# 1-Methylcyclopropene Influences 'Empire' and 'Delicious' Apple Quality during Long-term Commercial Storage

Jennifer R. DeEll[1,4], Jennifer T. Ayres[2], and Dennis P. Murr[3]

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**Summary. This study evaluated the effects of 1-methylcyclopropene (1-MCP) on 'Empire' and 'Delicious' apples (*Malus* ×*domestica*) in commercial controlled atmosphere (CA) storage for 12 months and in commercial cold storage for 6 months. Apples were harvested and delivered by growers to a local commercial storage facility. Four different grower lots were chosen for each of three 'Empire' and two 'Delicious' storage rooms. Fruit were treated with 1-MCP (≈0.8–1.0 ppm) for 24 hours, while control fruit samples were held in a similar nearby storage room. After treatment, control samples were placed with matching 1-MCP-treated samples into either CA (2.5% $O_2$ + 2.5% $CO_2$ at 2.2 °C or 0 °C for 'Empire' and 'Delicious', respectively) or air storage at 0 to 1 °C. Initial maturity was relatively uniform among the grower lots, with internal ethylene concentration (IEC) averaging less than 1 ppm for 'Empire' and 2 to 3 ppm for 'Delicious'. IEC was lower in apples treated with 1-MCP after air (3 or 6 months) or CA (6, 9, or 12 months) storage, but this effect was reduced after a 14-day ripening period at 22 °C, and was less dramatic in fruit from CA than from air storage. Apples treated with 1-MCP were also firmer than non-treated fruit upon removal from air or CA storage, and this difference became greater with increased poststorage time at 22 °C. 1-MCP-treated apples stored in air had higher soluble solids concentration (SSC), while there was no significant effect of 1-MCP on SSC in fruit held in CA. Core browning developed in 'Empire' held in air for 6 months or in CA for 9 or 12 months, and in 'Delicious' after 9 or 12 months in CA. 1-MCP decreased the incidence of core browning in 'Empire', but increased the incidence in 'Delicious'. There was no significant effect of 1-MCP on the incidence of internal browning and storage rots, which developed in both cultivars.**

The postharvest gaseous application of 1-methylcyclopropene (1-MCP) has been shown to improve many physiological characteristics of apples, such as reduced ethylene production and respiration, enhanced fruit firmness and acidity retention, and reduced superficial scald development, peel greasiness, and various chilling-related disorders (Bai et al., 2005; DeEll et al., 2002; Fan and Mattheis, 2001; Fan et al., 1999b; Rupasinghe et al., 2000; Watkins and Nock, 2005). The efficacy of 1-MCP on apples is influenced by cultivar and storage conditions (Watkins et al., 2000), as well as treatment temperature and duration (DeEll et al., 2002). Since 1-MCP inhibits the action of ethylene and consequently retards fruit ripening, apples can be stored longer and transported farther, thus creating new markets. As a result of these beneficial effects, worldwide commercial utilization of 1-MCP (SmartFresh; AgroFresh, Springhouse, Pa.) is increasing quickly.

However, 1-MCP can also increase the susceptibility of apples to certain physiological disorders, such as external $CO_2$ injury (DeEll et al., 2003; Zanella, 2003). Such negative responses to 1-MCP are often exacerbated by the presence of other anti-ethylene technologies or are negated by the use of antioxidants. For example, the preharvest application of aminoethoxyvinylglycine (ReTain; Valent BioSciences Corp., Libertyville, Ill.) further promotes external $CO_2$ injury in apples treated with 1-MCP (DeEll et al., 2003), whereas a postharvest drench with the antioxidant diphenylamine reduces susceptibility to external $CO_2$ injury (Watkins et al., 1997). The use of low $O_2$ (0.7% to 1.5%) storage regimes, high levels of $CO_2$ (>2%), low temperatures (<3 °C), or ethylene scrubbing can also aggravate the development of disorders by subjecting the apples to additional stress (DeEll et al., 2005b; Johnson and Colgan, 2003).

Most studies investigating the effects of 1-MCP on apples have been conducted as small-scale research trials within ideal conditions. Little work has been done to determine whether similar changes in apple quality and disorder incidence occur in a large-scale commercial setting. Furthermore, in most research studies fruit have not been held for more than 8 or 9 months. DeEll et al. (2006) evaluated the effects of commercial 1-MCP treatment on 'Empire' apples held in controlled atmosphere (CA) for up to 9 months, but they suggested that this was not long enough to observe the full benefits of 1-MCP.

The objective of this work was to investigate the effects of 1-MCP on 'Empire' and 'Delicious' apples in commercial CA storage for 12 months, as well as in commercial cold storage for 6 months.

## Materials and methods

Apple harvest and treatment. 'Empire' and 'Delicious' apples were harvested in Norfolk County, Ont., in 2004 and delivered by growers to a local commercial storage facility.

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[1]Ontario Ministry of Agriculture, Food, and Rural Affairs, 1283 Blueline Road at Highway #3, Box 587, Simcoe, Ontario, Canada N3Y 4N5.

[2]Research Assistant, c/o Ontario Ministry of Agriculture, Food, and Rural Affairs, 1283 Blueline Road at Highway #3, Box 587, Simcoe, Ontario, Canada N3Y 4N5.

[3]Department of Plant Agriculture, University of Guelph, Guelph, Ontario, Canada N1G 2W1.

[4]Corresponding author. E-mail: Jennifer.DeEll@omafra.gov.on.ca

**Units**

| To convert U.S. to SI, multiply by | U.S. unit | SI unit | To convert SI to U.S., multiply by |
|---|---|---|---|
| 29.5735 | fl oz | mL | 0.0338 |
| 0.3048 | ft | m | 3.2808 |
| 0.0283 | $ft^3$ | $m^3$ | 35.3147 |
| 25.4 | inch(es) | mm | 0.0394 |
| 0.4536 | lb | kg | 2.2046 |
| 4.4482 | lbf | N | 0.2248 |
| 1 | ppm | $\mu L \cdot L^{-1}$ | 1 |
| (°F – 32) ÷ 1.8 | °F | °C | (1.8 × °C) + 32 |

All apples were drenched with diphenylamine [1000 ppm a.i. for 'Empire' and 1500 ppm a.i. for 'Delicious' (ShieldBrite; Pace International, Seattle, Wash.)] and thiabendazole [500 ppm a.i. (Mertect; Syngenta, Wilmington, Del.)] upon arrival. Four lots from different growers were chosen for each of three commercial 'Empire' rooms and two 'Delicious' rooms. Ten boxes (≈20 kg each) of fruit per lot for each room and cultivar were used, which was equivalent to one box sample per lot for each storage regime and duration.

Individual storage rooms (800–1180 $m^3$) were treated with 1-MCP (≈0.8–1.0 ppm; SmartFresh) for 24 h within 1 and 3 d of loading for 'Empire' and 'Delicious', respectively (Table 1). Control (non-treated) apple samples were held for the 24-h period in a nearby storage room at approximately the same temperature (2.2 °C for 'Empire' and 0 °C for 'Delicious'). After each treatment, storage rooms were vented for 30 min. Control samples were then returned to the treated room and placed with the matching 1-MCP samples, and CA conditions (2.5% $O_2$ + 2.5% $CO_2$ at 2.2 °C or 0 °C for 'Empire' and 'Delicious', respectively) were established. Similar 1-MCP-treated and control 'Empire' and 'Delicious' samples were also placed in a cold room at 0 to 1 °C for air storage.

Gas levels within the static CA regimes were monitored daily using a DBI Oxystat 200 (DBI 750 $O_2$ analyzer and DBI $CO_2$ analyzer with Servomex sensors; Storage Control Systems, Sparta, Mich.) for 'Empire' rooms 1 and 2, and 'Delicious' room 1; and using an Oxystat GCS 660 (DBI 770 dual gas analyzer with Servomex sensors; Storage Control Systems) for 'Empire' room 3 and 'Delicious' room 2. Adjustments using air, nitrogen, or $CO_2$ were made accordingly so that atmospheres never fluctuated more than ±0.1%.

**Maturity and quality evaluations.** Initial maturity was evaluated on 10-apple samples from each lot in each room. In addition, similar 25-apple samples (with and without 1-MCP) were removed from each room immediately after room venting, stored at room temperature (22 °C) for 14 d, and then evaluated as a confirmation test for the 1-MCP treatment. After 3 and 6 months of air storage at 0 to 1 °C and 6, 9, and 12 months of CA storage at 2.2 °C or 0 °C for 'Empire' and 'Delicious', respectively (Table 1), 30 fruit per lot in each room were evaluated for quality after 1, 7, and 14 d at ≈22 °C.

Starch content was determined at harvest using 10-fruit samples. Apples were cut in half at the equator and evaluated on a scale of 1 to 9 points using starch charts (Chu and Wilson, 2000a, b). Internal ethylene concentration (IEC) was determined at harvest, after 14 d at 22 °C, and after each storage treatment combination. A 3-mL gas sample was withdrawn from the core of 10 fruit using a syringe, and ethylene was determined using a Varian CP-3800 gas chromatograph (Varian Canada, Mississauga, Ont.) equipped with a 1.8-m Porapak Q column and a flame ionization detector. Fruit firmness was determined on opposite sides (blush and green) of the same fruit after peel removal using an electronic pressure tester fitted with an 11-mm tip (Lake City Technical Products, Kelowna, B.C.). Soluble solids concentration (SSC) in the juice expressed during firmness testing was determined using a hand-held temperature-compensated refractometer (Fisher Scientific, Nepean, Ont.). After storage, the incidence of core browning, internal browning, and storage rot were determined as a percentage of fruit with the problem, regardless of severity.

**Statistical analyses.** Data for each cultivar and type of storage were analyzed separately using the analysis of variance procedure of Genstat 5 (Payne, 2000). Grower lots were considered as replications within each storage room. Within each cultivar

**Table 1. Harvest dates and maturity indices of 'Empire' and 'Delicious' apples upon arrival at the commercial storage facility.**

| | Harvest (receiving) date | IEC (ppm)[z] | Starch index (1–9)[y] | Firmness (lbf)[x] | SSC (%) |
|---|---|---|---|---|---|
| Empire, Room 1 | | | | | |
| Lot 1 | 28 Sept. | 0.09 | 4.1 | 16.8 | 10.2 |
| 2 | 28 Sept. | 0.08 | 3.4 | 17.8 | 10.1 |
| 3 | 28 Sept. | 0.10 | 3.3 | 17.3 | 10.8 |
| 4 | 28 Sept. | 0.13 | 4.7 | 16.5 | 10.7 |
| Mean | | 0.10 | 3.9 | 17.1 | 10.5 |
| Empire, Room 2 | | | | | |
| Lot 1 | 29 Sept. | 0.06 | 3.1 | 17.7 | 11.1 |
| 2 | 29 Sept. | 1.60 | 4.1 | 17.1 | 10.2 |
| 3 | 29 Sept. | 0.13 | 4.0 | 16.6 | 11.1 |
| 4 | 29 Sept. | 0.89 | 5.0 | 16.6 | 11.0 |
| Mean | | 0.67 | 4.1 | 17.0 | 10.9 |
| Empire, Room 3 | | | | | |
| Lot 1 | 29 Sept. | 0.10 | 3.5 | 16.4 | 10.5 |
| 2 | 29 Sept. | 0.08 | 5.0 | 16.1 | 10.8 |
| 3 | 30 Sept. | 0.14 | 3.2 | 17.8 | 9.7 |
| 4 | 30 Sept. | 1.50 | 5.1 | 17.0 | 9.9 |
| Mean | | 0.46 | 4.2 | 16.8 | 10.2 |
| Delicious, Room 1 | | | | | |
| Lot 1 | 16 Oct. | 0.57 | 4.5 | 16.3 | 10.5 |
| 2 | 17 Oct. | 0.52 | 3.5 | 17.1 | 11.7 |
| 3 | 18 Oct. | 2.10 | 3.3 | 16.6 | 9.9 |
| 4 | 18 Oct. | 9.40 | 3.8 | 17.2 | 10.9 |
| Mean | | 3.10 | 3.8 | 16.8 | 10.8 |
| Delicious, Room 2 | | | | | |
| Lot 1 | 20 Oct. | 6.70 | 3.3 | 16.9 | 12.1 |
| 2 | 21 Oct. | 0.07 | 3.9 | 17.3 | 10.0 |
| 3 | 21 Oct. | 1.10 | 3.9 | 17.5 | 10.9 |
| 4 | 22 Oct. | 0.03 | 4.3 | 17.0 | 11.0 |
| Mean | | 2.00 | 3.9 | 17.2 | 11.0 |

[z]1 ppm = 1 $\mu L \cdot L^{-1}$.
[y]Starch staining using charts by Chu and Wilson (2000a, 2000b).
[x]1 lbf = 4.4482 N.
IEC, internal ethylene concentration; SSC, soluble solids concentration.

and storage type, the effects of 1-MCP, storage duration, and days at 22 °C were determined. Sources of variation were considered significant at $P < 0.05$.

## Results and discussion

Maturity of 'Empire' apples at harvest was relatively uniform among the different grower lots (Table 1). IEC of 'Empire' averaged less than 1 ppm in all three rooms, indicating optimum fruit maturity for 1-MCP efficacy (DeEll et al., 2006). Similarly, maturity of 'Delicious' apples was fairly uniform among the different grower lots (Table 1). However, IEC was more than 1 ppm in half the 'Delicious' lots, indicating some fruit were climacteric.

After 1-MCP treatment and 14 d at 22 °C, treated 'Empire' and 'Delicious' had substantially lower IEC and greater fruit firmness (Table 2). This confirms that the 1-MCP application was effective. There was no significant effect of 1-MCP on SSC at this time.

**Table 2. IEC, firmness, and SSC of 'Empire' and 'Delicious' apples after 1-MCP treatment plus 14 d at 22 °C (71.6 °F) (confirmation test).**

| | IEC (ppm)[z] | Firmness (lbf)[y] | SSC (%)[x] |
|---|---|---|---|
| Empire, Room 1 | | | |
| Control | 291 | 14.9 | 11.4 |
| +1-MCP | 1.6 | 16.6 | 11.7 |
| Empire, Room 2 | | | |
| Control | 272 | 14.6 | 11.6 |
| +1-MCP | 1.3 | 16.4 | 11.6 |
| Empire, Room 3 | | | |
| Control | 241 | 15.2 | 11.4 |
| +1-MCP | 0.3 | 16.3 | 11.6 |
| SE | 10.1 | 0.14 | 0.13 |
| Significance | *** | *** | NS |
| Delicious, Room 1 | | | |
| Control | 185 | 15.1 | 12.5 |
| +1-MCP | 1.3 | 16.8 | 12.5 |
| Delicious, Room 2 | | | |
| Control | 83 | 16.0 | 13.4 |
| +1-MCP | 0.1 | 17.2 | 13.4 |
| SE | 19.4 | 0.26 | 0.36 |
| Significance | *** | ** | NS |

[z]IEC = internal ethylene concentration; 1 ppm = 1 $\mu L \cdot L^{-1}$.
[y]1 lbf = 4.4482 N.
[x]SSC = soluble solids concentration.
[NS,**,***]Nonsignificant or significant at $P < 0.01$ or 0.001 respectively.

'Empire' and 'Delicious' apples treated with 1-MCP and held in air storage for 3 months and 6 months at 0 to 1 °C were firmer than non-treated fruit, and this difference became greater with increased time at 22 °C (Tables 3 and 4). Similar effects on firmness were also observed in apples held in commercial CA for 6, 9, or 12 months. Improved firmness retention is a well-documented response of apples to 1-MCP (Bai et al., 2005; DeEll et al., 2002; DeLong et al., 2004; Fan and Mattheis, 2001; Fan et al., 1999a; Rupasinghe et al., 2000; Watkins and Nock, 2005; Watkins et al., 2000), although apples in these other studies were not held in CA for 12 months nor for 14 d at room temperature after removal from storage.

In this study, 'Empire' and 'Delicious' fruit treated with 1-MCP and held in air storage for 6 months had similar firmness values as those not treated and held in long-term CA storage (Table 3 and 4). However, 1-MCP-treated apples from air storage maintained firmness during the subsequent 14 d at 22 °C, whereas those not treated and held in CA exhibited firmness loss upon removal from storage.

1-MCP-treated 'Empire' and 'Delicious' held in air storage for 3 and 6 months at 0 to 1 °C had higher SSC (+0.3% to 0.4%) than those not treated (Tables 3 and 4). On the other hand, there was no significant effect of 1-MCP on SSC when fruit were held in commercial CA storage for 6, 9, or 12 months and subsequently 1, 7, and 14 d at 22 °C. Inconsistent effects of 1-MCP on SSC are reported throughout the literature, varying with apple cultivar and storage conditions. For example, no effect of 1-MCP on SSC was found in 'Empire' and 'Delicious' apples held in air for 4 months at 0 to 1 °C (DeEll et al., 2002; Rupasinghe et al., 2000), whereas higher SSC was observed in 1-MCP-treated 'Empire' and 'Delicious' stored in air at 0.5 °C for up to 7 months (Watkins et al., 2000). Lack of an effect on SSC was also found for 'Empire' apples held in small-scale research CA chambers (2.5% $O_2$ + 0% or 2% $CO_2$) for 4 months and 8 months at 2 °C (DeEll et al., 2005b) or in CA jars (2% $O_2$ + 2% $CO_2$) for up to 8 months at 2 °C (Watkins et al., 2000). Varying effects of 1-MCP on SSC have also been reported for several other apple cultivars (Bai et al., 2005; DeEll et al., 2002; DeLong et al., 2004; Fan and Mattheis, 2001; Fan et al., 1999a; Rupasinghe et al., 2000; Saftner et al., 2003; Watkins and Nock, 2005; Watkins et al., 2000).

IEC was lower in 'Empire' and 'Delicious' apples treated with 1-MCP (Tables 3 and 4). However, this difference was less evident after 14 d at 22 °C than at 1 d and 7 d, and less dramatic in CA than air storage. 1-MCP blocks the ethylene receptors and consequently prevents the effects of ethylene, such as those associated with fruit ripening. Therefore, reduced ethylene synthesis and accumulation in fruit tissues would be an expected response to proper 1-MCP treatment and this has been confirmed for numerous apple cultivars under various conditions (DeEll et al., 2005a, b, 2006; DeLong et al., 2004; Fan and Mattheis, 2001; Fan et al., 1999a; Rupasinghe et al., 2000; Watkins and Nock, 2005; Watkins et al., 2000). In this study, increased IEC with time at 22 °C suggests that this effect may be temporary or other receptor sites may be synthesized or developed.

Overall, no storage disorders developed in 'Empire' and 'Delicious' apples after 3 months of air storage, while there was less than a 1.5% incidence in 'Delicious' after 6 months in air and in 'Empire' and 'Delicious' after 6 months in CA (Tables 3 and 4). Core browning developed (18% to 52%) in control 'Empire' held in air

Table 3. Quality of 'Empire' apples with and without 1-methylcyclopropene (1-MCP) after 3 and 6 months in air at 0 to 1 °C (32.0–33.8 °F) and 6, 9, and 12 months in commercial CA (2.5% $O_2$ + 2.5% $CO_2$) storage at 2.2 °C (35.96 °F), plus 1, 7, and 14 d at 22 °C (71.6 °F).

| | Firmness (lbf)[z] | SSC (%)[y] | IEC (ppm)[x] | Core browning (%)[w] | Internal browning (%)[w] | Storage rots (%)[w] |
|---|---|---|---|---|---|---|
| Air | | | | | | |
| 3 mo., control | | | | | | |
| 1 d at 22 °C | 13.4 | 11.4 | 177 | 0 | 0 | 0 |
| 7 d | 13.0 | 11.3 | 282 | 0 | 0 | — |
| 14 d | 12.4 | 11.4 | 303 | 0 | 0 | — |
| 3 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.3 | 11.8 | 1.4 | 0 | 0 | 0 |
| 7 d | 16.1 | 11.7 | 1.2 | 0 | 0 | — |
| 14 d | 16.1 | 11.9 | 5.6 | 0 | 0 | — |
| 6 mo., control | | | | | | |
| 1 d at 22 °C | 13.1 | 11.1 | 140 | 0 | 0 | 3.8 |
| 7 d | 12.4 | 11.0 | 296 | 18.3 | 0 | — |
| 14 d | 12.2 | 10.6 | 308 | 51.6 | 0.6 | — |
| 6 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 15.9 | 11.4 | 1.4 | 0 | 0 | 2.2 |
| 7 d | 15.9 | 11.4 | 1.4 | 0.3 | 0 | — |
| 14 d | 15.8 | 11.2 | 55.9 | 0.6 | 0 | — |
| SE | 0.09 | 0.09 | 13.7 | 2.29 | 0.23 | 1.23 |
| Significance | MCP × day*** | MCP*** | MCP × day*** | MCP × day*** | MCP[NS] | MCP[NS] |
| CA | | | | | | |
| 6 mo., control | | | | | | |
| 1 d at 22 °C | 16.4 | 11.5 | 0.2 | 0 | 0 | 2.6 |
| 7 d | 16.2 | 11.3 | 11.9 | 0 | 0 | — |
| 14 d | 15.7 | 11.5 | 213 | 0.6 | 0 | — |
| 6 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.5 | 11.4 | 0.4 | 0 | 0 | 2.4 |
| 7 d | 16.3 | 11.3 | 0.5 | 0 | 0 | — |
| 14 d | 16.1 | 11.6 | 80.0 | 0 | 0 | — |
| 9 mo., control | | | | | | |
| 1 d at 22 °C | 15.9 | 11.5 | 3.2 | 3.9 | 2.8 | 9.1 |
| 7 d | 15.6 | 11.3 | 188 | 8.9 | 4.7 | — |
| 14 d | 14.1 | 10.9 | 281 | 10.9 | 7.7 | — |
| 9 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.3 | 11.4 | 0.6 | 3.3 | 1.4 | 7.9 |
| 7 d | 15.7 | 11.4 | 65.6 | 3.3 | 3.1 | — |
| 14 d | 15.2 | 10.9 | 268 | 7.1 | 6.0 | — |
| 12 mo., control | | | | | | |
| 1 d at 22 °C | 16.5 | 10.8 | 13.0 | 21.9 | 13.1 | 12.9 |
| 7 d | 14.9 | 10.6 | 298 | 34.4 | 31.7 | — |
| 14 d | 12.1 | 10.8 | 342 | 31.3 | 26.2 | — |
| 12 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 17.0 | 11.0 | 5.5 | 18.6 | 19.4 | 12.3 |
| 7 d | 16.0 | 10.7 | 267 | 30.3 | 25.6 | — |
| 14 d | 13.1 | 10.9 | 316 | 29.4 | 22.4 | — |
| SE | 0.16 | 0.10 | 16.3 | 2.34 | 2.38 | 2.05 |
| Significance | MCP × month** MCP × day*** | MCP[NS] | MCP × month × day*** | MCP* | MCP[NS] | MCP[NS] |

[z]1 lbf = 4.4482 N.
[y]SSC = soluble solids concentration.
[x]IEC = internal ethylene concentration; 1 ppm = 1 μL·L[−1].
[w]Percent incidence, regardless of severity.
[NS,*,**,***]Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001 respectively.

storage for 6 months plus 7 d or 14 d at 22 °C, but 1-MCP decreased the incidence to less than 1% (Table 3). Similarly, control 'Empire' held in CA for 9 and 12 months exhibited a high incidence of core browning, which was reduced by 1-MCP (Table 3). 'Delicious' fruit also developed core browning after 9 and 12 months in CA storage, but 1-MCP increased the incidence (1% to 17% vs. 4% to 27%, respectively), especially after 12 months (Table 4). This is in contrast to the 'Empire' in this study, as well as previous reports in which

**Table 4. Quality of 'Delicious' apples with and without 1-methylcyclopropene (1-MCP) after 3 and 6 months in air at 0 to 1 °C (32.0–33.8 °F) and 6, 9, and 12 months in commercial CA (2.5% $O_2$ + 2.5% $CO_2$) storage at 0 °C (32.0 °F), plus 1, 7, and 14 d at 22 °C (71.6 °F).**

| | Firmness (lbf)[z] | SSC (%)[y] | IEC (ppm)[x] | Core browning (%)[w] | Internal browning (%)[w] | Storage rots (%)[w] |
|---|---|---|---|---|---|---|
| Air | | | | | | |
| 3 mo., control | | | | | | |
| 1 d at 22 °C | 15.3 | 12.9 | 188 | 0 | 0 | 0 |
| 7 d | 15.2 | 12.8 | 141 | 0 | 0 | — |
| 14 d | 14.9 | 12.7 | 153 | 0 | 0 | — |
| 3 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.4 | 12.9 | 2.6 | 0 | 0 | 0 |
| 7 d | 16.8 | 13.0 | 2.5 | 0 | 0 | — |
| 14 d | 16.6 | 13.0 | 31.0 | 0 | 0 | — |
| 6 mo., control | | | | | | |
| 1 d at 22 °C | 14.6 | 12.6 | 165 | 0 | 1.3 | 2.8 |
| 7 d | 14.6 | 12.4 | 226 | 0 | 0.4 | — |
| 14 d | 14.2 | 12.4 | 189 | 0.4 | 0 | — |
| 6 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.8 | 12.9 | 4.7 | 0 | 0.4 | 1.4 |
| 7 d | 16.7 | 13.1 | 21.1 | 0 | 0 | — |
| 14 d | 16.8 | 12.7 | 122 | 0.4 | 0 | — |
| SE | 0.12 | 0.20 | 19.2 | 0.24 | 0.56 | 0.95 |
| Significance | MCP × day** | MCP* | MCP × day* | MCP[NS] | MCP[NS] | MCP[NS] |
| CA | | | | | | |
| 6 mo., control | | | | | | |
| 1 d at 22 °C | 16.5 | 12.9 | 34.9 | 0 | 0 | 2.0 |
| 7 d | 17.0 | 12.8 | 13.7 | 0.4 | 0 | — |
| 14 d | 16.8 | 12.8 | 58.1 | 0 | 0 | — |
| 6 mo., + 1-MCP | | | | | | |
| 1 d at 22 °C | 17.1 | 13.0 | 0.7 | 0 | 0 | 1.6 |
| 7 d | 17.1 | 12.9 | 0.4 | 0 | 0 | — |
| 14 d | 17.2 | 13.1 | 2.4 | 0 | 0 | — |
| 9 mo., control | | | | | | |
| 1 d at 22 °C | 17.1 | 13.1 | 9.6 | 1.3 | 0 | 2.6 |
| 7 d | 17.2 | 13.2 | 41.3 | 3.3 | 0 | — |
| 14 d | 16.4 | 12.8 | 112 | 3.3 | 0.9 | — |
| 9 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 17.0 | 13.1 | 1.0 | 3.8 | 0 | 3.6 |
| 7 d | 17.2 | 13.2 | 4.0 | 6.7 | 0.8 | — |
| 14 d | 17.0 | 12.9 | 50.2 | 7.1 | 2.1 | — |
| 12 mo., control | | | | | | |
| 1 d at 22 °C | 16.3 | 12.5 | 9.6 | 7.1 | 1.3 | 10.8 |
| 7 d | 16.4 | 13.3 | 41.3 | 16.7 | 6.7 | — |
| 14 d | 15.2 | 13.2 | 112 | 11.9 | 3.6 | — |
| 12 mo., +1-MCP | | | | | | |
| 1 d at 22 °C | 16.6 | 12.1 | 1.0 | 12.1 | 0.8 | 10.1 |
| 7 d | 17.0 | 13.2 | 21.6 | 21.2 | 4.6 | — |
| 14 d | 16.3 | 13.2 | 73.9 | 27.4 | 2.7 | — |
| SE | 0.14 | 0.21 | 13.3 | 2.0 | 1.21 | 1.55 |
| Significance | MCP × day** | MCP[NS] | MCP × day*** | MCP × month* | MCP[NS] | MCP[NS] |

[z]1 lbf = 4.4482 N.
[y]SSC = soluble solids concentration.
[x]IEC = internal ethylene concentration; 1 ppm = 1 $\mu L \cdot L^{-1}$.
[w]Percent incidence, regardless of severity.
[NS],*,**,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001 respectively.

1-MCP consistently reduced the incidence of core browning in other apple cultivars (DeLong et al., 2004; Fan et al., 1999b; Watkins et al., 2000). Therefore, storage operators should exercise some caution when storing 1-MCP-treated 'Delicious' in long-term CA.

Internal browning also developed in 'Empire' and 'Delicious' fruit; however, 1-MCP had no significant effect on the incidence (Tables 3 and 4). Other studies have also shown 1-MCP to have no effect on the incidence of internal or flesh browning in 'Empire' apples (DeEll et al., 2006; Watkins and Nock, 2005). External $CO_2$ injury is often found in 'Empire' apples treated with 1-MCP (DeEll et al., 2003, 2006), but all fruit in this study were drenched with the antioxidant diphenylamine, which has been shown to control $CO_2$ injury in apples (Watkins et al., 1997), and thus no such injury was observed.

Storage rots increased slightly with increased storage time, and 1-MCP had no significant effect on the incidence. Errampalli et al. (2004, 2005) found 1-MCP to have variable effects on postharvest blue mold (*Penicillium expansum*) and gray mold (*Botrytis cinerea*) in apples, including 'Empire' and 'Delicious'. Similar variability in 1-MCP effects on storage decay has been shown for 'Golden Delicious'. Saftner et al. (2003) found 1-MCP to decrease decay severity, but Leverentz et al. (2003) found 1-MCP to increase the incidence and development of decay while inhibiting ripening in 'Golden Delicious'.

## Conclusion

This work demonstrates that commercial 1-MCP treatment of 'Empire' and 'Delicious' apples effectively delays fruit ripening responses (i.e., ethylene production and firmness loss) during subsequent long-term commercial CA (up to 12 months) and air (up to 6 months) storage, plus during a ripening period of 14 d at 22 °C. These results confirm similar findings from small-scale research studies within laboratory settings in which apples were not held in storage for more than 8 or 9 months, or longer than 7 d after storage at ≈20 °C. In this study, 1-MCP-treated apples had a higher SSC in air storage, while there was no effect of 1-MCP on SSC in CA. 1-MCP reduced the incidence of core browning in 'Empire', but increased its incidence in 'Delicious' fruit. These results indicate that 1-MCP can have differential effects on apple quality and disorders, depending on cultivar and storage conditions. 1-MCP had no significant effect on the incidence of internal browning and storage rots, which also developed in both cultivars.

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