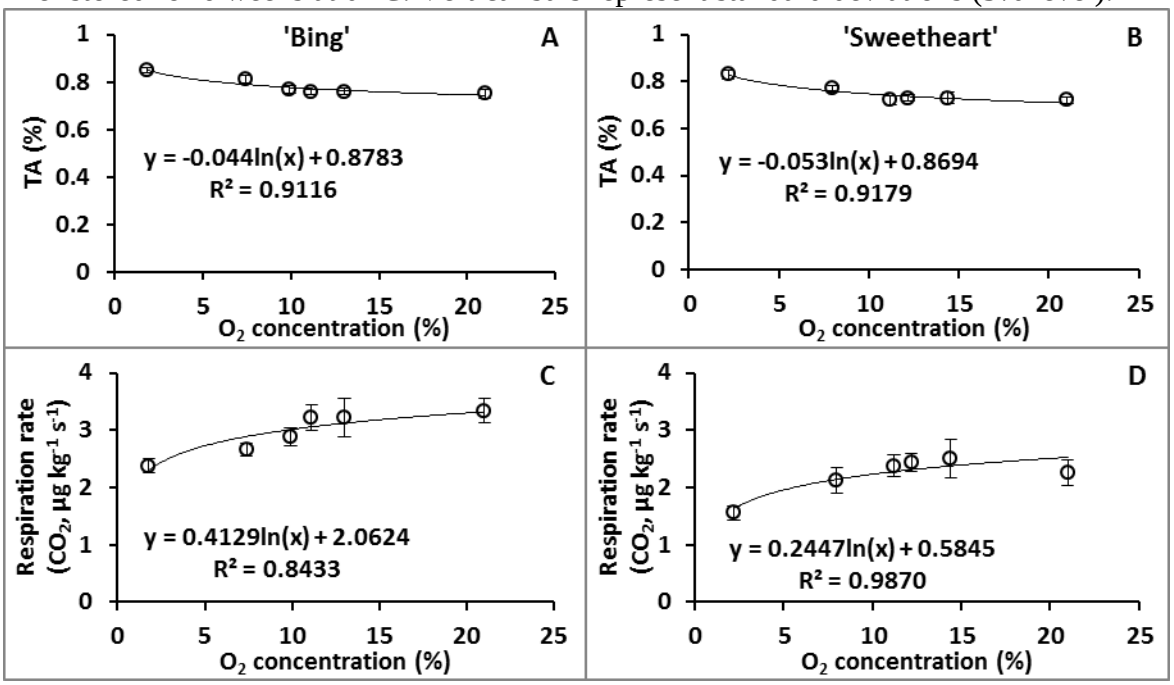

Table 1. Initial O_2 consumption rates (R_{O2}), initial CO_2 production rates (R_{CO2}), and constant aerobic respiratory quotients (RQ) at different temperatures and temperature quotients (Q_{10}) at 0-10 °C and 10-20 °C for 'Bing' and 'Sweetheart' cherries.

	T (0 °C)	R_{O2} (µg kg^{-1} s^{-1})	R_{CO2} (µg kg^{-1} s^{-1})	RQ (R_{CO2}/R_{O2})	Q_{10} (R_{CO2})
'Bing'	0	2.8±0.2[a]	1.8±0.2	0.62	
	10	9.1±1.0	5.9±1.1	0.66	3.3[b]
	20	17.8±1.8	12.4±1.3	0.70	2.1[c]
'Sweetheart'	0	2.2±0.2	1.6±0.2	0.60	
	10	6.5±0.8	4.4±1.0	0.66	2.8[b]
	20	12.1±1.4	8.3±1.4	0.68	1.9[c]

[a] Average ± SD

[b] Q_{10} = [R_{CO2} at 10 °C] ÷ [R_{CO2} at 0 °C].

[c] Q_{10} = [R_{CO2} at 20 °C] ÷ [R_{CO2} at 10 °C].