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Preharvest 1-Methylcyclopropene Treatment Reduces Soft Scald in 'Honeycrisp' Apples during Storage

Jennifer R. DeEll[1] and Behrouz Ehsani-Moghaddam
Ontario Ministry of Agriculture, Food and Rural Affairs, P.O. Box 587, Simcoe, Ontario, Canada N3Y 4N5

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***Abstract*. The main objective of this study was to investigate the effectiveness of preharvest 1-methylcyclopropene (1-MCP) treatment on the development of soft scald in 'Honeycrisp' apples. In addition, the effects of preharvest 1-MCP on fruit quality at harvest and after storage were examined. For two consecutive years of study, 'Honeycrisp' trees were sprayed preharvest with 1-MCP and fruit were harvested twice during each year. Preharvest 1-MCP treatments had little consistent effect on fruit maturity at the time of harvest. In both years of study, preharvest 1-MCP reduced the incidence of soft scald in 'Honeycrisp' apples after air storage at 0 or 3 °C for 5 or 6 months. Soggy breakdown developed only in the second year of study and high incidences were reduced by preharvest 1-MCP treatments. Preharvest 1-MCP often reduced flesh firmness loss in 'Honeycrisp' during storage, especially during the second year of study, and with 1-MCP application closer to harvest. Malic acid content was often higher in apples with the preharvest 1-MCP spray closer to harvest. Overall, the most important benefit of preharvest 1-MCP treatments on 'Honeycrisp' apples was the reduction in soft scald development. Due to the high potential for substantial fruit losses from this disorder, the use of preharvest 1-MCP sprays on 'Honeycrisp' apples could be very advantageous.**

'Honeycrisp' apple [*Malus sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] is a relatively new cultivar, which was released by the Minnesota Agricultural Experiment Station in 1991 (Luby and Bedford, 1992). The fruit has outstanding flavor characteristics and can remain crisp for at least 6 months in cold storage (Tong et al., 1999). Unfortunately, 'Honeycrisp' is also extremely susceptible to the storage disorders soft scald and soggy breakdown (Tong et al., 2003; Watkins et al., 2004).

Soft scald, also known as ribbon scald or deep scald, is a low-temperature disorder that is characterized by sharply defined, irregularly shaped brown lesions on the apple skin (Meheriuk et al., 1994; Snowdon, 1990). Damage can extend beneath the skin into the flesh and the lesions are often invaded by secondary infections. The disorder is induced by storing apples below 2 or 3 °C (Meheriuk et al., 1994; Snowdon, 1990). Other factors implicated in the occurrence of soft scald include advanced fruit maturity at the time of harvest, growing location and climate (dull, cool, wet summers), light crops, large fruit, vigorous trees on heavy soils, and fruit mineral content (Tong et al., 2003; Snowdon, 1990). Soft scald incidence has been shown to be negatively related to precipitation during 90 to 120 d from bloom (Moran et al., 2009).

Postharvest application of 1-methylcyclopropene (1-MCP), an inhibitor of ethylene action, has been shown to reduce certain storage disorders in apples (DeEll et al., 2002, 2007, 2008; Fan et al., 1999b; Watkins and Nock, 2005; Watkins et al., 2000). Soft scald was reduced by postharvest 1-MCP in 'Fuji' apples after 6 months of storage (Fan et al., 1999b). In contrast, postharvest 1-MCP treatment had little effect on soft scald incidence in 'Honeycrisp' apples over multiple years of study (DeEll and Murr, unpublished data). Preharvest 1-MCP application on apples has been recently investigated as orchard sprays with the major focus being on reduced fruit drop and fruit maturity (Elfving et al., 2007; McArtney et al., 2009; Yuan and Carbaugh, 2007; Yuan and Li, 2008). The objective of the current study was to investigate the effectiveness of preharvest 1-MCP treatment on the development of soft scald in 'Honeycrisp' apples. In addition, the effects of preharvest 1-MCP on fruit quality at harvest and after storage were examined.

Materials and Methods

Plant material and treatments. Uniform 'Honeycrisp' apple trees were selected within a commercial orchard in Norfolk County, Ontario, Canada. 'Honeycrisp'/M26 (8 years old, 593 trees/ha) and 'Honeycrisp'/M106 (5 years old, 664 trees/ha) were used in 2007 and 2008, respectively. A proprietary formulation of 1-MCP for spraying fruit trees (3.8% a.i.; Harvista™; AgroFresh Inc., Spring House, PA) was applied at ≈160 $mg \cdot L^{-1}$ using an application volume of 1850 $L \cdot ha^{-1}$. The 1-MCP formulation was supplemented with Silwet L-77 organosilicone surfactant (Helena Chemical Co., Collierville, TN) at 0.05% of the final volume. IAP Hi Supreme spray oil (Independent AgriBusiness Professionals, Fresno, CA) was also added, at 1% of the final volume, in 2007. All spray applications were made to the point of runoff using a backpack sprayer (R & D Sprayers, Opelousas, LA). Fruit maturity at the time of 1-MCP sprays is presented in Table 1.

Treatments were arranged in a randomized complete block design. A single-tree replicate in each of six blocks was sprayed on 5 Sept. (Spray 1), whereas another single-tree replicate in each block was sprayed on 9 Sept. (Spray 2) in 2007. More fruit were needed for the storage trials in 2008; thus, four trees in each of six blocks were sprayed on 3 Sept. (Spray 1) and four different trees were sprayed on 9 Sept. (Spray 2) in the second year of study. Comparable control trees were not sprayed within each block in each year. Previous results showed little difference between fruit from trees with no spray and those from trees that received the described solutions with no 1-MCP (data not presented).

In 2007, apples were harvested on 12 Sept. (Harvest 1) and 17 Sept. (Harvest 2). There was a wider range of fruit maturity among the treatments in 2008. Therefore, control apples (no spray) and those from Spray 2 were harvested on 15 Sept. and 23 Sept., whereas fruit from Spray 1 were harvested on 23 Sept. and 2 Oct. in 2008. The first harvest time for each year and treatment was determined by the apple grower with respect to fruit color.

All apples were cooled to 3 °C within a few hours of harvest. One box of at least 50 fruit from each of three single-tree replicates (reps) per treatment and harvest time were stored in air at 0 °C for 5 months in 2007. One box of at least 50 fruit mixed from four trees of each of three reps per treatment and harvest time were stored in air at 0 or 3 °C for 6 months in 2008.

Fruit quality evaluations. Initial fruit maturity at the time of 1-MCP spray applications and at harvest was evaluated on a 10-apple sample from each rep per treatment. Fruit firmness was determined on opposite sides of each apple after peel removal using an electronic texture analyzer fitted with an 11-mm tip (GÜSS, Strand, South Africa). Titratable acidity (expressed as mg equivalents of malic acid per 100 mL of juice) was determined by titrating a 2-mL juice sample with 0.1 N NaOH to an end point of pH 8.1 (as indicated by phenolphthalein), while soluble solids concentration (SSC) was determined using a digital refractometer (PR-32; Atago Co., Ltd, Japan). Starch content was determined using the Cornell Starch Chart (Blanpied and Silsby, 1992). Apples were cut

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[1]To whom reprint requests should be addressed; e-mail Jennifer.DeEll@ontario.ca.

Table 1. Maturity of 'Honeycrisp' apples at the time of 1-methylcyclopropene orchard spray applications and at harvest time in 2007 and 2008.[z]

	Internal ethylene (μL·L−1)	Firmness (N)	Soluble solids (%)	Titratable acidity (mg malic acid/ 100 mL juice)	Starch index (1–8)
2007					
At time of:					
Spray 1	N/A	81.0	14.2	N/A	6.0
Spray 2	N/A	77.9	14.4	N/A	6.1
Harvest 1					
No spray	2.6 a	71.1 ab	14.9 a	715 a	6.2 c
Spray 1	1.0 b	68.9 ab	14.3 ab	648 ab	5.3 d
Spray 2	1.4 b	72.5 a	14.7 ab	738 a	6.5 bc
Harvest 2					
No spray	1.9 ab	70.2 ab	14.3 ab	704 a	7.2 a
Spray 1	1.8 ab	69.8 ab	13.6 b	648 ab	6.5 bc
Spray 2	2.7 a	68.4 b	14.1 ab	536 b	6.8 b
Significance[y]					
Spray (S)	**	NS	NS	NS	****
S × harvest	***	*	*	*	****
2008					
At time of :					
Spray 1	N/A	82.8	12.1	N/A	2.1
Spray 2	N/A	79.2	12.7	N/A	3.5
Harvest 1					
No spray	1.7 cd	68.0 a	13.0 a	754 a	6.7 ab
Spray 1	1.6 cd	68.9 a	12.8 a	789 a	5.1 d
Spray 2	1.1 d	70.2 a	12.2 a	771 a	4.7 d
Harvest 2					
No spray	3.2 b	69.8 a	13.4 a	821 a	7.2 a
Spray 1	4.9 a	63.0 b	12.2 a	615 b	6.4 bc
Spray 2	2.3 bc	67.5 a	13.2 a	805 a	5.9 c
Significance[y]					
Spray (S)	****	**	NS	*	****
S × harvest	****	****	NS	*	****

[z]In 2007, Spray 1 was on 5 Sept., Spray 2 on 9 Sept., Harvest 1 on 12 Sept., and Harvest 2 on 17 Sept. In 2008, Spray 1 was on 3 Sept., Spray 2 on 9 Sept., Harvest 1 on 15 Sept. and Harvest 2 on 23 Sept. for control trees and Spray 2, and Harvest 1 on 23 Sept. and Harvest 2 on 2 Oct. for Spray 1.
[y]For each year, means within each column with the same letter are not significantly different at $P < 0.05$.
NS, ****, ***, **, * = Nonsignificant or significant at $P < 0.0001$, $P < 0.001$, $P < 0.01$, or $P < 0.05$, respectively.
N/A = not available.

Table 2. Quality attributes of 'Honeycrisp' apples from two harvest times, with or without preharvest 1-methylcyclopropene spray in 2007, after 5 months of air storage at 3 °C plus 1 or 7 d at 21 °C.[z]

	Soft scald (%)	Internal ethylene (μL·L−1)	Firmness (N)	Soluble solids (%)	Titratable acidity (mg malic acid/ 100 mL juice)
Harvest 1					
1 d at 21 °C					
No spray	13.3 a	43.0 ef	71.6 bc	13.4 b	540 bc
Spray 1	2.2 bc	58.5 ef	70.2 c	14.5 ab	590 abc
Spray 2	2.2 bc	28.8 f	72.9 abc	14.4 ab	610 a
7 d at 21 °C					
No spray	11.1 ab	207.5 ab	69.8 c	13.9 ab	430 d
Spray 1	2.2 bc	139.7 cd	70.2 c	13.8 ab	550 bc
Spray 2	0 c	76.1 ef	74.7 ab	14.5 ab	590 ab
Harvest 2					
1 d at 21 °C					
No spray	8.9 abc	56.2 ef	72.9 abc	14.1 ab	530 c
Spray 1	0 c	94.0 de	74.7 ab	14.7 ab	550 bc
Spray 2	0 c	85.5 e	72.0 abc	13.8 ab	540 bc
7 d at 21 °C					
No spray	17.8 a	160.5 bc	72.9 abc	14.1 ab	470 d
Spray 1	0 c	244.9 a	75.6 a	15.1 a	550 bc
Spray 2	2.2 bc	219.4 a	72.5 abc	14.9 a	460 d
Significance[y]					
Spray (S)	****	*	NS	NS	****
S × harvest (H)	NS	****	****	NS	***
S × day (D)	NS	NS	NS	NS	*
S × H × D	NS	**	NS	NS	NS

[z]In 2007, Spray 1 was on 5 Sept., Spray 2 on 9 Sept., Harvest 1 on 12 Sept., and Harvest 2 on 17 Sept.
[y]Means within each column with the same letter are not significantly different at $P < 0.05$.
NS, ****, ***, **, * = Nonsignificant or significant at $P < 0.0001$, $P < 0.001$, $P < 0.01$, or $P < 0.05$, respectively.

in half at the equator and rated on a scale of 1 to 8, in which 1 = 100% starch staining and 8 = 0% staining.

Internal ethylene concentration (IEC) was determined by withdrawing a 3-mL gas sample from the core of each fruit using a syringe and injecting the sample into a Varian CP-3800 gas chromatograph (Varian Canada Inc., Mississauga, Ontario, Canada) equipped with a 0.5-mL sample loop, flame ionization detector, and 15 m × 0.32-mm Restek Rt-SPLOT™ capillary column (Chromatographic Specialties Inc., Brockville, Ontario, Canada). The injector, column, and detector temperatures were 120, 35, and 225 °C, respectively. High-grade helium was used as the carrier gas at a flow rate of 0.37 mL·s−1 with a typical run time of 2 min.

After cold storage at 0 or 3 °C and 1 or 7 d at 21 °C, 10 fruit per replicate of each treatment were also measured for firmness, malic acid, SSC, and IEC. In addition, the incidence of soft scald and soggy breakdown was determined using 25 apples per replicate of each treatment. Incidence was calculated as a percentage of fruit with the disorder regardless of severity.

Statistical analyses. Data were analyzed by generalized linear models procedures using the SAS program (Version 9.1.3; SAS Institute Inc., Cary, NC). Mean separations were examined using Duncan's separation test and only differences significant at $P < 0.05$ are discussed.

Results and Discussion

Fruit maturity at harvest. Preharvest 1-MCP treatments had little consistent effect on fruit maturity at the time of harvest (Table 1). Fruit firmness ranged from 63.0 to 72.5 N, while IEC was less than 5 μL·L−1 in apples from all treatments and harvests. Starch degradation was delayed slightly by preharvest 1-MCP, as indicated by lower starch index values.

IEC of 'Honeycrisp' has been shown to be variable over a wide range of harvest dates among various growing regions, i.e., New York, Maine, and Michigan (Watkins et al., 2005). In addition, it was shown that a rapid increase in autocatalytic ethylene production was not always apparent and that the starch index, SSC, titratable acidity, and firmness had limited use as harvest indices. Wargo and Watkins (2004) also found that IEC, starch index, firmness, and SSC did not show consistent patterns of change over time. As such, the small inconsistent effect of preharvest 1-MCP sprays on fruit maturity of 'Honeycrisp' in this study could be due to the natural inconsistent development and ripening associated with this cultivar.

The effectiveness of preharvest 1-MCP at delaying fruit maturity is also thought to vary with apple cultivar and/or growing climate. It has been reported that preharvest 1-MCP spray delayed fruit maturity of 'Law Rome' and 'Golden Delicious' apples in Pennsylvania (McArtney et al., 2008) as well as 'Scarletspur Delicious' and 'Cameo' apples in Washington

(Elfving et al., 2007). In contrast, McArtney et al. (2009) recently showed minimal effects of 1-MCP sprays on fruit maturity of 'Law Rome' and 'Golden Delicious' apples in North Carolina.

Post-storage quality. Preharvest application of 1-MCP reduced the incidence of soft scald in 'Honeycrisp' apples after 5 months of air storage at 3 °C in 2007 (Table 2). There was 0% to 2.2% incidence of soft scald in 'Honeycrisp' sprayed with 1-MCP compared with 8.9% to 17.8% incidence in the non-sprayed control fruit. Similarly, preharvest 1-MCP treatments generally reduced the incidence of soft scald in 'Honeycrisp' apples after 6 months of air storage at 0 or 3 °C in 2008 (Table 3). The highest incidences of soft scald were observed in fruit from the second harvest that were stored at 0 °C, with an average of 46% incidence in non-treated apples and as low as 4.5% in those with 1-MCP spray. Soft scald incidence in fruit from the first harvest was only reduced by the earlier 1-MCP treatment (Spray 1) with 3.9% and 0.6% incidence compared with 11.6% and 16.3% in control apples stored at 0 and 3 °C, respectively (averages significantly different at $P < 0.05$ for both 0 and 3 °C).

Soggy breakdown developed in 'Honeycrisp' apples after 6 months of air storage in 2008 (Table 3), whereas there was no soggy breakdown exhibited in 2007. Similar to soft scald, the highest incidences of soggy breakdown were observed in fruit from the second harvest that were stored at 0 °C. After 7 d at 21 °C, apples treated with preharvest 1-MCP had a much lower incidence (8.2%) of soggy breakdown than non-treated apples (42.3%).

Soggy breakdown is an internal disorder, which is rarely mentioned in the literature. The apple flesh develops moist, soft brown spongy tissue, which can form as complete rings in severe cases (Watkins et al., 2004). To reduce the incidence of soft scald and soggy breakdown, it is recommended that 'Honeycrisp' be stored at 3 °C (Watkins et al., 2005) and undergo a cooling delay at 10 or 20 °C for 1 week before storage

Table 3. Quality attributes of 'Honeycrisp' apples from two harvest times, with or without preharvest 1-methylcyclopropene spray in 2008, after 6 months of air storage at 0 or 3 °C plus 1 or 7 d at 21 °C.[z]

	Soft scald (%)	Soggy breakdown[y] (%)	Internal ethylene ($\mu L \cdot L^{-1}$)	Firmness (N)	Soluble solids (%)	Titratable acidity (mg malic acid/ 100 mL juice)
Storage at 0 °C						
Harvest 1						
1 d at 21 °C						
No spray	6.7 def	11.1 bcd	23.8 ij	66.2 ef	12.8 c	503 c
Spray 1	4.4 def	0 d	36.8 hi	71.6 abc	13.0 ab	469 d
Spray 2	8.9 def	4.4 cd	21.8 ij	72.9 abc	12.6 efg	536 b
7 d at 21 °C						
No spray	16.5 cd	4.4 cd	142.8 c	67.5 de	12.5 ghi	436 e
Spray 1	3.3 def	0 d	127.3 cde	70.2 bcd	13.0 ab	402 f
Spray 2	7.1 def	0 d	110.8 ef	73.4 abc	13.1 ab	503 c
Harvest 2						
1 d at 21 °C						
No spray	46.7 a	8.9 bcd	11.0 j	61.2 g	13.2 a	402 f
Spray 1	15.6 cd	17.8 b	32.4 i	64.4 efg	12.9 b	402 f
Spray 2	4.5 def	0 d	22.1 ij	71.1 abc	13.0 b	402 f
7 d at 21 °C						
No spray	45.2 a	42.3 a	N/A	N/A	N/A	N/A
Spray 1	28.2 b	7.6 cd	117.8 de	62.1 g	13.0 b	402 f
Spray 2	11.3 def	8.9 bcd	129.3 cde	69.3 cd	13.0 ab	436 e
Storage at 3 °C						
Harvest 1						
1 d at 21 °C						
No spray	8.9 def	0 d	37.9 hi	71.1 abc	12.4 ijk	503 c
Spray 1	0 f	0 d	118.3 de	72.9 abc	13.0 ab	436 e
Spray 2	11.1 def	0 d	52.5 gh	74.3 a	12.3 jkl	604 a
7 d at 21 °C						
No spray	23.6 bc	4.5 cd	175.2 b	70.7 abcd	12.3 kl	402 f
Spray 1	1.1 ef	0 d	207.6 a	71.6 abc	12.7 cd	436 e
Spray 2	13.5 cde	2.2 cd	169.9 b	73.4 ab	12.4 hij	536 b
Harvest 2						
1 d at 21 °C						
No spray	8.9 def	8.9 bcd	60.7 g	67.1 de	12.3 jkl	436 e
Spray 1	2.2 ef	4.5 cd	94.2 f	61.7 g	12.7 cde	469 d
Spray 2	4.5 def	0 d	134.1 cd	72.5 abc	12.2 l	503 c
7 d at 21 °C						
No spray	5.5 def	13.4 bc	124.1 cde	67.1 de	12.6 defg	369 g
Spray 1	4.3 def	5.1 cd	172.0 b	62.1 fg	12.7 cdef	369 g
Spray 2	0 f	0 d	208.3 a	72.0 abc	12.5 fgh	469 d
Significance[x]						
Spray (S)	****	****	****	****	****	****
S × harvest (H)	****	****	****	****	****	***
S × temperature (T)	****	**	****	***	***	**
S × day (D)	NS	*	****	NS	****	****
S × H × T	****	NS	****	NS	NS	NS
S × H × D	*	**	****	NS	****	**
S × T × D	NS	NS	NS	NS	*	**
S × H × T × D	NS	**	**	NS	****	****

[z]In 2008, Spray 1 was on 3 Sept., Spray 2 on 9 Sept., Harvest 1 on 15 Sept. and Harvest 2 on 23 Sept. for control trees and Spray 2, and Harvest 1 on 23 Sept. and Harvest 2 on 2 Oct. for Spray 1.

[y]Soggy breakdown also includes symptoms resembling low temperature breakdown and internal CO_2 injury.

[x]Means within each column with the same letter are not significantly different at $P < 0.05$.

NS, ****, ***, **, * = Nonsignificant or significant at $P < 0.0001$, $P < 0.001$, $P < 0.01$, or $P < 0.05$, respectively.

N/A = not available.

(DeLong et al., 2006; Watkins et al., 2004). However, there was no cooling delay used in this study in order to have maximum potential for soft scald development. Similarly, storage at 0 °C was added in the second year of study to potentially increase soft scald incidence.

The biochemical mechanisms for soft scald and soggy breakdown development are not known. It has been suggested that soft scald is associated with respiratory metabolism, elevated hexanol concentration, oxidation of unsaturated fatty acids in the surface lipids, as well as possibly the timing of cold storage in relation to the climacteric (Hopkirk and Wills, 1981; Watkins et al., 2004; Wills, 1973). It has been shown that soft scald is not related to ethylene production rate in 'Honeycrisp' (Tong et al., 2003). In this study, there was no consistent effect of preharvest 1-MCP treatments on IEC in 'Honeycrisp', although 1-MCP sprays effectively reduced soft scald incidence (Tables 1 through 3). This confirms that ethylene is not directly related to soft scald development. Furthermore, previous results showed that gaseous 1-MCP applied postharvest (1 $\mu L \cdot L^{-1}$ for 24 h at 3 °C) reduced IEC in 'Honeycrisp' while there was no significant effect on soft scald incidence (DeEll and Murr, unpublished data). Therefore, the timing of 1-MCP application (preharvest versus postharvest) appears to be important in relation to its effectiveness at reducing soft scald development.

Preharvest 1-MCP often (but not always) reduced flesh firmness loss in 'Honeycrisp' apples during storage and it was more pronounced in the second year of study (Tables 2 and 3). This effect was greater with 1-MCP application closer to harvest (Spray 2) compared with the earlier spray (Spray 1). Elfving et al. (2007) also found that application closer to harvest improved the effect of preharvest sprayable 1-MCP on control of firmness loss in 'Scarletspur Delicious' and 'Cameo' apples during short-term storage at 1 °C. Positive effects of preharvest 1-MCP on the postharvest quality of 'Law Rome' apples declined when harvested 3 d or more after spraying, while positive effects on the postharvest quality of 'Golden Delicious' continued when harvested up to 9 d after spraying (McArtney et al., 2009). Softening of 'Honeycrisp' during storage is slow (Wargo and Watkins, 2004), as it maintains a crisp texture from harvest through long-term storage as a result of maintenance of high turgor potential and cell wall integrity (Tong et al., 1999). Therefore, large differences in firmness between 1-MCP-treated and non-treated fruit (typical of other apple cultivars) cannot be expected to occur quickly in 'Honeycrisp'.

There was no significant effect or little consistent effect of preharvest 1-MCP treatments on SSC (Tables 2 and 3). In addition, there were no notable differences in peel greasiness resulting from 1-MCP sprays (data not presented). Malic acid content was often higher in apples with the preharvest 1-MCP spray closer to harvest (Spray 2) compared with those with no spray or Spray 1 (Tables 2 and 3). This effect was the greatest at 3 °C in 2008, with differences greater than 100 mg of malic acid per 100 mL of juice. It is common for 1-MCP to have little or no effect on SSC in apples (DeEll et al., 2002; Watkins et al., 2005), whereas 1-MCP often improves acidity retention in apples during storage (Bai et al., 2005; Fan et al., 1999a).

The most important benefit of preharvest 1-MCP treatments on 'Honeycrisp' apples was the reduction in soft scald development. Large fruit losses have occurred commercially as a result of high incidences of soft scald and soggy breakdown in 'Honeycrsip' (DeEll, personal observation; Watkins et al., 2004). Therefore, the use of preharvest 1-MCP sprays on 'Honeycrisp' could be very advantageous.

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