Avoiding Chilling Damage in ‘Hass’ Avocado Fruit by Controlled Atmosphere Storage at Higher Temperature

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Abstract. Sea-freight distribution of ‘Hass’ avocado (*Persea americana*) is by refrigerated containers, sometimes supplemented by controlled atmosphere (CA). With both refrigeration and CA prolonging the storage life of the fruit, there is a question as to whether the technologies can be traded. That is, by using CA at warmer temperatures to extend storage without the risk of chilling damage. In this project, the potential to avoid chilling damage by storing fruit at 7 °C in 2% O₂/2% CO₂ CA instead of 5 °C in 2% O₂/2% CO₂ CA or air has been investigated for fruit stored for 4 or 6 weeks. Increasing the storage temperature from 5 °C to 7 °C did not affect the quality of fruit immediately out of CA storage, with no significant difference in skin color, firmness, or skin disorders. Both CA storage regimes, at 5 °C or 7 °C, resulted in better fruit quality than for fruit that had been stored in air at 5 °C. Overall, CA at 7 °C was less effective at retarding the progression of ripening in storage than CA at 5 °C, although after 4 weeks of storage, fruit from both CA regimes took longer to ripen than the air-stored fruit. After 6 weeks of storage, there was no difference in ripening time between fruit that had been stored in CA at 7 °C or in air at 5 °C, with fruit that had been in CA at 5 °C still taking longest to ripen. However, the incidence of diffuse flesh discoloration (DFD) in the air-stored fruit was high compared with that in fruit from CA at 7 °C or 5 °C. The main negative aspect to storing fruit in CA at 7 °C rather than at 5 °C was the higher incidence of rots in ripe fruit. While it was lower in the air-stored fruit, the incidence in fruit that had been stored in CA at 7 °C tended to be higher than that of the fruit stored in CA at 5 °C. It therefore appears that the potential for using CA at slightly higher temperatures to avoid chilling damage rests on the storage duration required and the risk of rots in the fruit.

‘Hass’ avocado (*Persea americana*) is the main internationally traded avocado fruit cultivar. With increasing global demand, and increasing numbers of suppliers, increasing volumes of fruit are being shipped between countries. In this global marketplace, New Zealand is a minor producer, yet its exporters are looking to diversify from the traditional Australian market to more distant markets as production volumes increase. Overall, New Zealand-grown fruit quality tends to be best ≈10–12 months postflowering, with a greater risk to quality earlier or later in the season, associated with less mature

or more mature fruit (Burdon et al., 2013; Dixon et al., 2004).

The avocado fruit is chilling sensitive, with potential for both flesh and skin disorders to occur at low temperature (Chaplin et al., 1983; Hofman et al., 2002). Traditional shipping at about 5 °C risks the development of CI. Irrespective of CI, if fruit are stored in air for longer than 30 d, the ripe fruit quality tends to decline (Dixon et al., 2003, 2004). Hence, the overall capacity for ‘Hass’ avocado fruit to be stored, or distributed over long distances, is limited. The inherent storage life, which declines with maturity, and not being able to cool the fruit to the same degree as fruit such as apples and kiwifruit, which may be stored at, or close to, 0 °C, both limit storage life.

The association between poor quality and fruit age beyond 30 d can be improved by the use of CA in combination with refrigerated storage, with potential for good ripe fruit quality to be maintained for 6–8 weeks (Burdon et al., 2008). The value in using CA for shipping avocado fruit has long been recognized, with a range of research reported along with recommendations for atmospheres to use (Kader, 2003; Thompson, 2010).

‘Hass’ avocado is a typical climacteric fruit (Kader, 2002) in which there is a pre-climacteric period before the ripening occurs and is associated with a climacteric increase in ethylene production and respiration. The preclimacteric period decreases the longer fruit are left on the tree, leading to the reduction in time to ripen as the fruit matures. CA storage retards the progression to ripening by extending the preclimacteric period at storage temperatures beyond that achieved by refrigeration alone. However, the maximum storage life achieved under CA may not always be needed to reach target markets. The storage life required when shipping from New Zealand is in the range 2–6 weeks, allowing export to Australia or Europe. As a result, it may be possible to remove the risk of chilling damage to the fruit by increasing the storage temperature slightly and by relying on the CA to provide adequate storage life.

In this project, the postharvest performance of ‘Hass’ avocado has been compared under CA at 5 °C or 7 °C. An additional sample of fruit was stored in air at 5 °C to provide the current non-CA practice for comparison.

Materials and Methods

Fruit were sourced on 16 Oct. 2014 from three commercial ‘Hass’ avocado orchards (designated O1, O2, and O3) in the Bay of Plenty, New Zealand. Fruit were harvested, handled, and packed commercially. Fruit were packed the day after harvest and packs for the trial (count size 25) were taken before fruit had been cooled. A total of 26 trays were taken for each of the three orchards; 24 trays for treatments and two trays for maturity assessment. The maturity assessment comprised a 20-fruit sample assessed for fruit firmness, skin color, and dry matter, and a further 20 fruit placed at 20 °C to determine the time to ripen. For each orchard, the 24 treatment trays were allocated randomly into six lots, each of four trays, all of which were placed into a cool store at 5 °C (four lots) or 7 °C (two lots) on the day of packing and left overnight to cool before commencing treatments.

The main treatment effect investigated was a comparison of fruit stored under CA of 2% O₂/2% CO₂ at either 5 °C or 7 °C. CA conditions were established in sealed 300-L chambers with the atmosphere being monitored and maintained by an OxyStat 2002 system (David Bishop Instruments, Heathfield, UK). The atmosphere in each chamber was kept ethylene-free by scrubbing with a catalytic ethylene scrubber. A sample of fruit was also stored in air at 5 °C to represent the current commercial practice. Fruit were assessed after 4 and 6 weeks of storage. Assessments were made immediately out of storage and also after holding at 20 °C until the fruit were ripe.

Fruit firmness was measured using a Fruit Texture Analyser (model GS14; GÜSS, Strand, South Africa) fitted with a flat plate.

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The Fruit Texture Analyser settings were: approach speed (forward) 5 mm·s⁻¹; trigger force 30 gf; measure speed 5 mm·s⁻¹; measure distance 2 mm; and return speed 40 mm·s⁻¹. Firmness was measured twice at the widest part of each fruit, with the two measurements taken at 90° to each other, with the values averaged to give a mean fruit firmness value. Firmness was measured as kgf and data converted to N, where 1 kgf = 9.81 N.

Fruit skin color was assessed immediately after removal from storage and also when ripe using a 0 to 100 scale, where 0 = bright glossy green, 30 = olive green, 60 = wood brown, 80 = purple brown, and 100 = dull black (New Zealand Avocado Industry Council Fruit Assessment Manual; Dixon, 2003).

Fruit flesh dry matter content was determined by taking two 18 mm diameter core samples at 90° to each other from the widest part of the fruit. The skin, seedcoat, and seed were removed and discarded, and the four pieces of fruit flesh were sliced into ≈1 mm discs, dried at 65 °C for 24 h, and then reweighed. The dry matter is expressed as the percentage mass remaining after 24 h of drying.

Fruit quality (rots and disorders) assessments were made according to the criteria in the New Zealand Avocado Industry Council Fruit Assessment Manual (Dixon, 2003). Fruit were assessed immediately after removal from storage and also after ripening at 20 °C. Each disorder was scored as present or absent, and where present, severity was rated on a 0 to 100 scale for the area of the fruit affected. Immediately after storage, the incidence and severity of any visible skin defects such as fuzzy patches (FPs), discrete patches (DPs), and external rots (ERs) were recorded. FPs are considered to be fungal in origin whereas DPs are physiological. Fruit were then held at 20 °C to ripen. Fruit were assessed daily for firmness by hand. Once the fruit had reached eating ripeness, determined by hand to be equivalent to a compression

firmness reading of ≈15–20 N, they were assessed for ERs and cut longitudinally to assess stem end rots (SERs), body rots (BRs) and vascular browning (VB). DFD was recorded as present or absent when ripe, with no severity score.

Statistical separation among sample means for treatment effects was by analysis of variance with blocking on orchards using GenStat Release 14.2 [(PC/Windows 7) Copyright 2011; VSN International Ltd, Hemel Hempstead, UK]. Where significant treatment effects were identified, separation among treatments was by Fisher's Protected least significant distance (LSD) at *P* = 0.05. Disorder incidence presented is for fruit with ≥5% severity; data were angular transformed before analysis, with the untransformed incidence data presented in the tables.

Results and Discussion

At harvest, the fruit from the three orchards on average had 29.4% dry matter, a firmness of 96.1 N, a skin color of 1.8, and took 13.3 d to ripen at 20 °C (Table 1).

The traditional maturity assessment for avocado fruit is dry matter, as a proxy for oil content (Lee et al., 1983). However, this is more to do with the way the fruit is eaten when ripe (sufficient oil such that the mouthfeel is not watery) rather than a measure of physiological maturity. As such, dry matter is merely a starting point for harvest on the basis of eating quality. The true physiological maturity is more associated with the preclimacteric period or time taken to ripen. For the three orchards used in the trial, the average time taken to ripen differed significantly between 10.8 d (O1) and 15.0 d (O3). In addition, the variability in individual fruit ripening times was 8–13 d for O1, 11–16 d for O2, and 11–17 d for O3. While the shortest time to ripen was for fruit with the highest average dry matter, and the longest time to ripen was for fruit with the lowest dry matter; the general relationship of increasing dry

matter with time on the tree and decreasing time to ripen does not always hold across orchards, and fruit with higher dry matter do not always have shorter ripening times (Burdon et al., 2015).

On removal of fruit from storage, there were significant differences in skin color and firmness among the treatments (Table 2). After both 4 and 6 weeks of storage, the skin color of fruit from both CA treatments was less advanced than in air-stored fruit. There was no significant difference between the skin color of fruit stored in CA at 5 °C or 7 °C.

After 4 weeks of storage, fruit in CA at 5 °C were firmest and fruit in air at 5 °C were softest, but not statistically softer than the fruit in CA at 7 °C (Table 2). After 6 weeks of storage, the fruit in CA at 5 °C were still firmest of the three treatments, being little changed from at harvest. However, the additional 2 weeks of storage resulted in the fruit in air being significantly softer (67.7 N) than the fruit in CA (96.1 N at 5 °C and 87.3 N at 7 °C). There was no statistical difference between the CA samples, possibly because of the high variability within each sample.

The overall incidences of FP and DP, individually and combined, were low (<3%) at both assessment times for fruit from all treatments (Table 3). There was no ER visible at the end of storage. While there was no statistically identifiable difference among treatments, there was a trend for a lower incidence of FP + DP in fruit stored in CA at 7 °C than either in CA or air at 5 °C. The lack of statistical significance, especially after 42 d of storage, may be the result of orchard differences, with a higher incidence of FP + DP in fruit from O1 compared with fruit from O2 and O3. The overall incidence of FP + DP in fruit from O1 (21.2%) was statistically significantly higher than O2 (3.2%) and O3 (7.1%), which did not differ statistically.

The cause of FP is often cited as being fungal, whereas DP is cited as being

Table 1. At-harvest fruit firmness, skin color, dry matter, and time taken to ripen at 20 °C for 'Hass' avocado fruit from three orchards (O1–O3). Values are the mean of 20 fruit per orchard.

Orchard	Firmness (N)	Skin color (0 to 100 scale)	Dry matter (%)	Time to ripen (d)
O1	95.2 a	2.8 b	31.8 b	10.8 a
O2	95.2 a	2.3 ab	28.6 a	14.1 b
O3	97.1 a	0.5 a	27.9 a	15.0 b
Mean	96.1	1.8	29.4	13.3
Statistical analysis: ANOVA <i>P</i> values				
Orchards	0.616	0.023	<0.001	<0.001

Values not sharing a common letter differ at *P* < 0.05 by Fisher Protected LSD.

Table 2. Skin color and firmness of 'Hass' avocado fruit after storage for 4 or 6 weeks in air at 5 °C or in a controlled atmosphere (CA) of 2% O₂/2% CO₂ at 5 °C or 7 °C. Values are the mean for three orchards, 20 fruit per orchard.

Storage conditions		Skin color (0 to 100 scale)		Firmness (N)	
Atmosphere	Temperature	4 wk	6 wk	4 wk	6 wk
Air	5 °C	7.5 b	26.2 b	89.3 a	67.7 a
CA	5 °C	1.6 a	9.9 a	100.1 b	96.1 b
CA	7 °C	1.7 a	10.9 a	92.2 a	87.3 ab
Statistical analysis: ANOVA <i>P</i> values					
Treatments		<0.001	<0.001	0.048	0.049

Values not sharing a common letter differ at *P* < 0.05 by Fisher Protected LSD.

physiological; e.g., chilling (Dixon, 2003). However, while fungal pathogens have been isolated from FP in New Zealand fruit (Everett et al., 2008), it is possible that the fungal infection/FP arises due to an initial point of physiological damage. Hence, it is perhaps valid to consider FP and DP together, with FP merely developing from initial DP, and therefore FP and DP being symptoms from a common cause. The overall lack of DP is indicative of the lack of understanding about the factors that make fruit susceptible to this form of physiological disorder, yet it can have a significant impact on commercial shipments of fruit under conditions that are reportedly the same.

There were statistically significant treatment effects on the time taken for fruit to ripen at 20 °C after storage (Table 4). While fruit from all treatments ripened considerably more rapidly than the at-harvest average of

13.3 d, the fruit that had been stored in CA at 5 °C ripened significantly more slowly (6.7 d after 6 weeks) than fruit that had been in CA at 7 °C (5.4 d after 6 weeks) or in air at 5 °C (5.2 d after 6 weeks). This finding demonstrates the capacity of CA at 7 °C to retard the ripening of fruit both in storage and also subsequently at 20 °C when compared with fruit stored in air at 5 °C. The skin color of ripe fruit from all treatments after 4 or 6 weeks of storage and ripening at 20 °C was similar (range 80.1–81.0).

In fruit ripened after 4 weeks of storage, there was no statistical difference among treatments for the incidence of SER (4.8% to 6.8%), BR (9.4% to 16.4%) or ER (none, Table 5). However, after 6 weeks of storage, the incidence of rots in the ripe fruit was affected by the storage environment. While fruit from both CA regimes were lower in SER than the air-stored fruit (30.0%), there

were more SER in fruit from CA at 7 °C (22.3%) than CA at 5 °C (12.1%). The pattern of BR incidence was similar to that for SER, the highest BR incidence in the air-stored fruit (42.7%) and lower incidence in the CA-stored fruit. There was no statistical difference in the BR incidence in fruit stored in CA at 5 °C (8.2%) or in CA at 7 °C (15.3%). The incidence of ER was between 1.0% and 1.9%, with no significant treatment differences.

VB was common in ripe fruit from all treatments, with incidences of up to 56% after 6 weeks of storage (Table 6). For fruit stored for 4 weeks, the lowest incidence of VB was in the fruit stored in CA at 5 °C (8.9%), with the incidence in air-stored and CA at 7 °C not being statistically different (23.9% and 30.9%, respectively). After 6 weeks of storage, all treatments differed statistically. The VB incidence in CA at 5 °C was still lowest (20.8%) and with higher

Table 3. Incidence of fuzzy patches (FP) and discrete patches (DP) and sum of FP+DP on 'Hass' avocado fruit after storage for 4 or 6 weeks in air at 5 °C or in a controlled atmosphere (CA) of 2% O₂/2% CO₂ at 5 °C or 7 °C. Values are the mean for three orchards; four trays each of 25 fruit per orchard.

Storage conditions		FP (%)		DP (%)		FP + DP (%)	
Atmosphere	Temperature	4 wk	6 wk	4 wk	6 wk	4 wk	6 wk
Air	5 °C	0.2	2.7	0.0	0.2	0.2	2.9
CA	5 °C	0.2	1.2	0.0	0.0	0.2	1.2
CA	7 °C	0.0	0.2	0.0	0.5	0.0	0.7
Statistical analysis: ANOVA <i>P</i> values							
Treatments		0.444	0.184		0.616	0.444	0.264

Table 4. Time taken to ripen and skin color when ripe of 'Hass' avocado fruit after storage for 4 or 6 weeks in air at 5 °C or in a controlled atmosphere (CA) of 2% O₂/2% CO₂ at 5 °C or 7 °C, followed by ripening at 20 °C. Values are the mean for three orchards; four trays each of 25 fruit per orchard.

Storage conditions		Time to ripen (d)		Skin color (0 to 100 scale)	
Atmosphere	Temperature	4 wk	6 wk	4 wk	6 wk
Air	5 °C	5.1 a	5.2 a	80.9 b	80.8 a
CA	5 °C	7.5 c	6.7 b	80.1 a	80.4 a
CA	7 °C	6.5 b	5.4 a	80.9 b	81.0 a
Statistical analysis: ANOVA <i>P</i> values					
Treatments		<0.001	<0.001	0.005	0.055

Values not sharing a common letter differ at *P* < 0.05 by Fisher Protected LSD.

Table 5. Incidence of stem end rot (SER), body rot (BR), and external rot (ER) on ripe 'Hass' avocado fruit after storage for 4 or 6 weeks in air at 5 °C or in a controlled atmosphere (CA) of 2% O₂/2% CO₂ at 5 °C or 7 °C, followed by ripening at 20 °C. Values are the mean for three orchards; four trays each of 25 fruit per orchard.

Storage conditions		SER (%)		BR (%)		ER (%)	
Atmosphere	Temperature	4 wk	6 wk	4 wk	6 wk	4 wk	6 wk
Air	5 °C	6.0 a	30.0 c	15.2 a	42.7 b	0.0	1.2 a
CA	5 °C	4.8 a	12.1 a	9.4 a	8.2 a	0.0	1.0 a
CA	7 °C	6.8 a	22.3 b	16.4 a	15.3 a	0.0	1.9 a
Statistical analysis: ANOVA <i>P</i> values							
Treatments		0.650	0.001	0.168	<0.001		0.523

Values not sharing a common letter differ at *P* < 0.05 by Fisher Protected LSD.

Table 6. Incidence of vascular browning (VB) and diffuse flesh discoloration (DFD) in ripe 'Hass' avocado fruit after storage for 4 or 6 weeks in air at 5 °C or in a controlled atmosphere (CA) of 2% O₂/2% CO₂ at 5 or 7 °C, followed by ripening at 20 °C. Values are the mean for three orchards; four trays each of 25 fruit per orchard.

Storage conditions		VB (%)		DFD (%)	
Atmosphere	Temperature	4 wk	6 wk	4 wk	6 wk
Air	5 °C	23.9 b	55.8 c	6.8 b	26.5 b
CA	5 °C	8.9 a	20.8 a	0.5 a	0.0 a
CA	7 °C	30.9 b	43.0 b	1.2 a	1.0 a
Statistical analysis: ANOVA <i>P</i> values					
Treatments		<0.001	<0.001	<0.001	<0.001

Values not sharing a common letter differ at *P* < 0.05 by Fisher Protected LSD.

incidences in air-stored (55.8%) and CA at 7 °C (43.0%) stored fruit. VB is often discussed as a physiological disorder, yet it is often found closely associated with the presence of SER. This was also found to be the case in this trial. In terms of the purpose of the trial, raising the storage temperature by 2 °C, from 5 to 7 °C, reduced the effectiveness of CA to control VB, in line with the effect on SER.

The incidence of DFD was consistently highest in the air-stored fruit after both 4 and 6 weeks of storage, with no effect of temperature on the CA stored samples of fruit (Table 6). In air-stored fruit, the incidence of DFD increased from ≈7% after 4 weeks to ≈27% after 6 weeks of storage. By contrast, there was no increase in the DFD incidence with storage time for both samples of CA-stored fruit.

DFD is often described as a CI, although more specifically it is a result of the fruit ripening at storage temperatures (Burdon et al., 2008). As such, it tends to be viewed commercially as an indication that fruit have been stored for too long. The trial results suggest that raising the storage temperature from 5 to 7 °C when in conjunction with CA had no effect on the incidence of DFD. This suggests that the fruit did not reach the point at which ripening started in storage under CA. In this respect, CA did maintain the storage life of the fruit at 7 °C compared with fruit stored in air at 5 °C.

The increased incidence of DFD when air storage was extended from 4 to 6 weeks is a reflection of the variability in time taken for the fruit to start ripening at storage temperature. This is seen in the ripening times for individual fruit at harvest being in the range 8–17 d. Low-temperature storage tends to compress this variability as the fruit ripen more rapidly when removed from storage. However, there is always some degree of variability, which is at a minimum if fruit are stored to the point just before DFD commences. Shorter periods of storage will have less effect on reducing this fruit to fruit variability, and uniformity in the ripe fruit is best achieved through ripening with ethylene.

The overall impact of raising the storage temperature from 5 °C to 7 °C for CA-stored fruit was to reduce the incidence of sound fruit; from 83% to 57% after 4 weeks of storage, and from 75% to 55% after 6 weeks. The incidence of sound fruit after 4 and 6 weeks of storage in air was 68% and 33%, respectively. The large decrease in sound fruit incidence when air storage was extended from 4 to 6 weeks contrasts with the relatively small decrease in the CA-stored fruit at the same time points. These data demonstrate the decline in fruit quality that occurs when air-storage is taken past 4 weeks and also the potential for CA to extend the storage period before quality declines markedly.

In conclusion, increasing the storage temperature from 5 to 7 °C did not markedly affect the quality of fruit immediately out of CA storage, with no significant effect on skin color, firmness, or skin disorder (DP or FP). Both CA storage temperature regimes provided better quality fruit than air storage, with the fruit having less advanced skin color and being firmer. Fruit ripening times after 4 weeks of storage suggest that CA at 7 °C was more effective than air at 5 °C for retarding the progression of ripening in storage. However, by 6 weeks of storage there was no difference in ripening times of fruit from CA at 7 °C and air at 5 °C. Also, at this time, the incidence of DFD in the air-stored fruit was high compared with that in fruit from CA at 7 °C. The main negative aspect to raising the CA storage temperature to 7 °C was the incidence of rots in the ripe fruit. While lower than in the air-stored fruit, the incidence in fruit that had been stored in CA at 7 °C was higher than that in fruit stored in CA at 5 °C. It therefore appears that the potential for using slightly higher temperatures in conjunction with CA to avoid chilling damage rests on the storage duration required and the risk of rots in the fruit.

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