Journal of the American Pomological Society 76(3): 94-102 2022

'Honeycrisp' Apple Maturity, Quality and Storage Disorders According to Interior and Exterior Tree Canopy Position

Renae E. Moran[a*], Jennifer R. DeEll[b], and Cindy B.S. Tong[c]

Additional index words: bitter pit, chilling injury, ethylene, *Malus xdomestica*, shade, soft scald, soggy breakdown

Abstract

Apples are typically spot picked according to color and, therefore, indirectly according to canopy light exposure that affects fruit peel anthocyanins. We studied how interior and exterior canopy positions influenced fruit maturity and storage disorder incidence in 'Honeycrisp' apples grown in Maine (ME) USA, Minnesota (MN) USA and Ontario (ON) Canada, and harvested two to three times. Harvest maturity was more advanced in exterior compared with interior fruit. In both ME and ON, index of absorbance difference (I_{AD}) was higher for interior fruit compared to exterior fruit. Starch pattern index (SPI) was lower in interior fruit in ME and ON during the first harvest, but not the later harvests, and not in MN where starch breakdown was advanced. Internal ethylene concentration (IEC) at harvest, measured in ON only, was lower in interior fruit during the first harvest, but no difference occurred between the two positions in the latter two harvests. After four months of cold storage plus 1- and 7-d shelf tests, IEC (measured in ON only) was lower in exterior fruit. In all three sites, soft scald, soggy breakdown and bitter pit incidence did not vary between the canopy positions. Fruit were not conditioned to 10 degrees C and stored at 0.5 °C to allow for full development of chilling injury disorders. Canopy position altered fruit maturation and quality with no significant effect on soft scald or bitter pit.

'Honeycrisp' apples are prone to several storage disorders that vary with harvest maturity and other unknown factors that may be environmentally related (Lachapelle et al., 2013; Leisso et al., 2019; Moggia et al., 2015; Moran et al., 2009; Watkins et al., 2005). The light and temperature environment within a tree canopy varies according to canopy position as shoots intercept sunlight (Jackson and Sharples, 1971; McTavish et al., 2020; Woolf and Ferguson, 2000). Despite the use of size-controlling rootstocks that maximize light, high density systems with closer row spacing of tall trees can lead to poor light in the lower canopy (Robinson et al., 2011). The effect of light and canopy exposure on fruit quality is well documented (Jackson and Sharples, 1971; Robinson et al., 1983), but understanding the influence on maturity and storability is increasingly important for new cultivars that are prone to postharvest losses. Apples are typically spot picked according to color and, therefore, indirectly according to canopy light exposure that affects anthocyanin synthesis and red skin color of fruit (Giap et al., 2021). Interior fruit with less sun exposure and less color are typically harvested later than exterior fruit in orchards where spot picking is practiced. These potential differences in environment can influence how fruit perform in the supply chain and can cause losses when storage practices are inappropriate for the maturity of the fruit (McTavish et al., 2020).

Canopy position influences fruit maturity and ripening, but not in a consistent manner.

[a] School of Food and Agriculture, University of Maine, Monmouth, ME 04259, USA; rmoran@maine.edu

[b] Ontario Ministry of Agriculture, Food and Rural Affairs, Simcoe, Ontario, Canada, N3Y 4N5; jennifer.deell@ontario.ca

[c] Department of Horticultural Science, University of Minnesota, Saint Paul, MN 55108, USA; c-tong@umn.edu

[*] Corresponding author

In shaded or interior apples, ethylene production and IEC at harvest can be lower (Jackson et al., 1977), similar (Chu, 1980; Nilsson and Gustavson, 2007), or greater (Kalcits et al., 2019) than in exterior or sun exposed apples. After ripening, interior fruit can have greater ethylene production (Nilsson and Gustavson, 2007), or lower ethylene production after long term storage (Chu, 1980) than exterior apples. Starch breakdown, another indicator of maturity, is slower in shaded 'Honeycrisp' grown in Quebec, Canada (Chouinard et al., 2019), but is unaffected by shading in 'Honeycrisp' grown in Washington (Serra et al., 2020). The disparity among these studies in the effect of position on maturity and ripening may be due to variations in cultivars, climate, tree size, degrees of canopy shading, and physiological maturity at harvest.

The influence of canopy position may have an impact on 'Honeycrisp' storage disorders that are also influenced by harvest maturity such as bitter pit (DeLong et al., 2014; Meheriuk et al., 1994), soggy breakdown and soft scald (Ehsani-Moghaddam and DeEll, 2013). 'Honeycrisp' apples are highly prone to bitter pit, a disorder that is more severe in fruit from the lower compared to upper canopy fruit (Kalcits et al., 2019), but unlike 'Cox's Orange Pippin', in which bitter pit is less severe in fruit from shaded interior or lower canopy positions (Ferguson and Triggs, 1990; Jackson and Sharples, 1971). In a controlled shading study, fruit from trees shaded in the previous growing season had greater bitter pit than those from unshaded trees, possibly due to seasonal carry over effects on calcium (Jackson et al., 1977). Soft scald, a chilling injury, was less prevalent in fruit from the lower canopy in Washington-grown 'Honeycrisp' where incidence is relatively low (Kalcits et al., 2019). The effect of canopy position on soft scald may be different in the cooler production regions of the Midwest and northeastern USA and Canada where incidence can be severe (DeLong et al., 2014; Moran et al., 2020; Watkins et al., 2005).

Understanding how canopy position influences fruit maturity and disorder development is important for harvest management of apples that are prone to quality issues and storage disorders. The objective of this study was to compare harvest maturity, fruit quality and storage disorder development in 'Honeycrisp' apples from the canopy interior and exterior in three geographical locations in the Midwest and northeastern USA and Canada.

Materials and Methods

'Honeycrisp' apples were harvested from trees grown in three locations which were 1) Monmouth, ME USA (44° 13' 51" N, 70° 4' 5" W), 2) Lake City, MN USA (44° 51' 30" N, 93° 39' 41" W) and 3) Norfolk County, ON Canada (42° 52' 44" N, 80° 15' 22.6" W). Trees were grafted to 'Geneva 30' (G.30) rootstock planted in 2007 in ME, 'Budagovsky 9' (B.9) planted circa 1997 in MN and 'Malling 26' (M.26) planted in 1998 in ON. In each location, fruit were harvested according to canopy position, the exterior representing greater exposure to light, and the interior representing shade or partial shade. Fruit were harvested twice in ME (19 Sept. and 2 Oct. 2018), and three times in ON (14 Sept., 28 Sept. and 4 Oct.) and MN (19 Sept., 25 Sept., and 2 Oct.). In ME, 40 to 60 fruit per tree and canopy position were harvested from each of five trees at each harvest date. In ME, a different set of five trees was harvested each time. Fifteen fruit per tree and canopy position in MN and 30 fruit per tree in ON were harvested from the same set of trees at each harvest date. Fruit were stored at 0.5 °C for 4 months in air at each location and with no conditioning.

Quality and maturity at harvest were measured on a subsample of 10 fruit in ME and ON, and 5 fruit in MN. Harvest measurements included fresh weight, percent peel blush, SPI, soluble solids concentration (SSC) and flesh firmness. In addition, I_{AD} was measured in only ME and ON using a Delta Absorbance Meter® (Sinteleia, Bologna, Italy). Measurements 1 and 7 days after removal from cold storage included SSC and firmness for 10 fruit in ME and ON, and 5 fruit in MN.

Starch staining with iodine was measured by dipping or spraying each cross-sectioned apple in or with potassium-iodine solution and using a visual rating where 1 = all starch remaining and 8 = no starch (Blanpied and Silsby, 1992). Flesh firmness was measured on two peeled sides of each fruit using a drill press-mounted penetrometer (McCormick Fruit Tester model FT 327, Italy) in MN; an electronic texture analyzer (Güss, South Africa) in ON, and an EPT-1 (Kelowna, BC, Canada) in ME, all equipped with an 11-mm diameter plunger. Soluble solids concentration was measured using a hand-held temperature-compensated refractometer (Atago, Tokyo, Japan) models PAL-1 3810A in ME, ATC-1E in MN, and PR-32 in ON) from juice expressed during pressure testing. Soluble solids was measured on a pooled sample, except in MN, where SSC was measured for each individual fruit. The percentage of peel with red coloration was visually estimated for each fruit.

In ON, IEC was measured in 10 fruit at harvest, and at 1 and 7 d after removal from storage. A 3-mL gas sample was withdrawn from the core using a syringe and injected into an Agilent 7820A gas chromatograph (Agilent Technologies Canada Inc., Mississauga, ON, Canada) equipped with a 0.25 mL sample loop, flame ionization detector, and 25 m x 0.53 mm CarboBOND capillary column (Agilent Technologies Canada Inc., Mississauga, ON, Canada). The injector, column and detector temperatures were 150, 80 and 250 °C, respectively. High-grade helium was used as the carrier gas, with a typical run time of 1.5 min.

The proportion of fruit with soft scald, soggy breakdown, bitter pit, diffuse flesh browning, lenticel breakdown and leather blotch was measured on 30 to 50 fruit per tree and canopy position in ME, 20 fruit in ON and 10 fruit in MN.

This experiment had a randomized design with factorial arrangement of harvest date and canopy position. Each combination of harvest date and canopy position had five single-tree replications. The main effects of site, harvest date, canopy position and their interactions were subjected to analysis of variance using the SAS GLIMMIX procedure (software version 9.1, SAS Institute, Inc, Cary, NC) with means separation performed by LSMEANS and using the slice option to dissect interactions (Marini, 2022). Disorder incidence data was arcsine transformed, and IEC was log-transformed for analysis, but actual means are presented.

Results and Discussion

Maturity indicators. Starch pattern index (SPI) varied between canopy positions (Table 1) with significant harvest and site interactions. In ME and ON, SPI was lower in fruit from the interior, but by the 2nd harvest differences became non-significant. A lower SPI indicates less starch breakdown. Canopy position did not significantly affect SPI in MN. In all three sites, SPI increased with later harvest consistent with advancing maturity, and was nearly complete by harvest 2 for ME and MN fruit.

Fruit peel I_{AD}, a measure of peel chlorophyll, varied with canopy position with site interactions. In both ME and ON, I_{AD} was higher for interior fruit with all harvest dates indicating less advanced maturity. Site differences occurred as well, but only for interior fruit. During harvest 1, I_{AD} was greater in ME than ON, but the opposite occurred during harvest 2 when I_{AD} was lower in ME than in ON. Fruit peel I_{AD} was not measured in MN.

Internal ethylene concentration (IEC), measured in ON only, varied with canopy position and harvest date (Table 2). At harvest, IEC was lower for interior fruit than exterior, but this occurred only for the first harvest. An increase in IEC occurred with later harvest date but only in fruit from the interior. For exterior fruit, there was no harvest date effect. After four months of cold storage,

Table 1. Harvest maturity and fruit quality of 'Honeycrisp' apples according to harvest date (H1, H2 and H3) and canopy position in Maine (ME), Minnesota (MN) and Ontario (ON).

	ME		MN			ON		
Position	H1	H2	H1	H2	H3	H1	H2	H3
				Starch pattern index				
Exterior	6.0	7.8	7.1	7.9	7.9	4.1	5.6	6.6
Interior	4.5	7.4	6.5	7.1	7.9	2.7	5.2	6.3
P-value	*0.001* [z]	*ns*	*ns*	*0.072*	*ns*	*0.002*	*ns*	*ns*
				Index of absorbance difference				
Exterior	0.86	0.56	--	--	--	0.90	0.76	0.62
Interior	1.34	0.79	--	--	--	1.02	0.89	0.79
P-value	*0.001*	*0.001*	--	--	--	*0.039*	*0.024*	*0.004*

[z] *P*-values for pairwise comparisons. ns indicates nonsignificance.

IEC was greater for interior fruit than for exterior fruit at both d1 and d7 at room temperature. This position effect was significant in fruit from each harvest.

The delay in maturity in fruit from the canopy interior was based on less starch breakdown and higher I_{AD} values in ME and ON and lower IEC during the first harvest in ON. Differences in harvest maturity were minimal in MN. 'Honeycrisp' apples grown in WA also had greater IEC in fruit from the lower canopy compared to the upper, but in fruit closest to the tree trunk, IEC was greater than in fruit towards the outer tip of the limbs (Kalcits et al., 2019). Pear fruit from the lower canopy display slower maturity at harvest as measured by greater I_{AD} and firmness at harvest, but elevated ethylene biosynthesis gene expression compared to fruit from the canopy top (Jaho et al., 2014). In our study, differences in I_{AD} persisted through the 2nd and 3rd harvest, but IEC differences did not, and were reversed after storage becoming greater for interior than for exterior fruit. Shaded apples and plums not placed in cold storage display a more rapid ripening despite no difference or delay in harvest maturity (Murray et al., 2005; Nilsson and Gustavsson, 2007). In contrast, pears from the canopy interior held in long-term controlled atmosphere storage ripened more slowly (Serra et al., 2018). We stored apples in air

Table 2. 'Honeycrisp' apple internal ethylene concentration ($\mu L \cdot L^{-1}$) in fruit harvested at three dates (H1, H2 and H3) from the interior and exterior canopy in Ontario, and measured at harvest and after 4 months of cold storage at 0.5°C plus 1 and 7 days at room temperature.

	At harvest			Stored + 1d			Stored + 7d		
Position	H1	H2	H3	H1	H2	H3	H1	H2	H3
Exterior	16.0 [z]	15.4	7.2	41.7	22.7	23.0	64.6	35.9	26.5
Interior	3.4	14.6	9.6	64.4	32.0	32.2	97.1	61.4	44.4
P-value	*0.001* [y]	*0.083*	*ns* [y]	*0.001*	*0.003*	*0.004*	*0.001*	*0.001*	*0.025*

[z] Log transformed for analysis with back transformed means.
[y] *P*-values for pairwise comparisons. ns indicates nonsignificance.

for four months, so these storage conditions may have led to altered effects on ripening according to canopy position compared with long-term controlled atmosphere storage or with 1-methylcyclopropene treatment.

Fruit quality. Fruit quality was generally affected by canopy position and harvest date, but also varied with site. Fruit weight was greater for fruit from the exterior compared to interior during both harvests in ME, and with the first harvest in both MN and ON (Table 3). Fruit were largest in ON, intermediate in ME and smallest in MN. Fruit from

Table 3. Fruit quality of 'Honeycrisp' apples at harvest and after 4 months cold storage, and according to harvest date (H1, H2 and H3) and canopy position in Maine (ME), Minnesota (MN and Ontario (ON).

	ME		MN			ON		
Position	H1	H2	H1	H2	H3	H1	H2	H3
				Fruit weight (g)				
Exterior	203	236	174	183	184	248	251	253
Interior	159	200	142	168	189	220	235	232
P-value	*0.001*	*0.004*	*0.010*	*ns*	*ns*	*0.019*	*ns*	*0.072*
				Peel blush (% of surface)				
Exterior	69	74	73	85	84	40	52	66
Interior	23	54	47	57	66	13	24	36
P-value	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*	*0.001*
				Soluble solids concentration (%) at harvest				
Exterior	11.5	12.5	12.7	12.7	11.8	11.1	11.3	11.8
Interior	9.8	11.2	11.7	12.0	12.5	10.1	10.8	11.1
P-value	*0.001*	*0.001*	*0.002*	*0.026*	*0.030*	*0.002*	*ns*	*0.019*
				Soluble solids concentration (%) after storage + 1d				
Exterior	11.0	11.2	12.5	12.7	12.7	11.9	12.0	12.0
Interior	9.8	10.4	11.7	12.1	12.4	10.8	11.1	10.9
P-value	*0.001*	*0.065*	*0.057*	*0.098*	ns	*0.005*	*0.024*	*0.006*
				Firmness (N) at harvest				
Exterior	66.2	62.6	55.1	49.4	46.1	66.4	62.5	60.8
Interior	68.2	62.5	57.6	54.4	48.9	67.7	63.1	60.1
P-value	*ns* [z]	*ns*	*0.071*	*0.001*	*0.046*	*ns*	*ns*	*ns*
				Firmness (N) after storage + 1d				
Exterior	63.5	60.4	57.2	53.0	40.6	67.2	65.5	63.5
Interior	66.3	62.6	57.6	54.7	48.5	68.8	65.6	65.1
P-value	*ns*	*ns*	*ns*	*ns*	*0.001*	*ns*	*ns*	*ns*

[z] *P*-values for pairwise comparisons. ns indicates nonsignificance.

the canopy exterior had greater peel surface with blush than fruit from the interior. This was significant for all sites and harvest dates. Fruit from MN generally had more blush than from ME or ON, and ON fruit had less blush than the other two locations. Exterior fruit had greater SSC than interior fruit for all harvest dates and in all three sites except for the second harvest in ON. After storage, SSC was greater in fruit from the canopy exterior compared with the interior, but this difference was not significant for fruit from the latter harvests in ME and MN. After a 7-d shelf test, SSC was significantly greater with exterior fruit (not shown) with no harvest date or site interactions. In ME and ON, fruit firmness at harvest and after storage did not vary between canopy positions. In MN, fruit firmness at harvest was greater in fruit from the canopy interior, but after storage, this was significant for only the third harvest. After and a 7-day shelf test, canopy position had no effect on firmness in any site except in ON for fruit from the third harvest which was greater in fruit from the interior (data not shown).

When comparing apples from the canopy interior harvested at a later date to exterior apples harvested earlier, maturity and fruit quality were generally similar. Fruit from the interior at the 2nd harvest had similar I_{AD} and fresh weight as exterior fruit at the 1st harvest, but peel color of interior fruit did not become as great as exterior fruit until the 3rd harvest.

Storage disorders. Storage disorders occurred in all three sites, but with no consistent canopy position effect (data not shown). Soft scald did not differ between the two canopy positions, except in MN fruit from the third harvest when it was more severe in interior fruit. Diffuse flesh browning and lenticel breakdown incidence varied between canopy position in ME with the 2nd harvest date when it was more severe in fruit from the exterior (5.6%) compared with the interior (0.6%). In MN and ON, diffuse flesh browning was less than 1%. Soggy breakdown, bitter pit and leather blotch did not vary with canopy position.

The lack of canopy position effect on bitter pit was not consistent with previous studies (Kalcits et al., 2019; Marini et al., 2022). Despite the standard foliar calcium, bitter pit occurred in ME and ON where incidence was as high as 11% and 14%, respectively. No bitter pit occurred in MN where size was generally smaller and trees were grafted to B.9 rootstock which increases leaf and fruit calcium compared to M.26 (Fazio et al., 2020), the rootstock used in ON.

The lack of canopy position effect on soft scald contrasts with a previous study where soft scald was greater at lower positions, but with no difference between fruit closest to the trunk compared with near the tip of the limb (Kalcits et al., 2019). In our study, harvest maturity was delayed in fruit from the interior, but this did not influence soft scald

Supplement 1. ANOVA *P*-values for the main effects and their interactions.

Factor	Starch pattern index	Index of absorbance difference	Fruit weight	Peel blush	Soft scald	Soggy breakdown	Bitter pit	Lenticel breakdown	Diffuse flesh browning	Leather blotch
Site	0.001	0.058	0.001	0.001	0.010	0.003	0.001	0.007	0.002	0.004
Harvest	0.001	0.001	0.001	0.001	0.001	ns	0.023	0.100	0.024	ns
Position	0.001	0.001	0.001	0.001	ns	ns	ns	0.039	0.046	ns
S x H	0.001	ns[z]	ns	0.092	0.005	ns	0.045	0.009	0.002	ns
H x P	0.041	ns	ns	ns	ns	ns	ns	ns	0.076	ns
S x P	ns	0.001	ns	ns	0.076	ns	ns	0.038	0.002	ns
S x H x P	ns	ns	ns	0.014	0.086	ns	ns	0.045	0.018	ns

[z] ns indicates nonsignificance.

Supplement 2. ANOVA *P*-values for the main effects and their interactions.

	IEC			firmness			SSC		
	harvest	d 1	d 7	harvest	d 1	d 7	harvest	d 1	d 7
Site	--	--	--	0.001	0.001	0.001	0.001	0.001	0.001
Harvest	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.086	0.034
Position	0.001	0.001	0.001	0.002	0.001	0.003	0.001	0.001	0.001
S x H	--	--	--	ns[z]	0.001	0.001	0.002	ns	ns
H x P	--	--	--	ns	0.041	ns	ns	ns	ns
S x P	0.001	0.002	ns	0.016	ns	ns	0.040	ns	ns
S x H x P	--	--	--	ns	ns	ns	ns	ns	ns

[z] ns indicates nonsignificance.

Supplement 3. Storage disorder incidence (%) in 'Honeycrisp' apples after 4 months cold (0.5°C) storage and according to harvest and tree canopy positions in Maine (ME), Minnesota (MN) and Ontario (ON).

	Soft Scald		MN			ON		
Position	H1	H2	H1	H2	H3	H1	H2	H3
				Soft scald				
Exterior	0.4	19	4	30	38	0	4	58
Interior	0.0	30	0	40	66	0	2	42
P-value	*ns*	*ns*	*ns*	*ns*	*0.001*	*ns*	*ns*	*ns*
				Soggy breakdown				
Exterior	0	0.0	6	2	0	0	0.0	1.0
Interior	0	0.4	4	10	0	0	0.5	0.5
P-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
				Bitter pit				
Exterior	9.5	10.6	0	0	0	6.0	7.5	0.5
Interior	12.0	7.5	0	0	0	11.5	13.5	3.0
P-value	*ns*	*ns*	*ns*	*ns*	*ns*	*0.091*	*0.063*	*ns*
				Diffuse flesh browning				
Exterior	0	5.6	0	0	0	0	0	0
Interior	0	0.6	0	0	0	0.5	0.5	0
P-value	*ns*	*0.001*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
				Lenticel breakdown				
Exterior	0	5.3	0	0	0	0.5	0	0
Interior	0	0.6	0	0	0	0.0	0	0
P-value	ns	*0.079*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

[y] ns indicates nonsignificance.

or soggy breakdown compared with exterior fruit.

Canopy position altered fruit maturation and fruit quality with no significant effect on soft scald or bitter pit, two storage disorders that are associated with harvest maturity.

Acknowledgements

This research was conducted as part of the multistate project NE1336 USDA National Institute of Food and Agriculture. The authors are grateful for funding from the Ontario Apple Growers, Canadian Horticultural Council, the Minnesota Agricultural Experiment Station for project # MN 21-028. This project was supported by the USDA National Institute of Food and Agriculture, Hatch Project Number ME0-31404 through the Maine Agricultural & Forest Experiment Station. We thank Pepin Heights Orchard for their collaboration. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product, nor does it imply approval or disapproval to the exclusion of other products or vendors that may also be suitable.

Literature Cited

Blanpied, G.D. and K. Silsby. 1992. Predicting harvest date windows for apples. Cornell Univ. (Ithaca, N.Y.) Info. Bul. 221.

Chouinard, G., J. Veilleux, F. Pelletier, M. Larose, V. Philion, V. Joubert, and D. Cormier. 2019. Impact of exclusion netting row covers on 'Honeycrisp' apple trees grown under northeastern North American conditions: effects on photosynthesis and fruit quality. Insects 10:2014. Doi:10:3390/insects10070214

Chu, C. L. 1980. Study of the current maturity indices in relation to the position of 'Red Delicious' apples on the tree. PhD Thesis, Washington State Univ.

DeLong, J., R. Prange, P. Harrison, D. Nichols, and H. Wright. 2014. Determination of optimal harvest boundaries for 'Honeycrisp'™ fruit using a new chlorophyll meter. Can. J. Plant Sci. 94:361-369. https://doi.org/10.4141/cjps2013-241

Ehsani-Moghaddam, B. and J. DeEll. 2013. Relationships among postharvest ripening attributes and storage disorders in 'Honeycrisp' apples. Fruits 68(4):323-332. https://doi.org/10.1051/fruits/2013078

Ferguson, I.B. and C.M. Triggs. 1990. Sampling factors affecting the use of mineral analysis of apple fruit for the prediction of bitter pit. New Zealand J. of Crop and Hort. Sci. 18:2-3. https://doi.org/10.1080/00140671.1990.10428086

Fazio, G., J. Lordan, M.A. Grusak, P. Francescatto, and T. Robinson. 2020. I. Mineral nutrient profiles and relationships of 'Honeycrisp' grown on a genetically diverse set of rootstocks under Western New York climatic conditions. Sci. Hort. 266:108477. https://doi.org/10.1016/j.scienta.2019.05.004

Giap, D.V., S. Kim, Y. Lee, and H-J Kweon. 2021. Effect of reflected sunlight on differential expression of anthocyanin synthesis-related genes in young apple fruit. Int. J. of Fruit Sci. 21: 440-455. doi.org/10.1080/15538362.2021.1896981

Jackson, J.E. and R.O. Sharples. 1971. The influence of shade and within-tree position on apple fruit size, colour and storage quality. J. of Hort. Sci. 46(3):277-287.

Jackson, J.E., J.W. Palmer, M.A. Perring, and R.O. Sharples. 1977. Effects of shade on the growth and cropping of apple trees. III. Effects on fruit growth, chemical composition and quality at harvest and after storage. J. Hort. Sci. 52:267-282.

Jaho, A., M.A. Rahim, S. Serra, F. Gagliardi, N.K. Jaho, S. Musacchi, G. Costa, C. Bonghi, and L. Tainotti. 2014. Impact of tree training system, branch type and position in the canopy on the ripening homogeneity of 'Abbé Fétel' pear fruit. Tree Genomics & Genomes 10(5):1477-1488. https://doi.org/10.1007/s11295-014-0777-2

Kalcits, L., J. Mattheis, L. Giordani, M. Reid, and K. Mullin. 2019. Fruit canopy positioning affects fruit calcium and potassium concentrations, disorder incidence, and fruit quality for 'Honeycrisp' apple. Can. J. of Plant Sci. 99:761-771.

Lachapelle, M., G. Bourgeois, J.R. DeEll, K.A. Stewart, and P. Séguin. 2013. Modelling the effect of preharvest weather conditions on the incidence of soft scald in 'Honeycrisp' apples. Postharvest Biol. Technol. 85:57-66. https://doi.org/10.1016/j.postharvbio.2013.04.004

Leisso, R., I. Hanrahan, and J. Mattheis. 2019. Assessing preharvest field temperature and at-harvest fruit quality for prediction of soft scald risk on 'Honeycrisp' apple fruit during cold storage. HortScience 54(5):910-915. https://doi.org/10.21273/HORTSCI13558-18

McTavish, C.K., B.C. Poirer, C.A. Torres, and J.P. Mattheis. 2020. A convergence of sunlight and cold chain: the influence of sun exposure on postharvest apple peel metabolism. Postharvest Biol. and Technol. 164:111164. https://doi.org/10.1016/j.postharvbio.111164

Marini, R.P. 2022. A note on the analysis and interpretation of designed experiments with factorial treatment structure. J. Amer. Pomol. Soc. 76(1):27-35.

Marini, R.P., E.K. Lavely, T.A. Baugher, R. Crassweller, and J.R. Schupp. 2022. Using logistic regression to predict the probability that individual 'Honeycrisp' apples will develop bitter pit. HortScience 57(3)391-399. https://doi.org/10.21273/HORTSCI16081-21.

Meheriuk, M., R.K. Prange, P.D. Lidster, and S.W. Porritt. 1994. Postharvest disorders of apples and pears. Agr. and Agri-Food Canada Pub. 1737/E.

Moggia, C. M Pereira, J.A. Yuri, C. A. Torres, O. Hernández, M.G. Icaza, and G.A. Lobos. 2015. Preharvest factors that affect the development of internal browning in apples cv. Cripp's Pink: Six years compiled data. Postharv. Bio. Tech. 101: 49-57.

Moran, R.E., J.R. DeEll, and W. Halteman. 2009. Effects of preharvest precipitation, air temperature, and humidity on the occurrence of soft scald in 'Honeycrisp' apples. HortScience 44(6):1645-1647. https://doi.org/10.21273/HORTSCI.44.6.1645

Moran, R., J. DeEll, and C. Tong. 2020. Regional variation in the index of absorbance difference as an indicator of maturity and predictor of storage disorders in apples. HortScience 55:1500-1508 https://doi.org/10.21273/HORTSCI15162-20

Murray, X.J., D.M. Holcroft, N.C. Cook, S.J.E. Wand. 2005. Postharvest quality of 'Laetitia' and 'Songold' (*Prunus salicina* Lindell) plums as affected by preharvest shading treatments. Postharvest Biol. and Technol. 37:81-92. doi:10.1016/j.postharvbio.2005.02.014

Nilsson, T. and K. Gustavsson. 2007. Postharvest physiology of 'Aroma' apples in relation to position on the tree. Postharvest Biol. and Tech. 43:36-46. https://doi.org/10.1016/j.postharvbio.2006.07.011

Robinson, T., E.J. Seeley, and B.H. Barritt. 1983. Effect of light environment and spur age on 'Delicious' apple fruit size and quality. J. Amer. Soc. Hort. Sci. 108(5):855-861.

Robinson, T.L., S.A. Hoying, S.A., and G.H. Reginato. 2011. The tall spindle planting system: principles and performance. Acta Hort. 903:571-579 https://doi.org/10.17660/ActaHortic.2011.903.79

Serra, S., N. Sullivan, J. Mattheis, S. Musacchi, and D. Rudell. 2018. Canopy attachment position influences metabolism and peel constituency of European pear fruit. BMC Plant Biol. 18:364. https://doi.org/10.1186/s12870-018-1544-6.

Serra, S., S. Borghi, G. Mupambi, H. Camagro-Alvarez, D. Layne, L. Kalcits, and S. Musacchi. 2020. Photoselective protective netting improves 'Honeycrisp' fruit quality. Plants 9:1708. https://doi:10.3390/plants9121708.

Watkins, C.B., M. Erkan, J.F. Nock, K.A. Iungerman, and R.E. Moran. 2005. Harvest date effects on maturity, quality and storage disorders of 'Honeycrisp' apples. HortScience 40(1):164-169. https://doi.org/10.21273/HORTSCI.40.1.164

Woolf, A.B. and I.B. Ferguson. 2000. Postharvest responses to high fruit temperatures in the field. Postharvest Biol. and Technol. 21:7-20. https://doi.org/10.1016/S0925-5214(00)00161-7