Factors and Time of Sample Collection for Correlating Storage Potential of ‘McIntosh’, ‘Spartan’, and ‘Golden Delicious’ Apples

William D. Wolk¹ and O.L. Lau

Okanagan Federated Shippers Association, Kelowna, BC, V1Y 3H5, Canada

G.H. Neilsen and Brian G. Drought

Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, BC, V0H 1Z0, Canada

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ABSTRACT. A study was undertaken to identify key factors associated with storage disorders in three commercially important apple cultivars in British Columbia and to determine how early in the season associations could be measured. Fruit mass, density, and concentrations of N, P, K, Ca, Mg, and dry matter were determined for ‘McIntosh’, ‘Spartan’, and ‘Golden Delicious’ apples (*Malus ×domestica* Borkh) from ≈30 commercial orchards 9, 6, 3, and 0 weeks before harvest. Storage samples were collected at commercial harvest and evaluated for the development of internal breakdown (‘McIntosh’ and ‘Spartan’) or bitter pit (‘Golden Delicious’) after 4 and 6 months of 0 °C air storage. Mass and [Ca] and the mass/[Ca] and [K]/[Ca] ratios were the factors most often significantly correlated with storage disorders within each year for all three cultivars. Correlations were as frequently significant 6 and 3 weeks before harvest as they were at harvest. Mass of ‘McIntosh’ and ‘Spartan’ was the only variable consistently related with breakdown in all 3 years of the study. There were no variables with a consistent relationship to bitter pit in ‘Golden Delicious’. Fruit [Ca] was associated with the relative levels of disorders within years but could not be associated with specific levels of disorders across all years.

The ability to predict the storage potential of apples accurately could be used commercially to reduce storage losses and increase fruit quality in the marketplace. The value of storage potential predictions would be maximized if they could be made well in advance of harvest. Relationships between fruit mineral concentrations and internal breakdown and bitter pit in apples during storage have long been recognized. Minerals associated with these disorders include Ca (Bramlage et al., 1985; Delong, 1937; Lidster et al., 1975; Perring, 1968), Mg (Sharples, 1968), K (Lidster et al., 1975), N (Faust and Shear, 1968; Perring 1976; Wills and Scott, 1976), and P (Perring, 1968). In addition to fruit minerals, Lidster et al. (1975) found a positive relationship between fruit size and breakdown in ‘Spartan’ apples that was independent of the effect of fruit size on [Ca]. The question remains whether reliable storage potential predictions can be based on nutrient analyses of midseason fruit samples. Bramlage et al. (1985) determined that breakdown in Massachusetts-grown ‘McIntosh’ could be predicted with multiple regression equations using fruit Ca, K, P, Mg, and N concentrations measured 2 weeks before harvest. Johnson et al. (1987) concluded that bitter pit in ‘Cox’s Orange Pippin’ grown in the U.K. could not be reliably correlated with [Ca] measured earlier than late August. Marmo et al. (1985) found that regression equations based on fruit size and [Ca] predicted breakdown in ‘McIntosh’ apples more accurately than equations based on [Ca] alone when size was a significant variable.

Regression equations predicting breakdown are unique for each

cultivar and, probably, growing region (Autio et al., 1986). It would follow that predicting storage potential of apples might be more successful for some cultivars and in some geographical areas than in others. Likewise, prediction equations developed from midseason fruit samples may be more effective in some growing regions than others. The present study was undertaken to determine which of several fruit parameters are significantly correlated with internal breakdown in ‘McIntosh’ and ‘Spartan’ and bitter pit in ‘Golden Delicious’ apples grown in the southern interior of British Columbia and to determine how early in the growing season significant correlations exist.

Materials and Methods

FRUIT SAMPLING. Thirty commercial ‘McIntosh’, ‘Spartan’, and ‘Golden Delicious’ orchards were sampled four times in each of three seasons, 1989 to 1991. The blocks selected represented a wide range of planting systems, rootstocks, and orchard management practices. A 30-fruit sample taken from all sections of each tree was collected from each orchard 9, 6, and 3 weeks before and at commercial harvest. The number of orchards sampled at harvest for mineral analysis and storage varied from 23 to 27 due to early harvest by some orchard operators or, in a small number of cases, severe hail damage. At least three trees were sampled in each orchard. The maximum number of trees sampled was determined by crop load so that no more than 20% of a tree’s total crop was removed by sampling before harvest. Sample size was reduced to 25 in the laboratory by removing excessively large and small fruit. The sample was then weighed and its density was determined by water displacement. Fruit were rinsed under distilled water and allowed to air dry.

SAMPLE PREPARATION AND ANALYSIS. Early in the season, whole fruit were used for mineral analysis. Later, when a sample’s mean fruit mass exceeded 72 g, opposite sectors were used. After removal of stems and seeds, the samples were blended for 2 min at high speed in a 4-L commercial blender with 1.5 times their mass

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of distilled water. A 225-mL subsample was then homogenized for 30 s with a tissue homogenizer. Three 3-mL slurry aliquots were combined and oven dried at 95 °C for 60 h. Dried samples were digested in 5.4 mL H₂SO₄ containing 0.67 g·L⁻¹ Se, 0.36 mL of 1.0 mol·L⁻¹ CuSO₄·5H₂O, and 1.8 g of Na₂SO₄ (digestion method provided by D.G. Jones, ADAS, Ministry of Agriculture Fisheries and Food, U.K.). Concentrations of Ca, Mg, and K were determined by atomic absorption spectrophotometry and [N] and [P] were determined colorimetrically with an autoanalyzer (Technicon Autoanalyzer II Industrial Methods no. 334-74A/A). Magnesium data were not collected in 1989. Mineral data were calculated on a mg·kg⁻¹ fresh mass basis. Dry matter concentration was determined after drying 6 mL of the homogenized slurry at 65 °C for 120 h in an 8-mL polystyrene weighing vial.

STORAGE TREATMENTS. A 130-fruit sample was collected from each orchard at a maturity status recommended for long-term storage (Lau, 1985). Twenty fruit were evaluated for maturity and firmness at harvest. Fifty fruit were evaluated for firmness and for the development of storage disorders (Lau, 1983) after 4 and 6 months of 0 °C air storage plus 7 d at 20 °C.

DATA ANALYSIS. Data were analyzed by linear correlation using the independent variables fruit mass; density; concentrations of dry matter, N, P, Ca, Mg, and K; and the ratios [K]/[Ca], mass/[Ca], and [Mg]/[Ca]. The dependent variables were percentage of internal breakdown for 'McIntosh' and 'Spartan' and percentage of bitter pit for 'Golden Delicious' after 4 and 6 months of 0 °C air storage. Correlations were calculated for each treatment-sampling time combination and reported within each year.

Results

An analysis of variance indicated significant year × variable interactions at a number of sampling times for many independent variables. Thus, data are reported separately for each year.

On average, mineral concentrations declined during the 9-week period before harvest in each season (Table 1). Except for [K], year-to-year differences in the mean concentration of a mineral for a given cultivar at a specific sampling period were greater earlier in the season and least at harvest. Potassium concentrations declined more linearly than other minerals so that between-year differences in [K] were similar at all sampling times. Fruit [N], [P], and [K] were generally lower at all sampling periods in 1989 than in 1990 and 1991. Preharvest [Ca] was lower for all cultivars in 1989 than in 1990 and 1991. However, 1989 harvest [Ca] values were either similar to ('McIntosh') or slightly greater than ('Golden Delicious' and 'Spartan') harvest values in 1990 and 1991.

The storage potential of the 'McIntosh' and 'Spartan' crops varied from year to year. In 1989, >8% of 'McIntosh' and 'Spartan' fruit had developed internal breakdown after 4 months of storage (Table 2). More than 17% of the fruit had developed the disorder after 6 months of storage. The incidence of breakdown for the same two cultivars was <4% at all 1990 evaluations. In 1991, <3% of 'McIntosh' and 'Spartan' fruit had developed breakdown after 4 months of storage. However, after 6 months of storage the incidence of breakdown had increased substantially to >7%. Thus, on a relative basis, storage potentials of the 'McIntosh' and 'Spartan' crops could be characterized as low in 1989, high in 1990, and moderate in 1991. The

Table 1. Mean fruit mass and N, P, Ca, K, and Mg concentrations² (fresh mass basis) of 'McIntosh', 'Spartan', and 'Golden Delicious' apples measured 9, 6, 3, and 0 weeks before harvest in 1989, 1990, and 1991. Standard errors are in parentheses below their respective means.

Cultivar	Weeks		Fruit			Concn (mg·kg ⁻¹ fresh mass)													
	before harvest	mass (g)				N			P			Ca			K			Mg ³	
			1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991	1990	1991
McIntosh	9	61	47	38	590	750	700	122	134	154	69	97	113	1210	1290	1540	68	85	
		(3)	(2)	(2)	(20)	(40)	(20)	(3)	(3)	(5)	(3)	(4)	(4)	(20)	(20)	(20)	(2)	(2)	
		107	82	76	430	520	450	106	111	115	53	70	69	1140	1210	1350	59	65	
	6	(3)	(3)	(3)	(10)	(20)	(20)	(3)	(3)	(3)	(2)	(3)	(2)	(20)	(20)	(20)	(2)	(1)	
		157	126	115	330	380	340	98	101	101	46	52	51	1040	1150	1270	52	58	
		(4)	(3)	(5)	(10)	(10)	(10)	(3)	(3)	(3)	(2)	(3)	(2)	(20)	(20)	(20)	(1)	(1)	
	3	201	160	152	280	320	280	94	94	97	40	41	41	990	1040	1200	47	54	
		(4)	(3)	(5)	(10)	(10)	(10)	(3)	(3)	(3)	(2)	(2)	(2)	(20)	(20)	(30)	(1)	(1)	
		Spartan	9	70	47	47	710	850	780	123	134	145	80	121	118	1350	1570	1690	82
	(2)			(2)	(2)	(20)	(30)	(30)	(3)	(3)	(4)	(3)	(6)	(7)	(20)	(30)	(30)	(3)	(2)
	113			81	85	540	610	500	112	121	115	61	80	77	1290	1520	1590	67	69
	6		(3)	(3)	(3)	(20)	(20)	(20)	(3)	(3)	(4)	(2)	(4)	(3)	(20)	(30)	(30)	(2)	(1)
159			117	119	410	450	380	99	108	105	52	66	57	1200	1390	1530	59	61	
(3)			(4)	(4)	(20)	(20)	(20)	(3)	(3)	(4)	(2)	(2)	(2)	(20)	(20)	(50)	(1)	(2)	
3	192		147	154	350	370	310	97	98	100	49	46	47	1170	1310	1500	50	55	
	(5)		(5)	(5)	(20)	(10)	(10)	(4)	(3)	(4)	(2)	(2)	(2)	(30)	(30)	(40)	(1)	(1)	
	Golden Delicious		9	55	45	39	700	850	890	124	138	174	85	114	123	1410	1610	1890	77
(2)				(1)	(2)	(30)	(40)	(50)	(3)	(5)	(8)	(3)	(5)	(6)	(20)	(30)	(40)	(20)	(4)
100				87	75	500	600	550	11	116	116	65	78	74	1250	1450	1560	64	70
6			(2)	(2)	(3)	(20)	(30)	(20)	(3)	(4)	(4)	(2)	(3)	(3)	(20)	(30)	(30)	(2)	(2)
		144	131	122	390	440	390	91	102	95	59	58	55	1110	1320	1400	54	59	
		(3)	(3)	(4)	(10)	(20)	(10)	(3)	(4)	(3)	(1)	(2)	(2)	(30)	(20)	(20)	(1)	(1)	
3		199	174	172	320	360	320	84	94	91	49	42	41	1050	1220	1310	47	53	
		(4)	(4)	(5)	(10)	(20)	(10)	(3)	(3)	(3)	(2)	(2)	(1)	(20)	(20)	(30)	(1)	(1)	

²Whole fruit were used for samples with mean fruit mass ≤72 g. Opposite fruit sectors were used for samples with mean fruit mass >72g.

³Magnesium data were not collected in 1989.

Table 3. Correlation coefficients relating concentrations of fruit Ca and K, fruit mass, [K]/[Ca], and mass/[Ca] with percentage breakdown in 'McIntosh' and 'Spartan' and percentage bitter pit in 'Golden Delicious' apples. Minerals and mass were measured 9, 6, 3, and 0 weeks before harvest. Storage disorders were determined after 4 and 6 months of 0 °C air storage plus 7 d at 20 °C. Data are for the 1989, 1990, and 1991 crop years.

Variable	Weeks before harvest	McIntosh (n = 23) Breakdown		Spartan (n = 27) Breakdown		Golden Delicious (n = 27) Bitter pit	
		4 months	6 months	4 months	6 months	4 months	6 months
		1989					
[Ca]	9	-0.25	-0.05	-0.50**	-0.34	-0.55***	0.00
	6	-0.69***	-0.49*	-0.69***	-0.42*	-0.55**	-0.17
	3	-0.63**	-0.35*	-0.46*	-0.36	-0.48***	0.07
	0	-0.35	-0.37	-0.44*	-0.37*	-0.45*	-0.34
[K]	9	0.29	0.29	0.17	0.27	-0.18	0.23
	6	0.21	0.15	0.31	0.34	-0.04	-0.07
	3	0.45*	0.36	0.53**	0.46*	0.09	0.01
	0	0.14	0.21	0.51**	0.67***	0.26	0.01
Mass	9	0.11	-0.10	0.41*	0.43*	0.50**	0.19
	6	0.25	0.16	0.47*	0.35	0.49**	0.14
	3	0.51*	0.41*	0.46*	0.57**	0.46*	0.04
	0	0.65***	0.49*	0.41*	0.40*	0.26	0.07
[K]/[Ca]	9	0.35	0.15	0.55**	0.43*	0.56**	0.05
	6	0.76***	0.59**	0.78***	0.52**	0.53**	0.10
	3	0.68***	0.41*	0.64***	0.52**	0.39*	0.07
	0	0.43	0.47*	0.61***	0.61***	0.54**	0.29
Mass/[Ca]	9	0.19	-0.04	0.57***	0.45*	0.67***	0.05
	6	0.61**	0.45*	0.71***	0.43*	0.68***	0.15
	3	0.70***	0.45*	0.55**	0.54**	0.64***	0.10
	0	0.55**	0.50*	0.62***	0.48**	0.60***	0.37*
1990							
[Ca]	9	-0.37	-0.27	-0.44*	-0.28	-0.13	-0.02
	6	-0.42*	-0.25	-0.43*	-0.36	-0.30	-0.07
	3	-0.41*	-0.33	-0.44*	-0.20	-0.27	-0.03
	0	-0.41*	-0.31	-0.33	-0.27	-0.39*	-0.05
[K]	9	-0.03	-0.21	0.20	0.17	-0.04	0.11
	6	0.01	-0.26	0.31	0.17	-0.04	-0.15
	3	0.10	0.01	0.35	0.33	-0.10	0.45*
	0	0.27	0.06	0.53**	0.63***	0.05	-0.23
Mass	9	0.17	0.23	0.63***	0.16	-0.04	0.07
	6	0.25	0.22	0.65***	0.24	0.01	0.08
	3	0.24	0.19	0.64***	0.29	-0.24	0.11
	0	0.25	0.19	0.65***	0.22	-0.37*	-0.12
[K]/[Ca]	9	0.36	0.18	0.57**	0.36	0.13	0.05
	6	0.39*	0.18	0.59***	0.41*	0.34	-0.04
	3	0.41*	0.30	0.56**	0.26	0.28	-0.18
	0	0.39*	0.28	0.55**	0.54**	0.39*	-0.04
Mass/[Ca]	9	0.24	0.22	0.61***	0.20	0.08	-0.20
	6	0.41*	0.30	0.62***	0.29	0.24	0.05
	3	0.43*	0.34	0.64***	0.24	0.23	0.04
	0	0.39*	0.35	0.61***	0.30	0.17	0.02
1991							
[Ca]	9	-0.42*	-0.49*	-0.36	-0.42*	-0.38*	-0.23
	6	-0.37	-0.30	-0.57***	-0.65***	-0.40*	-0.17
	3	-0.41*	-0.36	-0.56***	-0.58**	-0.38*	-0.31
	0	-0.34	-0.20	-0.52***	-0.67***	-0.35	-0.24
[K]	9	-0.05	-0.26	0.13	0.19	-0.01	-0.09
	6	0.19	0.05	0.34	0.43*	0.12	-0.17
	3	0.26	0.22	0.22	0.29	0.21	-0.10
	0	0.19	0.01	0.33	0.27	0.29	-0.06
Mass	9	0.27	0.37	0.14	0.18	0.38*	0.30
	6	0.36	0.24	0.25	0.33	0.41*	0.24
	3	0.34	0.29	0.21	0.29	0.38*	0.25
	0	0.49**	0.27	0.30	0.26	0.25	0.25
[K]/[Ca]	9	0.42*	0.35	0.46*	0.53**	0.65***	0.36
	6	0.48*	0.25	0.68***	0.78***	0.67***	0.17
	3	0.50**	0.37	0.66***	0.71***	0.55**	0.31
	0	0.43*	0.13	0.61***	0.74***	0.45*	0.15
Mass/[Ca]	9	0.33	0.34	0.31	0.32	0.52**	0.35
	6	0.39*	0.23	0.57**	0.65***	0.58***	0.26
	3	0.42*	0.31	0.52**	0.59**	0.50**	0.36
	0	0.52**	0.25	0.56**	0.69***	0.39*	0.29

, **, *, * Significant at $p < 0.05$, 0.01, 0.001, or 0.0001.

Table 2. Mean percentage of 'McIntosh' and 'Spartan' fruit with internal breakdown and 'Golden Delicious' with bitter pit in 1989, 1990, and 1991. Standard errors are in parentheses below their respective means. Fruit were evaluated at harvest and after 4 and 6 months of 0 °C air storage plus 7 d at 20 °C.

Sampling time	McIntosh			Spartan			Golden Delicious		
	1989	1990	1991	1989	1990	1991	1989	1990	1991
	(n = 23)	(n = 26)	(n = 24)	(n = 27)	(n = 26)	(n = 27)	(n = 27)	(n = 27)	(n = 27)
	Breakdown (%)			Breakdown (%)			Bitter pit (%)		
At harvest	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
After 4 months storage	11.0 (1.9)	1.0 (0.3)	1.4 (0.6)	8.7 (1.7)	1.2 (0.5)	2.3 (0.8)	0.8 (0.3)	0.2 (0.1)	2.0 (1.2)
After 6 months storage	21.8 (2.9)	3.1 (0.9)	13.1 (3.6)	17.8 (4.0)	1.4 (0.6)	7.2 (3.2)	1.9 (0.8)	1.0 (0.3)	0.8 (0.4)

incidence of bitter pit in the three 'Golden Delicious' crops never exceeded 2% (Table 2) and therefore its storage potential could be considered high in each year of the study.

FRUIT [Ca]. Overall, fruit [Ca] was the individual variable having the greatest number of significant correlations with storage disorders. Absolute values of correlation coefficients for fruit [Ca] with designated storage disorders after 4 months of storage were as great or greater for samples collected 6 and 3 weeks before harvest than for samples collected at harvest, except for 1990 'Golden Delicious' (Table 3). Absolute values of correlation coefficients for samples collected 9 weeks before harvest tended to be lower and not as frequently significant as for samples collected later in the growing season. For 6-month storage samples, no sampling time was consistently better for relating [Ca] to storage disorders.

FRUIT [K]. In 1989 and 1990, fruit [K] at harvest was significantly correlated with breakdown in 'Spartan' after 4 and 6 months of storage (Table 3). Correlations of [K] with storage disorders were rarely significant and were generally without sampling period trends for 'McIntosh' and 'Golden Delicious'.

FRUIT [K]/[Ca]. Although fruit [K] was not generally highly correlated with storage disorders, correlations of the [K]/[Ca] ratio with storage disorders were frequently significant, especially for 'Spartan'. The absolute values of correlation coefficients for [K]/[Ca] after 4 months of storage were greater than either of the coefficients for [K] or [Ca] alone in 58%, 100%, and 67% of the times for 'McIntosh', 'Spartan', and 'Golden Delicious', respectively. In general, absolute values of correlation coefficients for [K]/[Ca] were greater than correlation coefficients for the reciprocal [Ca]/[K] values (data not shown).

FRUIT MASS. Fruit mass was considerably greater in 1989 than in 1990 and 1991 for all three cultivars at all sampling times (Table 1). Correlations of storage disorders with fruit mass in individual years were less frequently significant than those with [Ca] (Table 3). Although relationships for many variables with storage disorders differed from year to year, there were no significant year $\times$ mass interactions for 'Spartan' at any sampling period or for 'McIntosh' at 9 and 6 weeks before and at harvest.

MASS/[Ca]. Correlations of the mass/[Ca] ratio with storage disorders for fruit stored 4 months were consistently significant for samples collected from 6 weeks before harvest through harvest, except for 'Golden Delicious' in 1990. Absolute values of correlation coefficients for the reciprocal [Ca]/mass values were generally not as great as those for mass/[Ca] (data not shown).

OTHER VARIABLES. No Mg data were collected in 1989. In 1990 and 1991, correlations with [Mg] were rarely significant (data not shown). In 1990, correlation coefficients for correlations of [Mg]/[Ca] with bitter pit in 'Golden Delicious' after 4 months of storage were positive and similar in absolute value to coefficients for [Ca]

alone (data not shown). In 1991, however, correlation coefficients for [Mg]/[Ca] and bitter pit in 'Golden Delicious' at 4 months of storage were greater in absolute value than [Ca] alone; 0.57**, 0.56**, 0.54**, and 0.42* for 9-, 6-, 3-, and 0-week samples, respectively.

In general, correlations of [N] and [P] with disorders were rarely significant and without sampling period trends for all three cultivars (data not shown). Moreover, signs of correlation coefficients, positive or negative, for [N] and [P] were not consistent between or within sampling periods, storage treatments, or years.

Correlations of fruit density and the concentration of dry matter with storage disorders were not consistently either positive or negative and were rarely significant (data not shown). In all cases where correlations with density were significant the relationship was negative.

Discussion

Previous work has indicated that correlations of fruit mineral concentrations with storage potential are greatest when minerals are measured at harvest (Bramlage et al., 1985; Johnson et al., 1987). The primary concern in using preharvest mineral concentrations for storage potential prediction models has been the extent to which early or midseason concentrations are correlated with harvest mineral concentrations. Abrupt changes in growing conditions between the time of fruitlet analysis and harvest or growing seasons with uncharacteristic precipitation or temperatures could shift the pattern of fruit mineral accumulation (Wilkinson, 1968; Perring, 1979) and thereby increase the possibility of error in storage potential predictions using models that are based on past years' data.

The tree fruit production region in the southern interior of British Columbia has a semi-arid, temperate climate, with mean maximum July and August temperatures of 27 to 30 °C and an average rainfall of <50 mm during the 6-week period before harvest. The second half of the growing season tends to be consistently warm and dry with a high percentage of possible sunlight. Almost all water is applied through irrigation. Part of the rationale for this study was that the consistency of temperature, water supply, and light would minimize the potential for large changes in patterns of mineral accumulation within and between seasons so that midseason mineral concentrations would be highly enough correlated with harvest mineral concentrations and, thus, storage potential, to be reliable for use in prediction models.

The relationship between mass and breakdown after 4 months of storage in 'McIntosh' and 'Spartan' was the same in each year of the study based on the lack of significant mass $\times$ year interactions with the single exception of 'McIntosh' 3 weeks before harvest. Mass was the only independent variable with such a consistent relationship with breakdown. Larger 'McIntosh' and

'Spartan' fruit consistently developed higher levels of breakdown in storage than smaller fruit. Overall, 1989 was a large-fruit year and levels of disorders were higher than in the smaller-fruit years of 1990 and 1991. When 3 years' 'McIntosh' and 'Spartan' mass and breakdown data were combined for sampling periods for which there were no significant mass $\times$ year interactions, all correlations between mass and breakdown were significant at $P < 0.0001$ (data not shown). Fruit size has previously been significantly correlated with breakdown in 'McIntosh' (Marmo et al., 1985) and 'Spartan' (Lidster et al., 1975) based on one season's data. Our study indicates that the relationship is consistent from season to season even when mean fruit size varies considerably between years and that the relationship can be measured as early as 9 weeks before harvest.

Within each year for a given cultivar, samples with lower [Ca] developed higher levels of storage disorders. Unlike fruit mass, however, the relationships between [Ca] and breakdown and bitter pit were not consistent from year to year, as indicated by frequent significant [Ca] $\times$ year interactions. For example, the mean incidence of breakdown in 'McIntosh' and 'Spartan' after 4 months of storage was substantially greater in 1989 than in either 1990 or 1991, even though [Ca] at harvest in 1989 was similar to ('McIntosh') or greater than ('Spartan') harvest [Ca] in the subsequent 2 years. Therefore, while [Ca] could be associated with relative levels of storage disorders within each year, 3 years' [Ca] values could not be combined and correlated with specific levels of disorders.

Overall, in orchards representing a wide range of soil types, rootstocks, and planting systems, correlations of [Ca], fruit mass, [K]/[Ca], and mass/[Ca] measured 6 and 3 weeks before harvest were generally as great or greater than correlations at harvest within each year of the study. This occurred even though, in 2 of the 3 years, weather patterns deviated substantially from normal during fruitlet sampling periods. Precipitation in July through September 1989 was 56% greater than the long-term mean for that period (Drought and Stretch, 1992) and, in 1990, extreme heat from late August through the end of September coincided with a net loss of fruit Ca in many blocks. Thus, for a cultivar within a given year, the storage potential of the fruit from one orchard block could be estimated relative to the storage potentials from a range of orchard blocks as early as 6 weeks before harvest using [Ca], fruit mass, [K]/[Ca], and mass/[Ca]. However, the lack of year-to-year consistency in the relationship of fruit mineral concentrations with storage disorders suggests that models based on past years' mineral data are not feasible for predicting absolute levels of disorders with current year's data. Models predicting breakdown in 'McIntosh' and 'Spartan' could be derived using cumulative years' mass data collected as early as 9 weeks before harvest. Although prediction models could not be based on mineral data, it was noted that for each cultivar at a given sampling period there was a minimum [Ca] value approximately the same in each year above which no disorders developed after 4 months of storage. For example, at 6 weeks before harvest, these values were 85, 100, and 95 mg·kg⁻¹ fresh mass for 'McIntosh', 'Spartan', and 'Golden Delicious', respectively.

These results have important implications for commercial fruit growers, storage operators, and marketers in British Columbia. Although year-to-year differences in the relationships between fruit minerals and storage disorders preclude development of models for predicting absolute levels of storage disorders based on cumulative past years' data, relative storage potentials for a range of orchard blocks can be estimated using mineral data as early as 6 weeks before harvest within a given year. Using this information, operators and marketers could develop storage and marketing strategies well in advance of harvest. In addition, growers would

have sufficient time to apply at least three Ca sprays to low [Ca] blocks before harvest.

The absolute value of correlation coefficients and the number of significant correlations for 'McIntosh' and 'Spartan' were generally greater in 1989 when there were higher levels of breakdown compared to 1990 and 1991 when the levels of the disorder were low. In that respect our results are like those of van der Boon (1980), who also found greater correlation of fruit minerals with bitter pit in 'Cox's Orange Pippin' in years when the incidence of the disorders was greater. In a similar study by Johnson et al. (1987), however, correlations were not greater in years in which the incidence of storage disorders was greater. The poorer correlations in 1990 and 1991 can be explained, at least in part, by the large number of samples that did not develop breakdown in those 2 years. In 1990 and 1991, $\geq 60\%$ of all 'McIntosh' and 'Spartan' samples had 0% breakdown after 4 months of storage. In contrast, 93% of 'McIntosh' and 78% of 'Spartan' samples developed breakdown after 4 months of storage in 1989. Although within each year the samples that developed breakdown in all 3 years of the study were, in general, larger fruit with lower [Ca], the 1990 and 1991 data sets were a poor straight-line fit with linear correlation because of such a large number of samples with no breakdown. Results with 'Golden Delicious' were similar, although not as pronounced. In each of the 3 years, 69% or more of the 'Golden Delicious' samples had 0% bitter pit after 4 months of storage. In spite of these low numbers, 'Golden Delicious' correlations tended to be stronger for 4-month samples in 1989 and 1991, when the levels of bitter pit were slightly higher than in 1990.

Overall, 4-month storage samples were more highly correlated with disorders than 6-month samples. In commercial practice, the cultivars used in this study are generally held no longer than 4 months in 0 °C air storage. The 6-month storage treatment was included in the hope that greater incidence of disorders at the longer duration might help to identify more clearly associations between the independent variables and storage disorders. This was not realized. Poorer correlations with 6-month samples may have been at least partially due to the development of disorders in samples representing a wide range of mineral concentrations and fruit sizes. Fruit lots that had nil or very low levels of disorders at the maximum commercial storage duration of 4 months, and thus were of high storage potential from a marketing perspective, often had developed higher levels of breakdown after 6 months storage.

In conclusion, [Ca], fruit mass, mass/[Ca], or [K]/[Ca] were frequently significantly correlated with storage disorders within each of the 3 years of the study. Correlations were generally as great 6 and 3 weeks before harvest as they were at harvest. The absolute values of correlation coefficients for the mass/[Ca] and [K]/[Ca] ratios tended to be greater and more consistently significant than those for the individual variables making up the ratios. Fruit mass was the only variable for which the relationship with breakdown in 'McIntosh' and 'Spartan' was consistent in each of the 3 years of the study. The relationship between mass and breakdown in 3 years' combined data was significant as early as 9 weeks before harvest. There were no variables with a consistent year-to-year relationship with bitter pit in 'Golden Delicious'. For each cultivar at a given sampling period, there was a minimum [Ca] approximately the same in all years above, for which the designated storage disorder did not develop during 4 months of storage.

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