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1-MCP reduces physiological storage disorders of 'Hass' avocados

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Abstract

Physiological disorders occur when 'Hass' avocados are stored for more than approximately 4–6 weeks. The major disorder is diffuse flesh discolouration ("flesh greying", or "internal chilling injury"), but others include vascular browning, vascular leaching (browning of flesh around the vascular bundles), stringy vascular tissue (thickening and separation of the vascular strands), and outer flesh blackening (blackening of the outmost layer of the mesocarp). We have examined 1-MCP effects on 'Hass' avocados stored for 4 or 7 weeks at 5.5 °C following treatment with 50–1000 nl l^{-1} 1-MCP for 6–24 h, at 6 or 15 °C. The effect of harvest date (fruit maturity) on responsiveness to 100 and 500 nl l^{-1}1-MCP was examined. 1-MCP treated fruit were firmer following storage, had reduced skin colouration (purpling) at removal from storage (4 or 7 weeks), increased time to softening, and reduced physiological disorders associated with long-term storage. Relatively little difference was observed between fruit treated at 15 and 6 °C, and thus a treatment temperature of 6 °C was used in the remaining experiments. For lower 1-MCP concentrations, short treatment durations influenced time to ripen, but not fruit quality. Treatment times of 12 and 24 h produced similar results. Harvest date (fruit maturity) influenced the levels of disorders in non-1-MCP treated fruit, but had little overall effect on 1-MCP efficacy. 1-MCP treatment was of little benefit for fruit stored for 4 weeks but, particularly if the 1-MCP concentration was high (250 nl l^{-1}), excessively delayed the time to ripen. After 7 weeks storage 100 nl l^{-1} 1-MCP almost completely eliminated some long-term storage disorders. A small trial showed that 500 nl l^{-1} 1-MCP did not reduce external chilling injury (skin blackening) of 'Hass' avocados induced by 0 °C storage. Overall, 1-MCP shows promise as a tool for reducing internal physiological disorders due to long-term storage of 'Hass' avocados.

Keywords: *Persea americana* (Mill.); 1-Methylcyclopropene; Quality; Maturity; Softening; Chilling injury; Fruit firmness

1. Introduction

The main limitation to storing 'Hass' avocados for longer than about 4 weeks is the occurrence of internal diffuse flesh discoloration ("flesh greying", or "internal chilling injury"; Fig. 1A), which can also occur

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for shorter storage times under poor temperature management. It is recommended that fruit are stored under low ethylene conditions (Chaplin et al., 1983), and recently it has been shown that ethylene is involved in development of this disorder (Pesis et al., 2002). Other disorders that occur during long-term storage are stringy vascular tissue (thickening of the vascular bundles such that when a quarter is broken in half, the flesh comes away from some or all of the vascular bundles without the fibres being broken; Fig. 1B), vascular leaching (browning diffusing out from vascular strands; Fig. 1C), and outer flesh blackening (blackening of the outer 2 mm of flesh tissue; Fig. 1D). 'Hass' avocados stored at temperatures of <2 °C show skin damage symptoms generally called *external* chilling injury (skin blackening) and this precludes storage at these low temperatures which could reduce the incidence of internal chilling injury (i.e. by slowing softening).

Research has shown that the inhibitor of ethylene perception, 1-methylcyclopropene (1-MCP; Blankenship and Dole, 2003) can effectively delay ripening of 'Hass' avocados which have not been coolstored (Feng et al., 2000; Hofman et al., 2000). Concentrations as low as 15 nl l^{-1} can delay softening, and 5 nl l^{-1} can delay colour change (Feng et al., 2000). The ethylene climacteric and activity of associated cell wall softening enzymes are also delayed by 1-MCP application in a concentration dependent manner (Feng et al., 2000). Jeong et al. (2001) examining 1-MCP effects on 'Simmonds' fruit (a

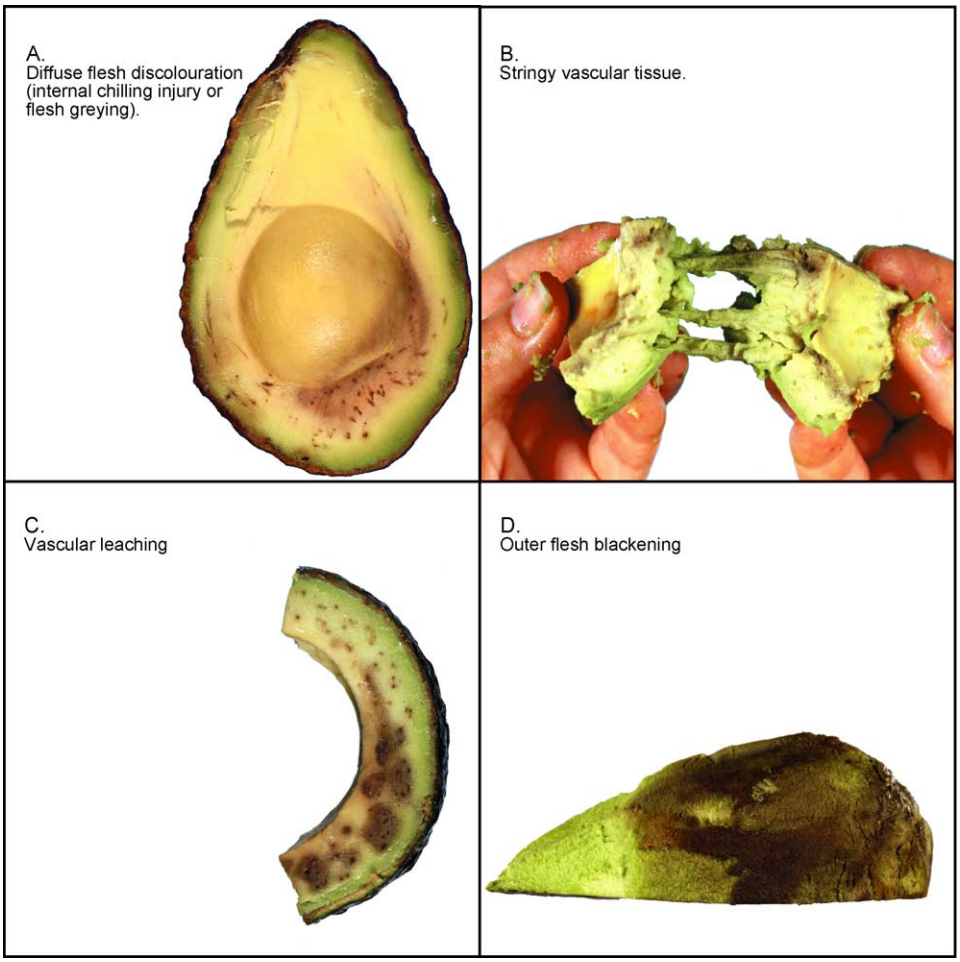

Fig. 1. Long-term storage disorders of 'Hass' avocados.

West Indian cultivar), confirmed some of these results (delays of ethylene climacteric, firmness, colour, and cell wall enzyme activity) and also that delays were correlated with levels of cell wall breakdown products (e.g. uronic acid).

In seeking to optimise storage quality of 'Hass' avocados, an obvious step is to examine the potential of using 1-MCP to reduce the incidence of internal "chilling injury" (or flesh greying). Initial trials found that internal chilling injury could be reduced in long-term stored fruit (6 weeks at 6 °C; Woolf and White, unpublished data). However, the 1-MCP concentrations employed were high, and fruit did not soften adequately after storage. Pesis et al. (2002) examined the effect of 1-MCP at 100 and 300 nl l^{-1} on flesh greying of 'Hass' avocado and found that both 1-MCP concentrations reduced greying. However, the levels of greying in control fruit were low (≅7% incidence), and treatment was carried out at only one time in the harvest season. These results suggest that there is potential for 1-MCP to reduce physiological disorders (such as flesh greying) in stored 'Hass' avocados.

In this work we aimed to examine a range of factors which might influence the potential of 1-MCP to reduce physiological storage disorders of 'Hass' avocados after moderate and long storage periods (4 and 7 weeks) at standard storage temperatures (≅6 °C). Four weeks could be viewed as a moderate storage duration at which disorders are beginning to become a problem. Such storage periods are not uncommon for exports from southern to northern hemispheres after packing, transport and distribution are taken into account. Seven weeks is a very long storage time for avocados and is a significant challenge in terms of quality maintenance. We examined the effect of 1-MCP treatment conditions (concentration, duration and temperature) and fruit factors (time of harvest in the season (maturity) and storage duration). We also carried out a preliminary examination of the potential for 1-MCP to reduce external chilling injury induced at 0 °C.

2. Materials and methods

2.1. Overall description of treatments

Although the various experiments examined different aspects of 1-MCP application, the following description gives an overview of the experimental system. 'Hass' avocados were treated with 1-MCP in barrels prior to storage at 5.5 °C for 4 (moderate storage period) or 7 weeks (very long storage period). After removal from coolstore, skin colour and firmness were measured. Fruit were ripened at 20 °C and when ripe, internal quality was assessed.

2.2. Fruit

'Hass' avocados (*Persea americana* Mill.) were harvested from commercial orchards in Katikati, New Zealand and commercially packed to export standards. Fruit were held in the packhouse at ambient temperatures (minimum of 13–19 °C) overnight prior to grading and packing to export standards. Fruit were generally of 24-count size (211–257 g). On the same day of packing, fruit were transported to the Mt Albert Research Centre, Auckland where fruit were randomised into the treatment barrels. After treatment fruit were stored and ripened in single-layer cardboard trays containing a moulded cardboard pocketpack.

2.3. Experiments

2.3.1. Experiment 1. Treatment temperature and initial examination of 1-MCP concentration

Fruit were harvested in November 2000 (early summer, dry matter of 26.8%). The following treatments were applied; 0, 50, 100, 250, 500 and 1000 nl l^{-1} 1-MCP at a temperature of 6 °C, and 0, 50, 100 and 250 nl l^{-1} 1-MCP at 15 °C. All treatments were carried out for 24 h. Fruit were then stored for 7 weeks at 5.5 °C air temperature. In addition, 1-MCP treated fruit (500 nl l^{-1}) and a control were stored at 0 °C to determine the effect of 1-MCP on external chilling injury (skin blackening).

2.3.2. Experiment 2. Treatment duration and 1-MCP concentration

Fruit were harvested in late January 2001 (midsummer, dry matter of 26.4%). The following treatments were applied; 0, 100 or 500 nl l^{-1} 1-MCP at 6 °C for 6, 12 or 24 h. Fruit were stored for 4 or 7 weeks at 5.5 °C air temperature.

2.3.3. Experiment 3. Harvest date and 1-MCP concentration

Avocados are harvested over a period of up to 8 months, and therefore 1-MCP efficacy at a number of harvest dates (viz. fruit maturities) is an important factor from a commercial perspective. Fruit were obtained from three orchards at three harvest dates in the 2001/2002 season; September 2001 (early season; average dry matter of 24.6%), November 2001 (mid-season; average dry matter of 29.3%), and February 2002 (late season; average dry matter of 36.9%). The following treatments were applied; 0, 100 and 250 nl l^{-1} 1-MCP at 6 °C for 24 h. Fruit were stored for 4 or 7 weeks at 5.5 °C air temperature.

2.3.3.1. 1-MCP treatment. Each treatment had three replicate barrels containing a 36–48 fruit, which resulted in 0.22–0.26 kg of fruit per litre. The barrels used were 50 l with screw top lids (with rubber seals) and a septum fitted for 1-MCP injection and atmosphere sampling. Fruit were held overnight in open barrels to achieve the target temperature (generally 5.5 °C). Once the barrel was sealed, the resulting fruit temperature was 6 ± 0.4 °C. The target 1-MCP concentration was obtained by removing various levels of headspace from two stock solutions (500 and 1000 μl l^{-1}). Stock gas was made up using EthylBloc® (a.i. 1-MCP 0.14%) in the first experiment only, but thereafter using SmartFresh™ (a.i. 1-MCP 3.3%) powder with 15 ml of warm distilled water injected into the bottle. About 1 h later, syringes were used to remove the calculated volume of stock gas (an equal volume of water was injected into the bottle as the gas sample was removed), and this was injected into the barrels through a rubber septa.

At the start of the experiments, gas tightness of the barrels was checked using ethylene. Verification of the 1-MCP concentration in stock bottles was carried out on one occasion. Control (non-1-MCP treated) fruit were either held for the same time as 1-MCP treated fruit in sealed barrels, or in some cases left in trays in air ("no barrel" control). Since no significant difference was found in the first experiment, Experiments 2 and 3 used only "in barrel" controls. All barrels contained bags of hydrated lime (≅650 g) to minimise CO_2 accumulation. Gas samples were taken after the treatment period for analysis of carbon dioxide and oxygen levels in the barrels. Gas chromatography, employing flame ionisation and thermal conductivity detectors (Philips PU4500; Pye Unicam, Cambridge, UK), was used to determine the concentration of these gases. For fruit treated at 6 °C, the highest CO_2 and lowest O_2 concentrations recorded were 0.11 and 16.4%, respectively. The only significant variation on this was in Experiment 1 where fruit treated at 15 °C had lower O_2 (≅10.4%) and higher CO_2 levels (0.11–0.16%). After treatment (generally for 24 h), all fruit were vented (≅5 h), placed into cardboard trays and coolstored.

2.3.3.2. Storage and ripening. Fruit were stored at 5.5 °C (RH ≅ 85 ± 5%), and the only exception to this was the preliminary trial in Experiment 1 where the effect of 1-MCP on external chilling injury was examined by placing fruit at 0 °C. Air and fruit temperatures were monitored throughout treatment using Squirrel Data Loggers (Model 1206; Grant Inc, Cambridge) equipped with thermistor temperature probes (CM-UU-V5-1; Grant Inc, Cambridge, UK). Control fruit were held in a different store for the first week (during which time the coolstore containing the 1-MCP treated fruit was vented daily), but thereafter all fruit were stored in the same coolstore. This was carried out because even very small temperature differences can lead to significant differences in fruit quality, and thus by having fruit in the same coolstore any potential temperature effects were eliminated.

2.4. Fruit measurements

2.4.1. Dry matter analysis

To obtain an indication of maturity, a sample of 12 fruit (three replicates of four fruit), were used to determine % dry matter. A quarter of each fruit was peeled and the seed coat removed. Two longitudinal slices of flesh were sampled from each quarter. The sample (approximately 20 g) was dried for 48 h at 65 °C (until constant weight) and then re-weighed.

2.4.2. Measurements immediately after storage

2.4.2.1. Fruit firmness. An Anderson digital Firmometer (White et al., 1999) was used to measure the effect of 1-MCP on fruit firmness of intact fruit (skin not removed). Fruit were re-warmed overnight to 20 °C and the following day fruit firmness was measured on 10 or 12 fruit per treatment. The Firmometer value derived (0–110) is the Firmometer reading (mm displacement

after 10 s) multiplied by 10 using a 300 g weight where a measurement of 90–100 indicates a fully ripe fruit. As fruit soften, Firmometer values increase. Fruit firmness was also measured 3 or 4 days after removal from storage to ascertain the effect of 1-MCP on ripening.

2.4.2.2. Skin colour assessments. Measurement of skin colour can provide an indication of ripening and its variability in 'Hass' avocados. Skin colour was measured on 12 fruit per treatment after overnight rewarming to 20 °C, using a Minolta Chromameter (light source D_{65}, three averaged measurements around the fruit equator) and expressed in L C h° units (lightness, chroma and hue). On the same fruit, skin colour was also rated by eye using a 6-point rating scale (1 = emerald green, 2 = forest green, 3 = approximately 30% of skin is coloured, 4 = approximately 70% of skin is coloured, 5 = 100% of skin is purple, 6 = 100% of skin is black; White et al., 2004).

2.4.2.3. Fruit quality; external damage. For fruit placed at 0 °C, the external appearance was rated 3 days after removal from storage for external damage (browning or blackening of the skin expressed on either lenticels, or as irregular dark patches on the skin which may be solid areas or smaller discrete areas). External damage was rated on a relative scale of 0–3 where 0 = no occurrence, 0.5 = <10%, 1.0 = 10–20%, 1.5 = 21–50%, 2.0 = 51–75%, 2.5 = 76–90%, 3.0 = >90% of the fruit surface affected.

2.4.3. Ripe fruit quality

Following storage, fruit were assessed for quality when designated as ripe (equivalent to an average Anderson Firmometer value of approximately 90–100 using a 300 g weight). Fruit were ripened at 20 ± 1.5 °C in an ethylene-free environment. Ripe fruit quality was assessed daily by gentle hand-squeezing by a trained assessor. When each fruit became ripe, the number of days taken to ripen once out of coolstore (days to ripe; DTR) was recorded and quality was assessed. The fruit were cut longitudinally into quarters, peeled, and the following factors evaluated: diffuse discolouration (grey/brown diffuse coloured flesh, usually starts at the blossom end of the fruit and spreads up and out; also known as chilling injury, mesocarp discolouration and flesh greying), vascular browning (browning of the vascular strands running longitudinally through the fruit tissue), vascular leaching (browning of the flesh around the vascular strands which run longitudinally through the fruit), stringy vascular tissue (thickening of the vascular strands), uneven ripening (uneven flesh softening such that flesh tissue adhered to the seed when fruit was cut in half or there were hard areas of flesh in otherwise soft tissue), outer flesh blackening (blackening of the flesh ~0.5–1 mm adjacent to the skin).

Each factor was rated on a scale from 0 to 3 increasing in half units where 0 = no occurrence; 1 = 10% of fruit affected; 2 = 25% of fruit affected; 3 = 50% or more of fruit affected. A factor rating ≥2 was regarded as unacceptable. The International Avocado Quality Manual (White et al., 2004) provides full details and photographs of this rating system for each disorder. Each fruit was recorded as 'sound' (acceptable to the consumer) or not by taking into account the overall quality of the whole fruit at the time of assessment.

2.5. Data presentation and analysis

Data are presented as the proportion of fruit with any level of the disorder (i.e. >0 rating). All data are presented as the mean percentage ± standard error of the mean (S.E.M.). Analysis of variance (Genstat 5) was carried out to compare statistical differences between means. Tukey's least significant difference (LSD) values were calculated, at the 5% level, from the standard errors of difference. Data analysis was carried out following angular transformation i.e. arcsin(sqrt(x)) for proportional data.

For fruit quality, both transformed and non-transformed data are presented in tables with transformed averages and LSDs presented in brackets. Data discussed in the text are non-transformed means.

3. Results

3.1. Experiment 1. Treatment temperature and initial examination of 1-MCP concentration

3.1.1. Fruit firmness

After 4 and 7 weeks storage at 5.5 °C, control (untreated) fruit which had been held at both 6 and 15 °C were softer than fruit which had been treated with 1-MCP (Fig. 2). After 7 weeks storage control fruit were almost ripe when removed from coolstorage (Firmome-

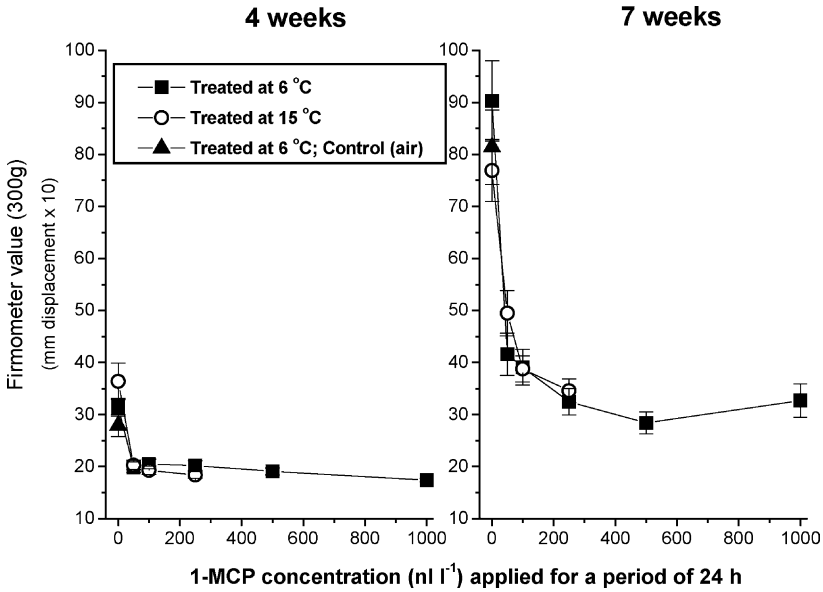

Fig. 2. Experiment 1. Fruit firmness of 'Hass' fruit after being treated with 0, 50, 100, 250, 500 or 1000 nl l^{-1} 1-MCP for 24 h at either 6 or 15 °C then stored for 4 (left) or 7 (right) weeks at 5.5 °C. Firmness was measured ≅16 h after removal from storage. Each point represents the average of three replicates of 10 fruit. Vertical bars = S.E.M.

ter value of 75–95). The "barrel" control fruit (held in a barrel with no 1-MCP) were of similar fruit firmness as controls held in air (data not shown). The temperature at which fruit were treated with 1-MCP (6 °C or 15 °C) had no significant effect on fruit firmness after storage.

After 4 weeks storage, fruit were slightly firmer with increasing 1-MCP concentration. After 7 weeks storage, fruit treated with ≥250 nl l^{-1} 1-MCP at 6 °C or ≥100 nl l^{-1} 1-MCP at 15 °C were firmer than fruit treated with lower concentrations.

3.1.2. Skin colour

After 4 weeks storage fruit treated with 1-MCP were greener (as rated by eye) than untreated fruit (Fig. 3). In addition there was less fruit to fruit variability in colour. 1-MCP treated fruit tended to be lighter, more vivid and greener than untreated fruit when measured by Minolta chromameter (data not shown). Chromameter colour values of fruit increased with 1-MCP concentration until 100 nl l^{-1}, but above this concentration there was little effect on colour measurements.

After 7 weeks storage, only fruit treated with ≥100 nl l^{-1} 1-MCP at 15 °C and ≥250 nl l^{-1} at 6 °C had greener skin colour than untreated fruit (Fig. 3). Fruit treated with ≥250 nl l^{-1} 1-MCP were different from untreated fruit in terms of Chromameter measurements (data not shown). As with the firmness measurements, there was little difference between fruit that had been treated at 6 °C and those treated at 15 °C in skin colour. Also, untreated fruit sealed in barrels were similar to untreated fruit held in trays.

3.1.3. Fruit quality

After 7 weeks of storage, the overall quality (as defined by % sound fruit) of 1-MCP treated fruit (17–31%) was better compared with untreated fruit (0–1%; Table 1). The incidence of diffuse discolouration was high in untreated fruit (68–88%) and was almost completely eliminated by 1-MCP application. The incidence of other long-term storage disorders outer flesh blackening (20–57%) and stringy vascular tissue (31–71%) were prevalent in untreated fruit but were reduced by 50 nl l^{-1} 1-MCP and eliminated at higher concentrations of 1-MCP (Table 1). 1-MCP treatment did not influence the incidence of vascular browning or vascular leaching. Uneven ripening occurred at >10% incidence at ≥250 nl l^{-1}1-MCP. Fruit treated with 1-MCP took almost twice as long to ripen (DTR) as untreated fruit, and time to ripen increased with increasing 1-MCP concentration (Table 1). Con-

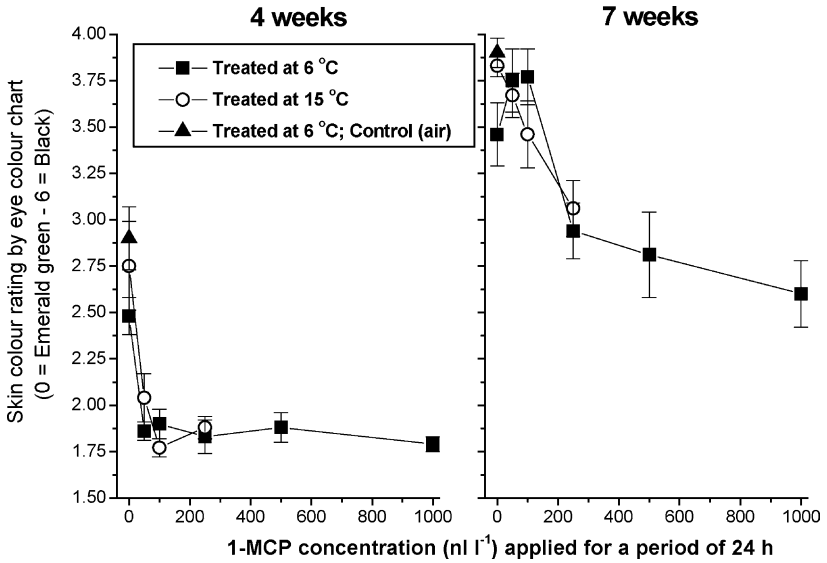

Fig. 3. Experiment 1. Skin colour (rated by eye) of 'Hass' fruit after being treated with 0, 50, 100, 250, 500 or 1000 nl l^{-1} 1-MCP for 24 h at either 6 or 15 °C then stored for 4 (left) or 7 (right) weeks at 5.5 °C. Colour was measured ≅16 h after removal from storage. Each point represents the average of three replicates of 12 fruit. Vertical bars = S.E.M.

sidering the incidence of uneven ripening at high 1-MCP concentrations, DTR for these treatments may have been even longer.

Overall, treatment temperature had no effect on disorders of 1-MCP treated fruit (Table 1).

3.1.4. External chilling injury

1-MCP failed to ameliorate external chilling injury (skin blackening) in fruit stored at 0 °C for 5 weeks. Fruit treated with 500 nl l^{-1} 1-MCP prior to storage at 0 °C had an average external damage rating of 1.2 ± 0.08 (0 = no damage, 3 = >90% skin damage), while untreated fruit had an average external damage rating of 1.1 ± 0.17.

3.2. Experiment 2. Treatment duration and 1-MCP concentration

3.2.1. Fruit firmness

Duration of 1-MCP treatment did not affect fruit firmness after 4 weeks storage (Table 2). 1-MCP concentration affected fruit firmness after 4 weeks storage plus 4 days at 20 °C. Fruit treated with 500 nl l^{-1} 1-MCP were firmer than fruit treated with 100 nl l^{-1} 1-MCP and all 1-MCP treated fruit were firmer than untreated control fruit (Table 2). After 7 weeks storage and 1 day at 20 °C there was no consistent effect of treatment duration on fruit firmness. Fruit treated with higher concentrations of 1-MCP were firmer than fruit treated with lower concentrations and all 1-MCP treated fruit were firmer than untreated control fruit (Table 2).

3.2.2. Skin colour

Treatment duration did not affect colour as rated by eye or chromameter after 4 and 7 weeks storage (Table 2). After 7 weeks storage fruit treated with 100 nl l^{-1} for 6 h, had darker skin (lower chromameter values and higher eye rating values) than fruit treated with 500 nl l^{-1} 1-MCP for 6 h (Table 2). Control fruit were more coloured than 1-MCP treated fruit in all cases.

3.2.3. Fruit quality

After 4 weeks storage, the effect of treatment duration on overall fruit quality (% sound) was significant, but not consistent (Table 3). Fruit treated with 100 nl l^{-1} for 6 h ripened more quickly than fruit treated for 12 and 24 h (6.4, 7.2 and 7.1 days, respectively). Duration of treatment did not influence ripening rate of fruit treated with 500 nl l^{-1}. 1-MCP concentration affected fruit quality and ripening rate. Fruit treated

Table 1
Experiment 1: fruit quality of control and 1-MCP treated fruit after 7 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		Days to ripe	% Sound		Incidence of disorders (%)											
Duration (h)	Concentration (nl l^{-1})				Diffuse flesh discolouration		Outer flesh blackening		Stringy vascular tissue		Vascular leaching		Vascular browning		Uneven ripening	
6	0	2.3	0.0	(0.0)	87.5	(69.5)	56.9	(49.0)	70.8	(57.4)	5.6	(8.0)	79.2	(63.6)	0.0	(0.0)
6	50	5.0	29.2	(32.2)	2.8	(7.9)	11.1	(18.6)	4.2	(9.5)	13.9	(21.0)	77.8	(62.2)	0.0	(0.0)
6	100	4.5	23.6	(28.9)	0.0	(0.0)	1.4	(3.9)	0.0	(0.0)	15.3	(21.7)	80.6	(64.0)	0.0	(0.0)
6	250	5.4	29.2	(32.6)	0.0	(0.0)	0	(0)	0.0	(0.0)	4.2	(9.5)	81.9	(65.0)	8.3	(16.4)
6	500	5.9	30.6	(33.1)	0.0	(0.0)	0	(0)	1.4	(3.9)	0.0	(0.0)	81.9	(65.8)	11.1	(19.4)
6	1000	5.8	26.4	(30.4)	0.0	(0.0)	0	(0)	1.4	(3.9)	2.8	(7.9)	77.8	(62.2)	26.4	(30.8)
15	0	3.2	1.4	(3.9)	68.1	(56.2)	19.5	(26.1)	30.6	(33.5)	9.7	(17.6)	88.9	(74.0)	1.4	(3.9)
15	50	4.5	16.7	(23.0)	0.0	(0.0)	5.6	(13.5)	9.6	(12.5)	30.6	(33.5)	77.8	(62.2)	1.4	(3.9)
15	100	4.8	19.4	(25.8)	2.8	(5.6)	0	(0)	0.0	(0.0)	9.7	(14.9)	80.6	(64.5)	5.5	(11.2)
15	250	5.9	27.8	(30.8)	0.0	(0.0)	0	(0)	0.0	(0.0)	2.8	(5.6)	86.1	(69.2)	18.1	(24.7)
LSDs																
(a) Between temperatures, Conc. <500 nl l^{-1}																
Temp. × Conc.		0.34		(13.65)		(11.18)		(7.70)		(8.41)		(16.53)		(14.97)		(10.29)
(b) Temp. 6 °C only, all concentrations																
Concentration		0.32		(13.06)		(5.32)		(8.69)		(10.20)		(13.50)		(13.90)		(4.57)
Significance																
(a) Between temperatures, Conc. <500 nl l^{-1}																
Temperature		***		NS		NS		***		*		NS		NS		*
Concentration		***		***		***		***		***		*		NS		***
Lin		***		***		***		***		***		NS		NS		***
Quad		***		***		***		***		***		*		NS		NS
Temp. × Conc.		***		*		NS		NS		***		*		NS		NS
Temp. Lin		NS		NS		NS		*		*		NS		NS		NS
Temp. Quad		***		NS		NS		*		*		NS		NS		NS
(b) Temp. 6 °C only, all concentrations																
Concentration		***		***		***		***		***		*		NS		***
Lin		***		*		***		***		***		NS		NS		***
Quad		***		*		***		***		***		NS		NS		***

Days to ripen (DTR) is defined as time to reach an average Firmometer value of 100. % sound is defined as the proportion of fruit showing no unacceptable quality factors. Disorders were rated on a scale of 0–3 (0 = none to 3 = severe) and data presented as disorder incidence (proportion of fruit with >0 rating; i.e. any level of the disorder). Data in brackets are transformed means. LSD: least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively; NS, *, ***: non-significant, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Durn., Conc., Temp.: 1-MCP treatment duration, 1-MCP concentration, 1-MCP treatment temperature, respectively.

Table 2
Experiment 2: fruit firmness (Firmometer value) and skin colour of control and 1-MCP treated fruit after storage for either 4 or 7 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		4 weeks						7 weeks				
Duration (h)	Concentration ($nl\,l^{-1}$)	Firmness		Skin colour				Firmness	Skin colour			
		1 day at 20 °C	4 days at 20 °C	Lightness	Chroma	Hue angle (°)	Eye rating (1–6)	1 day at 20 °C	Lightness	Chroma	Hue angle (°)	Eye rating (1–6)
6	100	21.9	58.9	29.6	22.4	122.8	1.9	40.5	29.3	11.8	103.4	3.2
6	500	18.3	29.1	29.8	23.4	124.5	1.7	30.3	31.3	15.8	116.6	2.5
12	100	18.4	46.0	30.8	22.6	123.8	1.7	31.5	29.9	14.6	113.0	2.6
12	500	19.3	31.2	31.9	23.9	123.4	1.7	27.6	30.9	16.4	114.3	2.4
24	0	22.6	105.9	32.1	20.3	120.7	2.1	62.8	28.3	10.6	104.8	3.7
24	100	18.5	44.6	30.8	23.1	123.3	1.8	43.2	29.8	13.6	109.9	2.9
24	500	18.2	30.6	30.9	22.9	124.6	1.7	31.4	30.7	15.8	112.8	2.6
LSDs												
(a) Conc. not equal 0												
Duration × Conc.		2.37	14.82	1.84	2.36	1.65	0.16	8.96	1.37	2.49	5.46	0.41
(b) Duration 24 h only, all concentrations												
Concentration		3.95	11.47	1.50	2.56	2.38	0.25	8.91	1.37	2.33	5.43	0.43
Significance												
(a) Conc. not equal 0												
Duration		NS	NS	*	NS	NS	NS	*	NS	NS	NS	NS
Lin		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Quad		NS	NS	*	NS	NS	NS	*	NS	NS	NS	*
Concentration		NS	***	NS	NS	NS	NS	*	*	***	***	***
Lin		NS	***	NS	NS	NS	NS	*	*	***	***	***
Duration × Conc.		*	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
Lin. lin		NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
Quad. lin		*	NS	NS	NS	NS	*	NS	NS	NS	*	NS
(b) Duration 24 h only, all concentrations												
Concentration		NS	***	NS	NS	*	*	***	*	***	*	***
Lin		NS	***	NS	NS	*	*	***	*	***	*	***
Quad		NS	***	NS	NS	NS	NS	*	NS	*	NS	*

LSD: least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively. NS, *, ***: non-significant, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Conc.: 1-MCP concentration.

Table 3
Experiment 2: fruit quality of control and 1-MCP treated fruit after 4 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		Days to ripe	% Sound		Incidence of disorders (%)											
Duration (h)	Concentration (nl l^{-1})				Diffuse flesh discolouration		Outer flesh blackening		Stringy vascular tissue		Vascular leaching		Vascular browning		Uneven ripening	
6	100	6.4	84.7	(67.2)	2.8	(7.9)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	5.6	(11.2)	1.4	(3.9)
6	500	9.0	48.6	(44.2)	2.8	(7.9)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	23.6	(28.7)	33.3	(34.8)
12	100	7.2	69.4	(56.5)	0	(0.0)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	22.2	(27.8)	0.0	(0.0)
12	500	8.8	36.1	(36.9)	2.8	(7.9)	0.0	(0.0)	0.0	(0.0)	1.4	(3.9)	22.2	(28.0)	43.1	(41.0)
24	0	4.6	94.4	(79.2)	6.9	(14.8)	0.0	(0.0)	4.2	(9.5)	0.0	(0.0)	11.1	(19.2)	1.4	(3.9)
24	100	7.1	80.6	(64.1)	2.8	(7.9)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	13.9	(21.2)	1.4	(3.9)
24	500	9.0	56.9	(49.0)	1.4	(3.9)	0.0	(0.0)	0.0	(0.0)	0.0	(0.0)	26.4	(29.9)	15.3	(23.0)
LSDs																
(a) Conc. not equal 0																
Durn × Conc.		0.18		(7.59)		(13.64)		na		(11.27)		(5.03)		(15.82)		(11.65)
(b) Duration 24 h only, all concentrations																
Concentration		0.17		(14.07)		na		na		(15.65)		na		(22.32)		(11.47)
Significance																
(a) Conc. not equal 0																
Duration		***		*		NS		na		na		NS		NS		NS
Lin		***		NS		NS		na		na		NS		NS		NS
Quad		*		***		NS		na		na		NS		NS		NS
Concentration		***		***		NS		na		na		NS		NS		***
Lin		***		***		NS		na		na		NS		NS		***
Durn. × Conc.		***		NS		NS		na		na		NS		NS		*
Lin. lin		***		NS		NS		na		na		NS		NS		NS
Quad. lin		***		NS		NS		na		na		NS		NS		NS
(b) Duration 24 h only, all concentrations																
Concentration		***		*		NS		na		NS		na		NS		*
Lin		***		*		NS		na		NS		na		NS		*
Quad		***		NS		NS		na		NS		na		NS		NS

Days to ripen (DTR) is defined as time to reach an average Firmometer value of 100. % sound is defined as the proportion of fruit showing no unacceptable quality factors. Disorders were rated on a scale of 0–3 (0 = none to 3 = severe) and data presented as disorder incidence (proportion of fruit with >0 rating; i.e. any level of the disorder). Data in brackets are transformed means. LSD: least significant difference for the two-way interaction at $P \leq 0.05$, Lin, Quad: Linear, Quadratic, respectively. NS, na, *, ***: non-significant, not applicable, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Durn., Conc.: 1-MCP treatment duration, 1-MCP concentration, respectively.

with 500 nl l^{-1} had less sound fruit, more uneven ripening and took longer to ripen than fruit treated with 100 nl l^{-1} and untreated fruit.

After 7 weeks storage, fruit treated for 6 h took less time to ripen than fruit treated for longer durations, but treatment duration did not affect ripe fruit quality (Table 4). All 1-MCP treatments reduced long-term storage disorders (diffuse discolouration and outer flesh blackening) and improved overall fruit quality compared with control fruit (Table 4). 1-MCP concentration had an effect on fruit quality and ripening rate. Fruit treated with 500 nl l^{-1} 1-MCP had less sound fruit, more uneven ripening but less vascular leaching and took longer to ripen than fruit treated with 100 nl l^{-1} 1-MCP.

3.3. Experiment 3. Effect of harvest date on efficacy of 1-MCP concentration

3.3.1. Fruit firmness

The effect of harvest date (fruit maturity) on firmness after storage was not significant. Fruit treated with 1-MCP were firmer (lower Firmometer value) than control fruit after both 4 and 7 weeks storage (Table 5). After 4 weeks storage plus 4 days at 20 °C and 7 weeks storage plus 1 days at 20 °C, fruit treated with 250 nl l^{-1} 1-MCP were firmer than fruit treated with 100 nl l^{-1} 1-MCP.

3.3.2. Skin colour

The effect of 1-MCP concentration on skin colour is illustrated in Fig. 4 where the appearance of fruit from one orchard is shown after removal from 4 and 7 weeks storage (top and bottom rows, respectively). The effect of harvest date on skin colour was significant after 4 weeks storage, but not 7 weeks storage (Table 5). Orchard source also affected skin colour following storage (data not shown).

1-MCP treated fruit were rated by eye as having greener skin and measured by chromameter as being lighter (higher L values), more vivid (higher chroma values) and more green (higher hue angle values) than untreated fruit after 4 and 7 weeks storage (Table 5). 1-MCP concentration had no effect on skin colour after 4 weeks storage. However, following 7 weeks storage fruit treated with 250 nl l^{-1} 1-MCP were rated by eye as having greener skin and measured by meter as being lighter, more vivid and more green than fruit treated with 100 nl l^{-1} 1-MCP (Table 5).

3.3.3. Fruit quality after 4 weeks storage

Late season fruit tended to be of poorer quality than fruit from early or mid-season harvests (Table 6). Fruit treated with 250 nl l^{-1} 1-MCP had lower overall fruit quality than fruit treated with 100 nl l^{-1} 1-MCP and untreated fruit (Table 6). This was because, although 1-MCP reduced the incidence of diffuse flesh discolouration, the incidence of vascular disorders and uneven ripening (later in the season) was often higher than control fruit.

DTR increased as 1-MCP concentration increased such that fruit treated with 250 nl l^{-1} 1-MCP took about twice as long to ripen as non-treated fruit (Table 6).

Early harvested fruit had more vascular leaching but less uneven ripening than later harvested fruit (Table 6). In later harvests levels of diffuse flesh discolouration and stringy vascular tissue increased in control fruit but not 1-MCP treated fruit. Diffuse flesh discolouration incidence, although low in control fruit, was reduced by 1-MCP (Table 6). In contrast, the incidence of uneven ripening was increased by 1-MCP of 250 nl l^{-1} in late season fruit.

3.3.4. Fruit quality after 7 weeks storage

Late harvested fruit were of poorer quality than early and mid-harvested fruit (Table 7). Contrary to observations after 4 weeks storage, 1-MCP treatment improved the overall quality of avocados following ripening after 7 weeks of storage (Table 7). Untreated fruit were of very poor overall quality (<7% sound), while 1-MCP treated fruit ranged from 15 to 57% sound. 1-MCP concentration had no effect on overall fruit quality.

1-MCP treatment increased DTR with fruit treated with 250 nl l^{-1} again taking almost twice as long to ripen as control fruit.

Although harvest date was generally had no statistically significant effect on the disorders, for a given 1-MCP treatment there was a trend for diffuse discolouration and vascular browning to increase as harvest date in the season progressed (Table 7).

The disorders diffuse flesh discolouration, outer flesh blackening and stringy vascular tissue were all reduced by 1-MCP application, although the magnitude of the reduction varied between these disorders (Table 7). For example, diffuse flesh

Table 4
Experiment 2: fruit quality of control and 1-MCP treated fruit after 7 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		Days to ripe	% sound		Incidence of disorders (%)											
Duration (h)	Concentration (nl l^{-1})				Diffuse flesh discolouration		Outer flesh blackening		Stringy vascular tissue		Vascular leaching		Vascular browning		Uneven ripening	
6	100	4.9	25.0	(29.8)	22.0	(28.0)	2.8	(5.6)	2.8	(5.6)	19.4	(26.1)	70.8	(57.8)	9.7	(17.6)
6	500	6.2	16.7	(23.0)	26.4	(30.9)	0.0	(0.0)	1.4	(3.9)	1.4	(3.9)	80.6	(63.9)	25.0	(29.8)
12	100	5.3	31.9	(34.3)	38.9	(38.4)	0.0	(0.0)	0.0	(0.0)	12.5	(20.5)	72.2	(58.2)	11.1	(19.4)
12	500	6.5	18.1	(25.1)	22.2	(28.1)	0.0	(0.0)	1.4	(3.9)	1.4	(3.9)	81.9	(65.4)	26.4	(30.8)
24	0	4.5	0.0	(0.0)	90.3	(71.9)	26.4	(30.8)	1.4	(3.9)	11.1	(19.4)	87.5	(69.5)	12.5	(20.5)
24	100	5.3	40.3	(39.2)	23.6	(28.0)	0.0	(0.0)	1.4	(3.9)	6.9	(12.5)	76.4	(61.8)	8.3	(13.6)
24	500	6.3	26.4	(30.7)	16.7	(23.6)	0.0	(0.0)	0.0	(0.0)	4.2	(9.5)	84.7	(67.3)	23.6	(28.2)
LSDs																
(a) Conc. not equal 0																
Durn. × Conc.		0.15		(12.78)		(12.88)		(7.19)		(10.32)		(13.52)		(11.96)		(13.35)
(b) Durn 24 h only, all concentrations																
Concentration		0.16		(12.02)		(21.26)		(5.38)		(14.07)		(20.54)		(16.63)		(18.57)
Significance																
(a) Conc. not equal 0																
Duration		***		NS		NS		NS		NS		NS		NS		NS
Lin		***		NS		NS		NS		NS		NS		NS		NS
Quad		***		NS		NS		NS		NS		NS		NS		NS
Concentration		***		*		NS		NS		NS		*		NS		*
Lin		***		*		NS		NS		NS		*		NS		*
Durn. × Conc.		*		NS		NS		NS		NS		NS		NS		NS
Lin. lin		*		NS		NS		NS		NS		*		NS		NS
Quad. lin		NS		na		NS		NS		NS		NS		NS		NS
(b) Durn 24 h only, all concentrations																
Concentration		***		*		*		***		NS		NS		NS		NS
Lin		***		*		*		***		NS		NS		NS		NS
Quad		***		***		*		***		NS		NS		NS		NS

Days to ripen (DTR) is defined as time to reach an average Firmometer value of 100. % sound is defined as the proportion of fruit showing no unacceptable quality factors. Disorders were rated on a scale of 0–3 (0 = none to 3 = severe) and data presented as disorder incidence (proportion of fruit with >0 rating; i.e. any level of the disorder). Data in brackets are transformed means. LSD = least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively. NS, na, *, ***: non-significant, not applicable, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Durn., Conc.: 1-MCP treatment duration, 1-MCP concentration, respectively.

Table 5
Experiment 3: fruit firmness (Firmometer value) and skin colour of control and 1-MCP treated fruit after storage for either 4 or 7 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		4 weeks						7 weeks				
Harvest date	Concentration (nl l^{-1})	Firmness		Skin colour				Firmness	Skin colour			
		1 day at 20 °C	4 days at 20 °C	Lightness	Chroma	Hue angle (°)	Eye rating (1–6)	1 day at 20 °C	Lightness	Chroma	Hue angle (°)	Eye rating (1–6)
E	0	36.6	96.5	35.2	16.6	111.5	2.6	56.3	30.6	9.4	73.1	4.1
E	100	23.2	46.1	37.6	22.6	121.0	1.9	37.7	33.2	14.5	94.2	3.6
E	250	20.5	28.7	37.9	23.5	122.0	1.9	29.2	34.5	17.4	108.6	2.7
M	0	26.2	100.3	36.3	20.3	120.2	2.0	45.3	30.4	8.6	84.6	3.7
M	100	24.2	50.7	36.9	21.6	123.2	2.0	34.9	32.3	11.7	98.9	3.2
M	250	22.7	28.7	37.0	21.2	123.7	2.0	31.9	34.6	15.6	109.6	2.9
L	0	36.1	105.5	33.0	15.8	115.4	2.7	70.6	29.4	8.0	87.1	3.9
L	100	25.5	50.1	34.4	19.2	120.9	2.1	43.6	30.8	10.6	95.0	3.4
L	250	23.6	30.9	33.4	17.6	120.7	2.3	32.7	32.6	14.1	106.9	2.9
LSDs												
Date × Conc.												
Between date		4.24	9.04	1.22	1.94	5.57	0.28	8.47	1.56	2.78	8.10	0.35
Within date		3.14	7.09	0.85	1.40	2.24	0.20	4.90	1.00	1.70	6.73	0.24
Significance												
Date		NS	NS	***	*	*	*	NS	NS	NS	NS	NS
Lin		*	NS	***	*	NS	NS	NS	*	NS	NS	NS
Quad		NS	NS	*	*	*	*	NS	NS	NS	NS	NS
Concentration		***	***	***	***	***	***	***	***	***	***	***
Lin		***	***	***	***	***	***	***	***	***	***	***
Quad		*	***	***	***	***	***	***	NS	NS	*	NS
Date × Conc.		***	NS	**	***	***	***	***	NS	NS	*	*
Lin. lin		*	NS	***	***	*	NS	*	NS	NS	*	*
Quad. lin		*	NS	NS	***	*	***	***	NS	NS	NS	*
Lin. quad		*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Quad. quad		NS	NS	NS	*	*	***	NS	NS	NS	NS	NS

Treatment was carried out using fruit harvested on three occasions in the season; early (E; September), mid (M; November) and late (L; February). E, M, L: early, mid or late season, respectively. LSD: least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively. NS, *, ***: non-significant, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Date, Conc.: Harvest date, 1-MCP concentration, respectively.

Fig. 4. Experiment 3. Effect of 1-MCP on fruit appearance of fruit stored for 4 (top row) and 7 weeks (bottom row) at 5.5 °C. Photos taken 1 day after removal from storage.

discolouration was high in control fruit (56–82% incidence) and was reduced by 1-MCP application (0–26% incidence) while outer flesh blackening (Fig. 1D), was present at 20–30% incidence in control fruit, but was almost completely eliminated by 1-MCP application. The incidence of uneven ripening was fairly low with no clear influence of 1-MCP application.

4. Discussion

1-MCP application is a powerful tool for reducing physiological disorders in 'Hass' avocados, particularly those associated with long coolstorage periods. Overall the results showed that 1-MCP treatments have potential to slow ripening during storage with concomitant reduction in physiological disorders such as diffuse flesh discolouration (greying) and outer flesh blackening. After 7 weeks storage (a very long storage time for 'Hass' avocados), 1-MCP reduced diffuse discolouration, and in almost all cases reduced the proportion of unacceptable fruit due to diffuse discolouration from 50–90% to below 10%. Other disorders which were present at significant levels following long-term storage were stringy vascular tissue, outer flesh blackening and vascular leaching. The reduction in diffuse discolouration (flesh greying) observed here was also observed by Pesis et al. (2002) following storage for 4 weeks at 5 °C (7.2 and 2.4% for control and 100 nl l^{-1}, respectively). Here we have demonstrated that this disorder can be reduced even with 7 weeks storage. The efficacy of 1-MCP is also supported by the statistical analysis which shows that concentration effects were highly significant for sound fruit and almost all disorders ($P < 0.001$), and were more significant than harvest date (Tables 6 and 7).

Table 6
Experiment 3: fruit quality of control and 1-MCP treated fruit after 4 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		Days to ripe	% sound		Incidence of disorders (%)											
Harvest date	Concentration (nl l^{-1})				Diffuse flesh discolouration		Outer flesh blackening		Stringy vascular tissue		Vascular leaching		Vascular browning		Uneven ripening	
E	0	6.9	69.4	(59.4)	1.9	(4.5)	0.0	(0.0)	0.0	(0.0)	14.8	(17.0)	43.5	(41.4)	0.0	(0.0)
E	100	9.6	81.0	(67.5)	0.9	(2.6)	0.0	(0.0)	3.2	(7.6)	1.9	(4.5)	36.6	(36.1)	0.0	(0.0)
E	250	12.9	51.4	(47.1)	0.0	(0.0)	0.0	(0.0)	14.4	(18.9)	11.1	(15.2)	56.9	(49.4)	0.0	(0.0)
M	0	5.1	85.6	(72.4)	5.0	(8.5)	0.0	(0.0)	6.1	(10.5)	2.2	(4.9)	18.9	(22.2)	0.0	(0.0)
M	100	7.7	86.1	(69.0)	1.1	(2.9)	0.0	(0.0)	8.9	(15.7)	0.6	(1.4)	24.4	(29.0)	0.0	(0.0)
M	250	10.9	56.7	(49.1)	0.0	(0.0)	0.0	(0.0)	15.6	(21.7)	2.2	(4.9)	57.8	(49.6)	3.3	(7.8)
L	0	5.4	67.8	(56.4)	10.5	(17.1)	0.0	(0.0)	25.0	(28.8)	2.8	(6.4)	40.6	(38.9)	1.7	(4.3)
L	100	8.3	33.3	(34.9)	0.6	(1.4)	0.0	(0.0)	6.9	(14.0)	0.0	(0.0)	45.3	(42.3)	3.1	(8.2)
L	250	10.4	11.7	(19.6)	1.1	(3.5)	0.0	(0.0)	3.3	(6.8)	0.0	(0.0)	30.6	(33.2)	30.3	(32.6)
LSDs																
Date × Conc.																
Between date		1.21		(15.08)		(8.11)		na		(12.07)		(8.97)		(14.22)		(4.53)
Within date		0.35		(14.78)		(5.21)		na		(7.32)		(8.99)		(12.71)		(4.80)
Significance																
Date		NS		*		NS		na		NS		*		NS		***
Lin		NS		*		NS		na		NS		*		NS		***
Quad		NS		*		NS		na		NS		NS		NS		*
Concentration		***		***		***		na		NS		*		*		***
Lin		***		***		***		na		NS		NS		*		***
Quad		***		NS		*		na		NS		*		NS		*
Date × Conc.		***		NS		*		na		***		NS		*		***
Lin. lin		***		*		*		na		***		NS		NS		***
Quad. lin		NS		NS		NS		na		*		NS		**		*
Lin. quad		*		*		*		na		*		NS		NS		*
Quad. quad		NS		NS		NS		na		NS		NS		NS		NS

Days to ripen (DTR) is defined as time to reach an average Firmometer value of 100. % sound is defined as the proportion of fruit showing no unacceptable quality factors. Disorders were rated on a scale of 0–3 (0 = none to 3 = severe) and data presented as disorder incidence (proportion of fruit with >0 rating; i.e. any level of the disorder). Data in brackets are transformed means. E, M, L: early, mid or late season, respectively. LSD: least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively. NS, na, *, ***: non-significant, not applicable, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Date, Conc.: harvest date, 1-MCP concentration, respectively.

Table 7
Experiment 3: fruit quality of control and 1-MCP treated fruit after 7 weeks storage at 5.5 °C and ripening at 20 °C

1-MCP treatment		Days to ripe	% sound		Incidence of disorders (%)											
Harvest date	Concentration ($nl\,l^{-1}$)				Diffuse flesh discolouration		Outer flesh blackening		Stringy vascular tissue		Vascular leaching		Vascular browning		Uneven ripening	
E	0	4.9	6.1	(10.5)	57.5	(49.8)	28.7	(31.7)	50.9	(45.6)	37.9	(37.8)	92.6	(75.5)	0.0	(0.0)
E	100	5.8	56.9	(49.1)	3.7	(8.9)	2.8	(7.1)	30.6	(32.5)	13.9	(21.1)	64.8	(53.9)	0.0	(0.0)
E	250	7.9	53.7	(47.8)	0.0	(0.0)	0.0	(0.0)	29.6	(32.0)	6.9	(13.1)	70.8	(58.4)	0.0	(0.0)
M	0	4.5	6.7	(12.9)	55.6	(48.3)	25.0	(29.2)	73.3	(59.2)	6.1	(11.1)	94.4	(79.1)	12.2	(18.6)
M	100	5.4	42.2	(40.0)	22.8	(27.2)	1.1	(2.9)	35.6	(36.1)	5.0	(10.3)	71.7	(58.9)	5.6	(9.1)
M	250	7.2	48.9	(44.2)	5.6	(8.9)	0.0	(0.0)	16.7	(23.9)	7.2	(13.4)	67.8	(55.9)	5.0	(8.4)
L	0	4.3	1.1	(2.9)	82.2	(67.5)	17.2	(21.7)	65.6	(54.4)	8.3	(13.3)	98.9	(87.1)	5.0	(10.5)
L	100	6.1	21.1	(26.4)	26.1	(30.1)	2.2	(5.7)	31.7	(33.5)	10.6	(12.5)	88.9	(72.5)	1.7	(4.3)
L	250	7.6	15.0	(21.9)	20.0	(25.6)	1.1	(2.9)	18.3	(25.1)	4.4	(9.0)	88.9	(72.1)	9.4	(14.1)
LSDs																
Date × Conc.																
Between date		0.56		(13.55)		(15.26)		(9.74)		(11.15)		(13.51)		(13.71)		(12.17)
Within date		0.25		(9.05)		(6.99)		(7.00)		(7.96)		(7.73)		(7.24)		(5.82)
Significance																
Date		NS		*		NS		NS		NS		NS		NS		NS
Lin		NS		*		*		NS		NS		NS		NS		NS
Quad		NS		NS		NS		NS		NS		NS		NS		NS
Concentration		***		***		***		***		***		***		***		*
Lin		***		***		***		***		***		***		***		NS
Quad		NS		***		***		***		***		NS		***		*
Date × Conc.		***		*		***		NS		*		***		NS		*
Lin. lin		NS		*		NS		*		*		***		NS		NS
Quad. lin		*		NS		NS		NS		*		***		NS		*
Lin. quad		***		NS		NS		NS		NS		NS		NS		*
Quad. quad		NS		NS		***		NS		NS		NS		NS		NS

Days to ripen (DTR) is defined as time to reach an average Firmometer value of 100. % sound is defined as the proportion of fruit showing no unacceptable quality factors. Disorders were rated on a scale of 0–3 (0 = none to 3 = severe) and data presented as disorder incidence (proportion of fruit with >0 rating; i.e. any level of the disorder). Data in brackets are transformed means. E, M, L: early, mid or late season, respectively. LSD: least significant difference for the two-way interaction at $P \leq 0.05$. Lin, Quad: linear, quadratic, respectively. NS, *, ***: non-significant, significant at the $P \leq 0.05$, $P \leq 0.001$, respectively. Date, Conc.: harvest date, 1-MCP concentration, respectively.

Our work confirms other 'Hass' studies in the ability of 1-MCP to delay ripening in non-coolstored fruit (Feng et al., 2000; Hofman et al., 2000; Adkins et al., 2004) and coolstored fruit (Pesis et al., 2002). We did not observe large differences in 1-MCP efficacy with different treatment duration of 12 and 24 h (Tables 2 and 3). Whereas Jeong et al. (2001) observed differences in the rate of softening between 6, 12 and 24 h treatment with 450 nl l^{-1} 1-MCP. However, their work was carried out on a cultivar of West Indian race ('Simmonds'), and the fruit was not coolstored after treatment.

Low 1-MCP treatment temperatures have been shown to reduce 1-MCP efficacy of other fruit such as apple (Mir et al., 2001), with a concentration-dependent effect (DeEll et al., 2002). Although we only examined the effect of temperature at one time (Experiment 1; 6 versus 15 °C), the results observed in this, and subsequent experiments, and other results (e.g. Lemmer and Kruger, 2003) supports the use of 6 °C as a reasonable and efficacious temperature. Thus, taking into consideration the above results and commercial logistical issues, it appears likely that an overnight 1-MCP treatment at storage temperature (≅6 °C) of packed and palletised product prior to shipping or storage is a logical and practical protocol.

In terms of 1-MCP treatment concentration, a level of 100 nl l^{-1} appears to be the best concentration, particularly if fruit are stored for shorter periods such as 4 weeks. This concentration achieves a balance of reducing physiological disorders without overly delaying time to ripen following removal from storage, and low incidence (<≅ 10%) of uneven ripening (which was as high as 30% for a concentration of 250 nl l^{-1} in some experiments; Table 6). The delayed ripening (extended 'shelf life') which results from 1-MCP treatment should be considered carefully from a commercial perspective since most markets are moving to a "ripe tonight" program. In these situations, fruit handlers rely on predictable ripening times in order to maintain supply, and thus, delays in fruit ripening may pose problems. Data from the first experiment, and other preliminary trials (data not shown) suggested that a concentration as low as 50 nl l^{-1} can effectively reduce physiological disorders. However, further work is required to determine whether this, or a similar concentration, might be most effective for shorter storage times such as 4 weeks. This should also be examined in combination with post-storage ethylene treatments. In addition, it is important that the commercial 1-MCP concentration be confirmed under commercial conditions (e.g. treatment in rooms in commercial post harvest facilities).

The response to a wide range of maturities (harvest dates over the picking season) treated in this work (dry matter of 24–37%), indicates that maturity has some influence on the development of disorders (Tables 6 and 7), but little effect on 1-MCP efficacy. This contrasts with results observed in apples (e.g. Watkins et al., 2000), but is perhaps not surprising considering that, unlike apple and most other crops, avocados do not ripen until they are harvested (Gazit and Blumenfeld, 1970). Further work should be carried out in the country of origin, with consideration for the duration of storage/shipping desired.

Physiological disorders in fruit may be either reduced, increased or unaffected by 1-MCP treatment. The beneficial or detrimental effects most likely reflect whether ethylene is associated with, or prevents, disorder development (Watkins, 2002). Our preliminary data showing that 1-MCP does not reduce *external* chilling injury (skin blackening) of avocado fruit suggests that ethylene does not play a role in this disorder. This contrasts with inhibition of *internal* chilling injury symptoms (diffuse flesh discolouration) by 1-MCP as demonstrated here and by Pesis et al. (2002).

5. Conclusion

During storage at commercial temperatures, 1-MCP can effectively slow softening, maintain green skin colour during storage, and reduce internal physiological disorders of ripe avocados. However, the beneficial effects of 1-MCP (reduced physiological disorders) should be balanced with possible negative commercial outcomes (such as excessively delayed ripening). 1-MCP does not appear to be effective in reducing external chilling injury caused by storage at low temperatures (0 °C).

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