Initial Short-term Storage at 33 °F Reduces Physiological Disorder Development in ‘Honeycrisp’ Apples

Yosef Al Shoffe¹ and Christopher B. Watkins

ADDITIONAL INDEX WORDS. *Malus domestica*, bitter pit, soft scald, soggy breakdown, conditioning

SUMMARY. Initial short-term storage is a treatment where fruit are cooled to 33 °F for a specific time period and then moved to 38 °F until the end of storage. Its effects on the development of physiological disorders in ‘Honeycrisp’ apples (*Malus domestica*) were investigated for two seasons. During the first season, fruit were harvested from two orchards and stored at 33 and 38 °F, with and without 1 week of conditioning at 50 °F, or stored for 4 weeks at 33 °F followed by 4 weeks at 38 °F. All fruit were stored for a total of 8 weeks. In the second season, fruit were harvested from one orchard and stored at 38 °F either with or without 1 week of conditioning at 50 °F, or stored for 1 week at 33 °F and moved to 38 °F for 15 weeks followed by 7 d at 68 °F. Short-term storage (1 to 4 weeks) at 33 °F decreased bitter pit for all orchards in the two seasons, except in comparison with the continuous 33 °F storage in the first season; soft scald was also reduced in the first season compared with continuous storage at 33 °F, with higher incidence of soft scald in orchard one compared with orchard two. Initial short-term storage at 33 °F resulted in lower soggy breakdown incidence compared with storage at 33 °F with 1 week of conditioning at 50 °F for fruit from orchard two in the first season, the only year when low-temperature injuries were observed. In conclusion, initial short-term storage at 33 °F followed by storage at 38 °F maintained the highest percentage of healthy fruit in the two seasons.

Manipulation of storage temperature for horticultural crops is an important approach for reducing physiological disorders and maintaining quality (Jackman et al., 1988; Lurie, 2002; Wang, 1993). Temperature manipulation involves using optimum storage temperatures with pre-storage conditioning, cold shock, or intermittent warming during storage (Al Shoffe, 2018; Hatton, 1990; Lurie and Crisosto, 2005; Lurie and Sabehat, 1997; Wang, 1994).

Managing the storage of ‘Honeycrisp’ apples is challenging for storage operators. At low temperatures around 33 °F, the cultivar can develop symptoms of chilling injury (CI) such as soft scald and soggy breakdown, whereas at a higher temperature of 38 °F the fruit can be susceptible to bitter pit development (Tong et al., 2003; Watkins et al., 2004). The development of these disorders during storage can cause significant economic losses. Preharvest factors that affect susceptibility of fruit to disorders include orchard location and season (Lachapelle et al., 2013; Moran et al., 2009, 2010; Tong et al., 2016).

Reducing risk of CI development in ‘Honeycrisp’ apples is usually accomplished by conditioning the fruit at 50 °F for 7 d before long-term storage at 38 or 33 °F (DeLong et al.,

2006; Watkins and Rosenberger, 2000; Watkins et al., 2004). However, bitter pit and greasiness may increase with conditioning, even though there are negligible effects on quality factors such as flesh firmness, titratable acidity, and soluble solids concentration (DeLong et al., 2006; Watkins et al., 2004).

To our knowledge, the effect of initial short-term storage at 33 °F prior to storage at 38 °F on physiological disorder development in ‘Honeycrisp’ has not been studied. Our results from the past few years show that bitter pit usually develops during the first month of storage, but CI first appears after the first month of storage (data not shown). Therefore, our goal in this study was to investigate the effect of initial short-term storage at 33 °F on reducing CI and bitter pit development in ‘Honeycrisp’ apples during storage.

Materials and methods

‘Honeycrisp’ fruit from trees grafted on M.9 rootstock under a high-density tall spindle planting system were harvested in 2016 from two commercial orchards (O1 and O2) in western New York, and in 2017 from one commercial orchard in western New York (O2 from the first year). In both seasons, fruit were harvested from 30 trees in three different rows per orchard (ten trees per row).

Three replicates of 10 fruit (fruit for every replication came randomly from 10 trees) each were used at harvest for initial assessments from each orchard during the two seasons. The internal ethylene concentration (IEC) of each fruit was measured on gas samples taken from the core of each apple as described by Nock and Watkins (2013). Firmness was measured on opposite peeled sides of each fruit using a penetrometer equipped with an 11.1-mm-diameter probe (Guss Manufacturing, Strand, South

Horticulture Section, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853

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¹Corresponding author. E-mail: yas24@cornell.edu
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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
10	%	g·L ⁻¹	0.1
29.5735	fl oz	mL	0.0338
25.4	inch(es)	mm	0.0394
4.4482	lbf	N	0.2248
1	ppm	μL·L ⁻¹	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Africa) and the expressed juice was used for measurement of the soluble solids concentration (SSC) with a refractometer (PR-100; Atago Co., Tokyo, Japan). Titratable acidity (TA) was measured on the same juice by titrating to pH 8.1 with 0.1 N sodium hydroxide (FL 12 titrator; Mettler Toledo, Hightstown, NJ) and expressed as a percentage of malic acid (grams malic acid per 100 mL of juice). The starch pattern index (SPI) of each fruit cut at the equator was assessed using the Cornell generic chart where 1 = 100% stained starch and 8 = 0% stained starch (Blanpied and Silsby, 1992). The I_{AD} index, which reflects the chlorophyll a content in the peel, was measured on the blushed and unblushed sides of each fruit using a handheld non-destructive delta absorbance (DA) meter (TR Turoni, Forli, Italy).

TREATMENTS. Five treatments in the first season and three treatments in the second season were tested (Table 1). We shortened the storage period for initial short-term storage at 33 °F from 4 weeks in the first season (treatment 1) to 1 week in the second season (treatment 6) because soft scald developed at 33 °F during 4 weeks in fruit from O1 in 2016.

PHYSIOLOGICAL DISORDER ASSESSMENT. Three replicates of 40 fruit per treatment were assessed for internal and external physiological disorders after 8 weeks of storage in the first season and after 16 weeks followed by 7 d at 68 °F in the second season. The disorder percentage was calculated based on the percentage of fruit that exhibited a certain disorder.

STATISTICAL ANALYSIS. Tukey's honest significant difference test was used to compare means at the 5% confidence level in a full factorial design after analysis of variance (ANOVA) was performed. ANOVAs were aggregated across years to test effects of orchard on IEC, firmness, SSC, TA, SPI, and I_{AD} , and the effects of temperature and orchard on bitter pit, soft scald, soggy breakdown and healthy fruit percentages. All statistics were carried out using the JMP statistical program (version 12; SAS Institute, Cary, NC). Percentage data were arcsine transformed for analysis and presented as back-transformed means.

Results and discussion

In the two harvest seasons, there was no significant difference detected

between the orchards for IEC, firmness and SPI, while SSC and TA were higher in fruit from O1 than from O2. I_{AD} was highest in O2 in the second season compared with the first season (Table 2).

In the first season, initial 4-week storage at 33 °F (treatment 1) or continuous storage at 33 °F (treatment 2) decreased bitter pit compared with the other treatments, while bitter pit development was highest in fruit from O2 in the other treatments (Fig. 1A). Treatment 1 decreased bitter pit in fruit from O1 by 23%, 22%, and 26% and reduced the disorder in O2 by 43%, 42%, 64% compared with treatments 5, 4, and 3, respectively. In addition, bitter pit was decreased in the second season by 28% and 50% by an initial 1-week storage at 33 °F (treatment 6) compared with treatments 7 and 8, respectively (Fig. 2). In O2, the difference in background fruit color from the I_{AD} index did not affect bitter pit development in either season. Disorder incidence was consistent in the two seasons for storage at 38 °F with and without 1 week of

conditioning at 50 °F (treatments 4, 5, 7, and 8). Bitter pit incidence was higher in the second season for treatment 6 compared with treatment 1 because the initial short-term storage at 33 °F was shortened to 1 week in the second season. Our results are in agreement with Watkins et al. (2004), who found that bitter pit development during storage was increased by conditioning and always was higher in warmer storage.

Soft scald was higher in fruit from O1 than O2 in the first season for treatments 1 and 2 (Fig. 1B) despite there being no difference between IEC and SPI in fruit from the two orchards at harvest. This is in agreement with Moran et al. (2010), who found that susceptibility to soft scald varied from region to region and did not correlate with maturity indices. Treatment 1 lowered soft scald development in fruit from O1 to 6% compared with 21% from storage at continuous 33 °F (treatment 2). This is inconsistent with Meheriuk et al. (1994) who recommended that apple cultivars that are susceptible to soft scald should be stored at temperatures

Table 1. Storage treatments and duration for 'Honeycrisp' apples harvested from two orchards in 2016 and from one orchard in 2017.

Harvest season	Treatment
2016	1: Storage at 33 °F for 4 weeks + 4 weeks at 38 °F ^z 2: Storage 8 weeks at 33 °F 3: Conditioning for 1 week at 50 °F + 7 weeks at 33 °F 4: Storage 8 weeks at 38 °F 5: Conditioning for 1 week at 50 °F + 7 weeks at 38 °F
2017	6: Storage for 1 week at 33 °F + 15 weeks at 38 °F followed by 7 d at 68 °F 7: Storage for 16 weeks at 38 °F followed by 7 d at 68 °F 8: Conditioning for 1 week at 50 °F + 15 weeks at 38 °F followed by 7 d at 68 °F

^z(°F - 32) ÷ 1.8 = °C.

Table 2. Harvest indices in 'Honeycrisp' apples harvested from two orchards in 2016 and from one orchard in 2017.

Season	Orchard ^a	IEC (ppm) ^y	Firmness (N) ^x	SSC (%) ^w	TA (%) ^v	SPI (1-8 scale) ^u	I_{AD} index (0-5 scale) ^t
2016	O1	1.44	71.6	13.8 a ^s	0.47 a	5.2	0.53 b
	O2	0.66	69.6	11.9 b	0.39 b	4.5	0.52 b
2017	O2	6.54	69.4	11.0 b	0.41 b	4.6	0.97 a
	P value	NS ^s	NS	***	**	NS	**

^aO1 = orchard 1, O2 = orchard 2 (same orchards used both seasons).

^yInternal ethylene concentration; 1 ppm = 1 µL·L⁻¹.

^x1 N = 0.2248 lbf.

^wSoluble solids concentration.

^vTitrate acidity; 1% = 10 g·L⁻¹.

^uStarch pattern index; 1 = 100% stained starch, 8 = 0% stained starch (Blanpied and Silsby, 1992).

^t I_{AD} index = reflectance of the chlorophyll a content in the peel.

^sMeans within a column not followed by the same letter are significantly different at $P \leq 0.05$ by Tukey's honest significant difference; NS, *, **, or *** are nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Fig. 1. (A) Bitter pit, (B) soft scald, (C) soggy breakdown, and (D) healthy fruit of 'Honeycrisp' apples from two orchards in 2016 and treated as follows: 1 = 4 weeks at 33 °F followed by 4 weeks of storage at 38 °F; 2 = 8 weeks at continuous 33 °F; 3 = 1 week at 50 °F followed by 7 weeks at 33 °F; 4 = 8 weeks at continuous 38 °F; 5 = 1 week at 50 °F followed by 7 weeks at 38 °F. Means with common letters are not different by Tukey's honest significant difference at $P \leq 0.05$. Data are presented as means $\pm$ SE; *** significant at $P \leq 0.001$; $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$.

Fig. 2. Bitter pit in 'Honeycrisp' apples from one orchard in 2017 and treated as follows: 6 = 1 week at 33 °F followed by 15 weeks at 38 °F followed by 7 d at 68 °F; 7 = 16 weeks at continuous 38 °F followed by 7 d at 68 °F; 8 = 1 week at 50 °F followed by 15 weeks at 38 °F followed by 7 d at 68 °F. Mean totals with a common letter are not different by Tukey's honest significant difference at $P \leq 0.05$. Data are presented as means $\pm$ SE; ** significant at $P \leq 0.01$; $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$.

higher than 36.5 °F for the first 6–8 weeks. On the other hand, our results are in agreement with the work of Little and Holmes (2000), who reported that soft scald development was delayed when fruit were stored at 32 °F. Soft scald was negligible in fruit from O2 in all treatments (Fig. 1B). We have found a big variation between orchards in the same region relating to soft scald susceptibility (unpublished data). However, conditioning treatments lowered the disorder more than initial short-term storage at 33 °F or storage at continuous 33 °F (Fig. 1B). Our results are consistent with previous studies (Delong et al., 2006; Watkins and Rosenberger, 2000; Watkins et al., 2004), where conditioning of 'Honeycrisp' apples was reported to reduce soft scald development.

Soggy breakdown was low in fruit from O1 in all treatments (Fig. 2C). Storage of fruit from O2 at 33 °F

after 1 week of conditioning at 50 °F (treatment 3) induced the highest development of the disorder. Treatment 1 reduced soggy breakdown incidence in fruit from O2 to 0.3% compared with 43% for treatment 3 (Fig. 2C). Our results were in agreement with Moran et al. (2010), who found that conditioning of 'Honeycrisp' apples for 7 d at 63.5 °F increased soggy breakdown with an early harvest in two orchards (when SPI was 4.9 and 3.9 for fruit from the two orchards, respectively), but only in one orchard with a later harvest (SPI for fruit from the two orchards was 6.9 and 6.6, respectively). In the second season, we observed no development of CI (data not shown).

Treatment 1 maintained the highest proportion of healthy fruit in the first season, for both orchards (Fig. 1D). The same effect was found for treatment 6 on healthy fruit percentage compared with other treatments in the second season (data not shown). From our results, it is clear that the initial short-term storage at 33 °F reduced bitter pit incidence. O1 was more susceptible to soft scald and treatment 1 worked well in reducing the disorder compared with stress-inducing temperatures for CI, constant 33 °F [treatment 2 (Fig. 1B)] and 50 to 33 °F [treatment 3 (Fig. 1C)]. O2 had higher bitter pit incidence than O1 but treatment 1 and treatment 6 lowered disorder incidence compared with stress-inducing temperatures for bitter pit, constant 38 °F (treatments 4 and 7) and 50 to 38 °F (treatments 5 and 8) in the two seasons. Treatment 1 reduced soggy breakdown in fruit from O2 compared with treatment 3 in the first season.

In conclusion, initial short-term storage at 33 °F (treatments 1 and 6) reduced bitter pit incidence in the two seasons compared with conditioning treatments or continuous 38 °F storage. Treatment 1 decreased soft scald incidence compared with continuous 33 °F storage in O1, and lowered soggy breakdown incidence relative to treatment 3 in O2 from the first season. Also, in both seasons, treatments 1 and 6 had the highest

percentage of healthy fruit compared with all other treatments. Therefore, the application of an initial short-term storage period at 33 °F might be a promising solution in managing physiological disorders in 'Honeycrisp' apples.

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