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Temperature and Carbon Dioxide Interactions on Quality of Controlled Atmosphere-stored 'Empire' Apples

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Abstract**. The storage potential of 'Empire' apples [*Malus ×sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] in controlled atmosphere storage has been studied. Fruit were treated with a range of partial pressures of CO_2 (pCO_2) from 0 to 5 kPa at storage temperatures of 0, 0.5, and 3 °C. The predominant storage disorders that developed were external CO_2 injury, flesh browning (chilling injury), senescent breakdown (soft flesh browning), and core browning. All disorders except external CO_2 injury increased with longer storage periods. The incidence of external CO_2 injury was usually greater with higher storage temperature, whereas flesh browning was worst at lower storage temperatures and senescent breakdown was higher at warmer storage temperatures. The effect of storage temperature on core browning was not consistent. External CO_2 injury, flesh browning, and core browning incidences were higher with increasing pCO_2, especially above 2 kPa. Flesh firmness was lowest at warmer storage temperatures and in the absence of CO_2. Orchard to orchard variation for all factors was high. Relationships of disorders with mineral concentrations were specific to disorder and storage conditions. The results suggest that 'Empire' should be stored at 1 to 2 °C, reflecting a compromise between risk of flesh browning at 0 °C and risk of senescent breakdown and unacceptably soft fruit at 3 °C and that pCO_2 should be maintained below 2 kPa and closer to 1 kPa.**

The 'Empire' is a major apple cultivar in the northeastern United States, especially in New York, and to a lesser extent in Michigan and Ontario, Canada, that is grown for both domestic and export markets. The cultivar is also favored for its fresh-cut slice quality because of maintenance of texture and slow browning (Kim et al., 1993). Market demand for 'Empire' apples is high and the industry would like to store the fruit for at least 10 months.

A number of physiological disorders limit the storage periods in controlled atmosphere (CA) storage for 'Empire' apples. The most serious of these is a diffuse flesh browning (DeEll et al., 2007; Watkins and Nock, 2005). The disorder is similar to flesh browning as described by Meheriuk et al. (1994), in which affected tissues remain firm and juicy and the disorder is distinct from senescent breakdown. This flesh browning is assumed to be a chilling injury (CI) (Snowden, 1990). In 'Empire' apples, the disorder typically becomes apparent in May/June but sometimes earlier depending on the season. Core browning (synonym core flush) is also a firm, moist disorder of 'Empire' and other apple cultivars and distinct from senile brown core (Smock, 1977). Core browning incidence is affected by storage temperature, high partial pressures of CO_2 (pCO_2) as well as factors such as mineral nutrition (Meheriuk et al., 1994; Snowden, 1990). Another disorder of 'Empire' apples that is important to the industry is external CO_2 injury (Watkins et al., 1997), but this injury is usually prevented by treatment of fruit with diphenylamine (DPA), an antioxidant used for control of superficial scald, or by use of low pCO_2 injury in the storage atmosphere (Burmeister and Dilley, 1995; Watkins et al., 1997).

Recently, the adoption of 1-methylcyclopropene (1-MCP)-based technology by apple industries has impacted 'Empire' storage. 1-MCP-treated fruit may have higher flesh browning incidence (Watkins, 2008), although the effect of treatment can be inconsistent (DeEll et al., 2007; Watkins and Nock, 2005). The incidence of external CO_2 injury is often increased by 1-MCP treatment (DeEll et al., 2003; Fawbush et al., 2008) but, like with untreated fruit, can be controlled by DPA treatment (DeEll et al., 2005; Fawbush et al., 2008).

However, neither 1-MCP nor DPA treatment is permitted for use on organic produce. Disorder development needs to be controlled without these chemicals, and therefore understanding factors that affect the incidence of browning disorders and external CO_2 injury is important. The objective of this work was to investigate the effects of storage temperature and pCO_2 on physiological disorders of 'Empire' apples.

Materials and Methods

Fruit used in these experiments were harvested from mature 'Empire' apple trees grown at the Cornell Univ. orchard at Ithaca, NY, or in commercial orchards in western New York. Three experiments were carried out in separate years.

Expt. 1. Fruit were harvested during the optimal harvest period for CA storage from two blocks with a history of flesh browning; one, a commercial orchard block in Wolcott, Wayne County, and the other, a block at the Cornell Univ. orchard. Approximately 500 fruit were harvested from three trees in each orchard and transported to Ithaca. The fruit from each orchard were randomly divided into 33 sets of 40 fruit, which were placed into unstoppered 19-L jars. These jars were divided to provide three replicates for each of the following treatments: 0, 1, 2, 3, and 5 kPa CO_2 (in 2% O_2) at 0 °C; 0, 3, and 5 kPa at 3 °C; and 0, 3, and 5 kPa at 5 °C. Each jar of fruit was kept at the desired storage temperature overnight before being exposed to the CA treatments as described subsequently. Flesh firmness and the starch index were measured on three replicate samples of 10 fruit per orchard. Fruit were removed after 7 months of storage and transferred to a controlled temperature evaluation room at 20 °C. After 1 d, the flesh firmness of 10 fruit per replicate was assessed, and the remaining fruit were assessed for presence or absence of external and internal disorders after a further 6 d at 20 °C.

Expt. 2. Fruit from five trees in each of two commercial orchard blocks in Wayne County were harvested and divided into replicates as described for Expt. 1, except that there were 18 sets of 40 fruit. Fruit were exposed to 1, 2, and 3 kPa CO_2 (in 2 kPa O_2) at 0 and 3 °C for 8 months. After 1 d, the flesh firmness of 10 fruit per replicate was assessed, and the remaining fruit were assessed for presence or absence of external and internal disorders after a further 6 d at 20 °C.

Expt. 3. Fruit were harvested from a minimum of 10 trees in each of six commercial blocks in Niagara and Orleans Counties to provide ≈600 fruit per orchard. For each orchard, the fruit were divided into three replicates, each with 20 fruit for measurement of maturity and mineral contents and 40 fruit for each CA treatment. Each replicate set of fruit was placed into unstoppered 19-L jars and kept overnight at the respective storage temperature. The treatments were 2 and 5 kPa CO_2 (in 2 kPa O_2) at 0.5 and 3 °C. Three jars per treatment and orchard were removed after 6 and 9 months of storage and transferred to a controlled temperature evaluation room at 20 °C. After 1 d, the flesh firmness of 10 fruit

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was assessed as described previously, and the remaining fruit were assessed for presence or absence of external and internal disorders after a further 6 d at 20 °C.

Harvest indices and mineral contents. Only flesh firmness and starch indices were measured in Expts. 1 and 2. In Expt. 3, internal ethylene concentration (IEC) and mineral contents were also measured. The IEC of each fruit was measured on a 1-mL sample of internal gas withdrawn by a syringe through a hypodermic needle inserted into the core cavity using gas chromatography (Model 3700; Varian Analytical Instruments, Walnut Creek, CA). Flesh firmness was measured on opposite sides of pared fruit using an EPT-1 pressure tester (Lake City Products, Lake City, Canada) fitted with an 11.1-mm head. The starch index was determined by dipping half of each fruit in potassium–iodine solution and rating hydrolysis of starch on a scale from 1 (100% starch) to 8 (0% starch) following Blanpied and Silsby (1992). The same 20 fruit were analyzed for mineral concentrations by taking two cortical plugs from each fruit (Turner et al., 1977). After drying, the plugs were wet-ashed and concentrations of calcium, magnesium, and potassium were determined using an inductively coupled argon plasma atomic emission spectrometer at the Analytical Laboratory, Cornell University, Ithaca, NY (Francesconi et al., 1996).

Storage atmospheres. CA regimes were applied to fruit after jars were being stoppered and connected to a purpose-built atmosphere-mixing system that delivered humidified pre-mixed gas mixtures at 200 $mL \cdot min^{-1}$. Atmospheres were monitored at 1- to 2-d intervals as described by Watkins et al. (1997).

Statistical analyses. Data were subjected to analysis of variance using the general linear model to determine main effects and interactions (Release 15; Minitab, State College, PA). The least significant difference was calculated for comparison of means (P = 0.05). Pearson correlations were used to quantify the relationships among mineral concentrations and disorders at 9 months of storage for Expt. 3.

Results

Expt. 1. At harvest, the flesh firmness and starch index was 65.3 N and 4.5 units and 62.3 N and 5.2 units in Orchards 1 and 2, respectively. Overall, external CO_2 injury was much higher in fruit from Orchard 2 than Orchard 1 and at 3 and 5 °C, respectively, compared with 0 °C (P < 0.001; Fig. 1A). Injury was absent at 0 kPa CO_2 in fruit at all storage temperatures and in fruit kept at 0 °C, in which a greater number of pCO_2 were examined; injury did not occur in pCO_2 from 0 to 2 kPa.

Flesh browning was not assessed separately as firm or soft (Fig. 1B). Orchards varied greatly in response to atmosphere treatments and also interacted with storage temperature (P < 0.001). At 0 °C, flesh browning in fruit from Orchard 2 increased with pCO_2 greater than 2 kPa. At 3 °C, flesh browning was generally low except for a very high incidence at 0 kPa CO_2 for Orchard 1. At

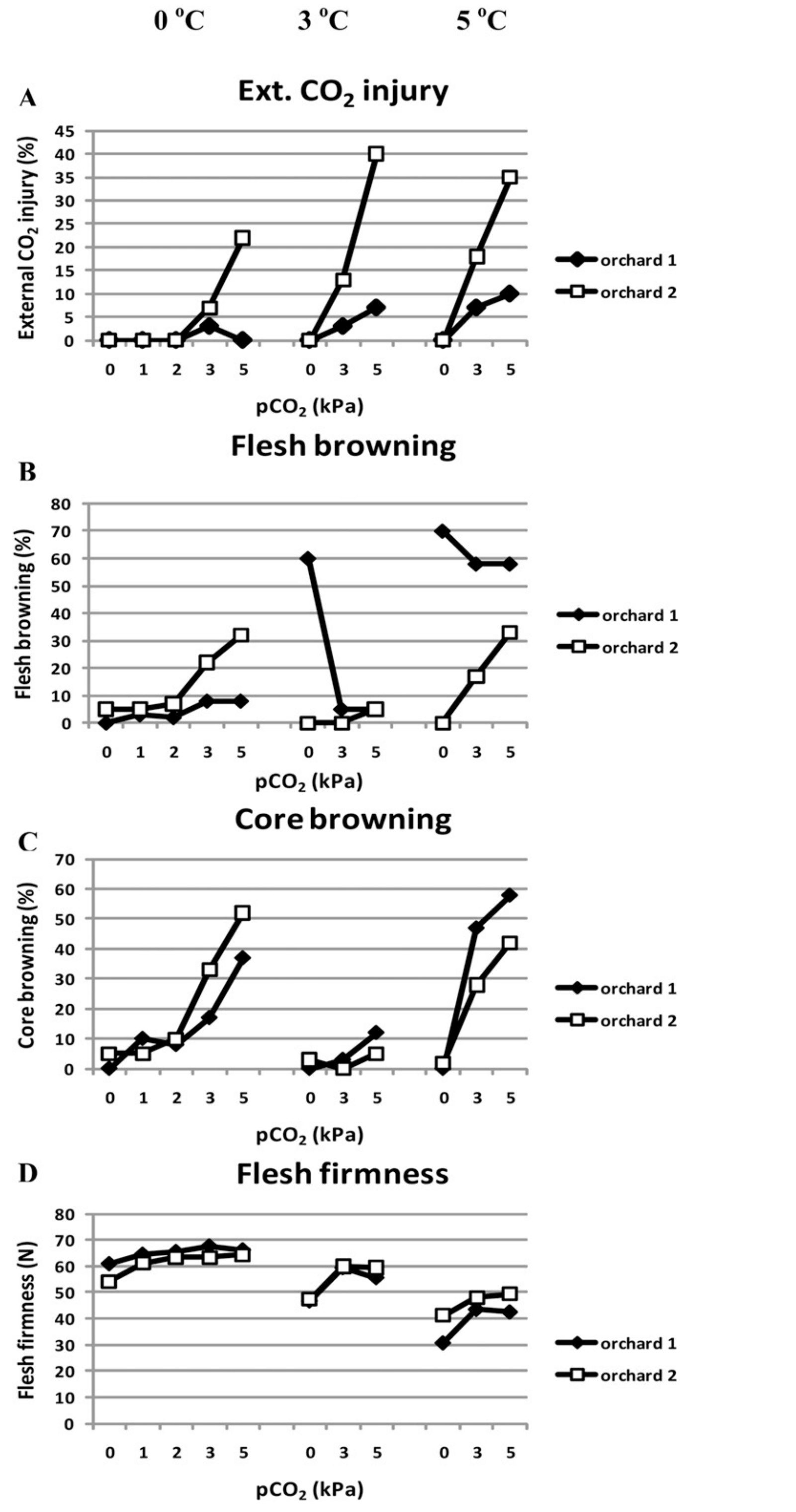

Fig. 1. (**A–D**) Percentages of external CO_2 injury, flesh browning, and core browning of 'Empire' apples stored in 0, 1, 2, 3, or 5 kPa CO_2 (in 2 kPa O_2) at 0 °C and 0, 3, or 5 kPa at 3 or 5 °C for 7 months plus 7 d in air at 20 °C. Flesh firmness (N) was assessed after 1 d at 20 °C. Least significant difference (LSD) (0.05) values for comparison of means are 10.8%, 9.4%, 8.8%, and 2.4 N for external CO_2 injury, flesh browning, core browning, and firmness, respectively.

5 °C, flesh browning increased with increasing pCO_2 in Orchard 2 but was consistently high at all pCO_2 in fruit from Orchard 1.

Core browning increased at pCO_2 greater than 2 kPa at 0 °C (Fig. 1C). Orchard block interacted with storage temperature and pCO_2 (P < 0.001); the increase in brown core incidence with increasing pCO_2 was much lower in fruit stored at 3 °C than at 0 or 5 °C. At 5 °C, some brown core may have been of the senile type.

Flesh firmness decreased with increasing storage temperature (Fig. 1D), but orchard block and pCO_2 interactions (P < 0.001) were detected. At 0 °C, fruit were slightly softer in 0 kPa CO_2 than at higher pCO_2 but only significantly so for Orchard 2, whereas fruit from both orchards were softer at 0 kPa CO_2 than in higher pCO_2 at higher storage temperatures.

Expt. 2. At harvest, the flesh firmness and starch index was 68.6 N and 4.9 units and 67.8 N and 4.8 units in Orchards 1 and 2, respectively. External CO_2 injury incidence increased at 3 kPa CO_2 from negligible levels at 1 and 2 kPa in fruit from Orchard 1 but no injury was found in fruit from Orchard 2 (Table 1).

Flesh browning was higher at 0 °C than at 3 °C, but the effect of temperature interacted with orchard and pCO_2 ($P < 0.001$; Table 1). Flesh browning was unaffected by pCO_2 at 3 °C, but at 0 °C, fruit from Orchard 1 had no injury at 1 kPa CO_2 and high levels at 2 kPa, which declined at 3 kPa. In contrast, fruit from Orchard 2 had 14% injury even at 1 kPa but higher levels at 2 and 3 kPa CO_2.

A storage temperature and pCO_2 interaction ($P < 0.001$) was detected for senescent breakdown (Table 1). Negligible injury was detected at 0 °C, whereas at 3 °C, incidence was similar in fruit stored at 1 and 2 kPa CO_2 but increased at 3 kPa CO_2.

Core browning was low at 3 °C, but at 0 °C increased at pCO_2 higher than 1 kPa (Table 1). Flesh firmness of fruit was lower at 3 °C than at 0 °C and was unaffected by pCO_2.

Expt. 3. The harvest indices of fruit from the six orchard blocks are shown in Table 2.

External CO_2 injury was unaffected by storage temperature or time (Table 3). Incidence of injury was greater in 5 kPa CO_2 than 2 kPa CO_2 ($P < 0.001$), averaging 20% and 2%, respectively. However, orchard blocks varied greatly in sensitivity to the gas ($P < 0.001$) with Blocks 1 and 3 being especially resistant to damage. The highest order interaction detected was orchard block × storage temperature × pCO_2 ($P = 0.033$).

The incidences of flesh browning, senescent breakdown, and brown core (Table 3) were each much greater after 9 months than 6 months of storage and therefore data for each removal time were assessed separately. The effects of storage temperature and pCO_2 interacted with orchard block for each disorder ($P < 0.001$).

Flesh browning was not detected in any orchard block at 3 °C after 6 or 9 months of storage. However, at 0.5 °C, injury had developed in fruit of two blocks at 2 kPa CO_2 and of three blocks at 5 kPa CO_2 by 6 months of storage and in all blocks by 9 months. Browning incidence was especially severe in fruit from Block 6, even after only 6 months of storage, and was high at both pCO_2 levels.

Senescent breakdown was not detected in any orchard block at 0.5 °C (Table 3). At 3 °C, trace amounts were found in 2 kPa CO_2, whereas it slightly more significant in 5 kPa after 6 months of storage. By 9 months, the breakdown incidence remained relatively low in fruit of all but one orchard block in 2 kPa CO_2 but increased much more markedly in 5 kPa CO_2.

Table 1. External CO_2 injury, flesh browning, senescent breakdown, and brown core (%) of 'Empire' apples stored in 1, 2, or 3 kPa CO_2 (in 2 kPa O_2) at 0 and 3 °C for 8 months plus 7 d in air at 20 °C.[z]

	0 °C			3 °C		
Orchard no.	1 kPa	2 kPa	3 kPa	1 kPa	2 kPa	3 kPa
			External CO_2 injury (%)			
1	0	0	10	2	0	16
2	0	0	0	0	0	0
$LSD_{0.05}$	4.4					
			Flesh browning (%)			
1	0	37	19	3	5	0
2	14	34	36	2	4	4
$LSD_{0.05}$	9.1					
			Senescent breakdown (%)			
1	2	0	1	9	8	16
2	0	0	0	0	5	17
$LSD_{0.05}$	6.1					
			Core browning (%)			
1	1	18	14	0	0	0
2	2	21	7	0	1	0
$LSD_{0.05}$	4.0					
			Flesh firmness (N)			
1	62.8	64.1	62.1	50.7	50.8	51.4
2	63.4	62.5	61.3	55.5	54.6	52.7
$LSD_{0.05}$	4.13					

[z]Flesh firmness (N) was assessed at 1 d at 20 °C.
LSD = least significant difference.

Table 2. Harvest indices and mineral concentrations (dry weight basis) in fruit from the six orchard blocks used in Expt. 3.

Orchard no.	IEC ($\mu L \cdot L^{-1}$)	Starch index (1–8)	Flesh firmness (N)	Calcium ($\mu g \cdot g^{-1}$)	Magnesium ($\mu g \cdot g^{-1}$)	Calcium/ magnesium	Potassium ($\mu g \cdot g^{-1}$)
1	0.129	5.9	70.2	19.48	27.95	0.70	752.3
2	0.141	6.5	73.2	19.61	30.92	0.63	851.7
3	0.192	7.5	69.8	16.37	28.73	0.57	841.3
4	0.144	6.1	72.5	17.81	30.17	0.59	972.7
5	0.114	6.4	72.2	22.77	32.74	0.70	899.0
6	0.419	6.9	72.1	17.97	29.83	0.60	853.0
Pooled SD	0.147	0.39	1.41	1.186	1.323	0.031	34.0
Significance	NS	**	NS	***	*	***	***

NS, *, **, ***Nonsignificant or significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively.
IEC = internal ethylene concentration.

Brown core incidence was detected in fruit of several orchard blocks at 6 months of storage and generally to a greater extent in 5 kPa CO_2 than in 2 kPa CO_2. However, the effects of storage temperature were not consistent at this time ($P < 0.001$). By 9 months of storage, brown core incidence was usually higher at 3 °C than at 0.5 °C and consistently higher in fruit stored in 5 kPa CO_2 than 2 kPa CO_2.

Flesh firmness was affected by orchard block, storage temperature, pCO_2, and storage period (Table 3). Overall, flesh firmness was 54.8 N at 3 °C compared with 63.6 N at 0.5 °C ($P < 0.001$), slightly softer in 5 kPa CO_2 (58.9 N) than in 2 kPa CO_2 (59.8 N) ($P < 0.001$), and 63.1 N after 6 months' storage compared with 55.3 N after 9 months of storage ($P < 0.001$). However, although the effects of storage temperature and pCO_2 each interacted with orchard block ($P < 0.001$), the effects of storage factors were much greater after 9 months than after 6 months of storage.

Overall, decay was 2% and 4% after 6 and 9 months storage, respectively ($P = 0.003$) but not consistently affected by other factors (data not shown).

Correlation analyses revealed only one relationship between external CO_2 injury and minerals, potassium at 3 °C and 2 kPa CO_2, that was also relatively weak (Table 4). No relationships were detected for firm flesh browning and brown core at 0.5 °C, whereas at 3 °C, calcium (Ca), magnesium (Mg), and Ca/Mg ratios were associated with soft flesh browning at 5 kPa CO_2 and brown core at 2 kPa CO_2.

Discussion

The three experiments reported here show that the development of external CO_2 injury, flesh browning disorders, and brown core in 'Empire' apple are affected by storage temperature and pCO_2 but that these effects are strongly influenced by orchard to orchard variation. Variation in susceptibility of disorders among orchard blocks is a commonly described phenomenon (DeEll et al., 2007; Ferguson and Watkins, 1989; Watkins et al., 1997; Wilkinson et al., 2008) but still poorly understood. Bramlage (1993) suggested that diversity of responses can be reduced to three

Table 3. External CO_2 injury, flesh browning, senescent breakdown, and brown core (%) of 'Empire' apples stored in 2 or 5 kPa CO_2 (in 2 kPa O_2) at 0.5 and 3 °C for 6 and 9 months plus 7 d in air at 20 °C.[z]

	6 months				9 months			
	0.5 °C		3 °C		0.5 °C		3 °C	
Orchard no.	2 kPa	5 kPa	2 kPa	5 kPa	2 kPa	5 kPa	2 kPa	5 kPa
				External CO_2 injury (%)				
1	0	8	0	1	0	5	0	2
2	0	28	3	32	6	30	5	43
3	0	5	0	2	0	0	0	3
4	6	30	11	36	4	33	10	36
5	0	2	0	14	1	3	0	9
6	1	51	2	36	1	48	3	44
Orchard mean	1	21	3	20	2	20	6	23
$LSD_{0.05}$	13.6							
				Flesh browning (%)				
1	0	0	0	0	9	40	0	0
2	0	11	0	0	94	86	0	0
3	0	0	0	0	44	58	0	0
4	0	0	0	0	77	78	0	0
5	3	17	0	0	48	82	0	0
6	19	52	0	0	47	90	0	0
Orchard mean	4	13	0	0	53	73	0	0
$LSD_{0.05}$	14.3							
				Senescent breakdown (%)				
1	0	0	0	0	0	0	1	4
2	0	0	0	1	0	0	11	59
3	0	0	0	4	0	0	0	33
4	0	0	0	0	0	0	3	48
5	0	0	1	13	0	0	3	71
6	0	0	1	4	0	0	1	24
Orchard mean	0	0	0	4	0	0	3	40
$LSD_{0.05}$	9.4							
				Core browning (%)				
1	0	0	0	0	0	7	18	72
2	0	8	1	1	0	40	34	94
3	0	0	4	21	0	22	10	83
4	0	0	0	2	24	39	26	86
5	3	16	0	9	6	47	57	81
6	4	22	0	3	36	73	13	79
Orchard mean	1	8	1	6	11	38	26	82
$LSD_{0.05}$	14.9							
				Flesh firmness (N)				
1	67.0	66.1	61.4	63.6	63.9	64.3	55.9	52.3
2	67.7	65.4	59.3	60.5	61.0	60.7	49.5	47.3
3	69.0	65.4	53.3	57.6	60.3	60.1	44.9	35.3
4	66.6	66.0	59.0	61.7	58.4	61.8	54.4	49.6
5	68.3	64.6	58.4	60.7	58.2	59.1	52.9	45.6
6	63.8	63.8	61.3	64.3	61.0	60.7	56.1	50.5
Orchard mean	67.1	65.2	58.8	61.4	60.9	61.4	52.3	46.8
$LSD_{0.05}$	3.57							

[z]Flesh firmness (N) was assessed at 1 d at 20 °C.
LSD = least significant difference.

factors: mineral composition at harvest, maturity/ripeness at harvest, and susceptibility to CI. Of these factors, most attention in the literature has been given to mineral concentrations, especially bitter pit and senescent breakdown (Bramlage, 1993; Ferguson and Watkins, 1989; Ferguson et al., 1993). Correlation analyses between storage disorders of 'Empire' apples and major minerals reveal few strong relationships (Table 4) and none for external CO_2 injury and flesh browning. Lau and Looney (1978) found an association of low potassium and Mg, but not Ca, with external CO_2 injury, whereas De Castro et al. (2007a) found inconsistent relationships between Ca, Mg, and boron and CO_2-induced flesh browning over several years. In general, relations between any disorder and mineral concentrations are characterized by considerable variation in disorder incidence among orchards at any give mineral concentration.

An interesting feature of the current study is that the relationships identified for senescent breakdown and brown core were specific to storage temperature and atmosphere (Table 4), suggesting that the applicability of mineral-based prediction models may not be easily applied to industries in which a variety of storage temperatures and atmospheres are used within a growing region, as commonly occurs commercially. Prediction models for development of physiological disorders based on mineral concentrations such as bitter pit (Ferguson and Watkins, 1989) and senescent breakdown (Bramlage et al., 1985) have been restricted to air storage. An additional feature of note is that the susceptibility of the disorders in 'Empire' apples is not consistent within fruit from a single block. For example, fruit susceptible to external CO_2 injury are not uniformly susceptible to flesh browning or core browning. Thus, mineral prediction systems would be specific not only to disorder, but also to storage temperature and atmosphere.

Regardless of the source of variation, recommendations for storage temperature and atmosphere regimens should result in minimal losses of fruit attributable to disorders. For external CO_2 injury, not surprisingly, increasing pCO_2 results in higher disorder incidence (Fig. 1; Tables 1 and 3), as shown earlier (Burmeister and Dilley, 1995; Fawbush et al., 2008; Watkins et al., 1997). Also, damage occurs early in the storage period and does not progress with increasing storage time (Table 3; Burmeister and Dilley, 1995; Fawbush et al., 2008). However, in contrast to Burmeister and Dilley (1995), who found that external CO_2 injury was higher at 0 °C than at 3 °C, injury in the current study was either unaffected (Table 3) or higher as storage temperatures increased (Fig. 1; Table 1). Overall, the data suggest that 'Empire' apples should be stored at 1 or 2 kPa CO_2 to minimize disorder risk because injury in susceptible fruit increased at 3 kPa CO_2, especially earlier in the storage period when susceptibility of fruit to injury is highest (Fawbush et al., 2008; Watkins et al., 1997). Maintaining low pCO_2 in the storage atmosphere is critical if DPA is not used to eliminate risk of external CO_2 injury (Burmeister and Dilley, 1995; DeEll et al., 2007; Fawbush et al., 2008; Watkins et al., 1997).

The effects of treatment on flesh browning are more complex. In fruit from Orchard 1, flesh browning (CI and senescent breakdown) increased slightly with increasing pCO_2 at 0 °C but at 3 °C was very high in the absence of CO_2 and at 5 °C was high at all pCO_2 (Fig. 1). In contrast, flesh browning incidence of Orchard 2 fruit increased with increasing pCO_2, but to a much greater extent at 0 and 5 °C than at 3 °C. In subsequent experiments, a clear distinction between much higher incidences of flesh browning at 0 or 0.5 °C and senescent breakdown at 3 °C was apparent (Tables 1 and 3). At 0 °C, flesh browning was higher at 2 and 3 kPa CO_2 than at 1 kPa CO_2, but significant injury was found even at 1 kPa CO_2 in fruit from Orchard 2 (Table 1). In Expt. 3 in which a larger number of orchards was assessed (Table 3), the incidence of flesh browning at 0.5 °C was much lower with 2 kPa CO_2 than 5 kPa CO_2. However, a high incidence was found in one orchard (Orchard 6) after only 6 months of CA storage, and by 9 months, incidence of flesh browning was unacceptably high even at 2 kPa CO_2.

Flesh browning has been an ongoing concern for several cultivars. In 'Delicious', a parent of 'Empire' (Derkacz et al., 1993), flesh browning can be reduced by early harvest and higher storage temperatures (Meheriuk et al., 1984). Meheriuk et al. (1984) also

Table 4. Pearson correlations among mineral concentrations and physiological disorders of 'Empire' apples after storage in 2 or 5 kPa CO_2 in 2 kPa O_2 at 0.5 and 3 °C for 9 months plus 7 d in air at 20 °C.

Storage temp. (°C)	pCO_2 (kPa)	Mineral	External CO_2 injury	Flesh browning	Senescent breakdown (%)	Brown core (%)
0.5	2	Ca	0.177 NS	0.366 NS	—	–0.240 NS
		Mg	0.233 NS	0.187 NS	—	–0.150 NS
		Ca/Mg	0.087 NS	0.414 NS	—	–0.247 NS
		K	0.182 NS	–0.014 NS	—	–0.111 NS
0.5	5	Ca	–0.212 NS	0.080 NS	—	0.051 NS
		Mg	0.291 NS	0.401 NS	—	0.385 NS
		Ca/Mg	–0.334 NS	–0.424 NS	—	–0.228 NS
		K	0.210 NS	0.442 NS	—	0.362 NS
3	2	Ca	–0.295 NS	—	0.276 NS	0.717***
		Mg	–0.078 NS	—	0.378 NS	0.584*
		Ca/Mg	–0.335 NS	—	0.102 NS	0.517*
		K	0.458*	—	0.128 NS	0.288 NS
3	5	Ca	0.151 NS	—	0.669***	0.312 NS
		Mg	0.123NS	—	0.530*	0.157 NS
		Ca/Mg	0.143NS	—	0.632**	0.365 NS
		K	–0.072NS	—	–0.173 NS	0.103 NS

NS, *, **, ***Nonsignificant or significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively.
Ca = calcium; Mg = magnesium; K = potassium.

found that flesh browning could be reduced by decreasing the pCO_2 to less than 1 kPa at –0.5 °C but not at 2 °C. More recently, De Castro et al. (2007a, 2007b) described a CO_2-induced flesh browning that occurs within as little as 2 months of harvest and that could be eliminated by postharvest DPA treatment. The browning in 'Empire' apples appears more similar to that of 'Delicious' in that the disorder develops over longer storage periods. Although pCO_2 is clearly involved (Fig. 1; Tables 1 and 3), it appears that as suggested by Meheriuk et al. (1984) for 'Delicious', high storage temperatures have the predominant role in arresting the disorder. Additional evidence that flesh browning in 'Empire' apples is not directly CO_2-related may be the absence of effects on the disorder by DPA treatment (unpublished data).

The effects of treatment on core browning incidence were not consistent across experiments. Core browning incidence was similar to that found for firm flesh browning in Expts. 1 and 2 with generally lower injury at 3 °C than either lower or higher storage temperatures and with increasing pCO_2 (Fig. 1; Table 1). However, in Expt. 3, the incidence of core browning was much higher at 3 °C than at 0.5 °C, although the effect of pCO_2 was consistent. The reason for these differences is unclear. Like with flesh browning, maintaining low pCO_2 in the storage atmosphere has been recommended as one strategy to reduce disorder incidence (Meheriuk et al., 1994).

Senescent breakdown was much higher at 3 °C than lower storage temperatures, and incidence was generally higher with increasing pCO_2 (Tables 1 and 3) and longer storage periods (Table 3). In addition, flesh firmness of fruit is lower with increasing storage temperature (Fig. 1; Table 1), especially as storage length increases (Table 3). Thus, there is an apparent tradeoff between development of low temperature-related disorders at storage temperatures close to 0 °C and senescent disorders at warmer storage temperatures, and occurrence of these disorders is further affected by pCO_2. Current recommendations for storage of 'Empire' are for 1 to 2 °C (Watkins, 2003), reflecting a compromise between risk of CI at 0 °C and risk of senescent breakdown and unacceptably soft fruit at 3 °C. pCO_2 should be maintained below 2 kPa and closer to 1 kPa, the importance of maintaining low partial pressures increasing with longer storage periods. Fruit with a known risk of disorder development should not be stored in CA.

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