Journal American Pomological Society 55(1):8-27 2001

Factors Affecting Apple Fruit Firmness – A Review

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Introduction

Fruit firmness is one of the most important characteristics of apple quality and therefore, obtaining and maintaining apple fruit firmness from the orchard through to the consumer tends to be one of the major issues facing the industry. Apple fruit firmness tends to be influenced greatly by many preharvest factors, such as genetics, cultural practices, and the applications of fertilizers or growth regulators. In addition, many postharvest factors have an enormous effect on apple firmness, such as maturity at harvest, cooling, postharvest dips, and storage conditions. This article is a review of the preharvest and postharvest factors that have been shown to affect apple fruit firmness.

In Canada, it is assumed that consumers find apples with a firmness of less than 44.5 N too soft (163). Packers of *Pommes-Qualité-Québec* must respect the minimum firmness values of 49.5 N for 'McIntosh' and 'Cortland,' and 54.0 N for 'Spartan' and 'Empire' apples (73). A sensory evaluation of 'McIntosh' in New York found crispiness to be directly related to firmness measurements; apples with pressure test values of 58.5 N were rated as "crisp, neither too hard nor too soft" by consumers, while those with firmness of 31.5 to 36 N were rated too soft (131).

Although Bourne (26) indicates it is impossible to give a precise definition of apple fruit firmness, horticulturists use firmness to describe the mechanical properties of fruit tissue. A natural decline in firmness occurs as fruit soften during the ripening process. At the cellular level firmness depends on cell size, cell wall thickness and strength, and turgor pressure and the manner in which cells bind together, which is controlled by cell-to-cell adhesion, cell shape and packing (93). In apple (165), extracellular space is as high as 20 to 25% and it is estimated that no more than 40% of the cell wall areas of apple are in contact with each other (195). Cells are small and radially flattened just beneath the apple skin (105). However, cells are radially elongated toward the core and organized in distinct columns with a maximum diameter of approximately 300 μm, 5 to 10 mm below the skin. When immature apple tissue is broken, cells fracture and a mixture of fractured and separated cells occurs as the fruit mature, with all cells separating out in mealy apples. As apples ripen, cell wall composition changes with an increase in soluble pectin and a net loss of the non-cellulosic neutral sugars, galactose and arabinose (111). During storage, apple volume and internal air space increases while tissue strength decreases with increasing ease of cell separation when force is applied.

Fruit firmness is usually determined as the maximum force required to push an 11 mm-diameter tip probe of specified shape into the flesh. The most widely used penetrometers consist of the Magness-Taylor tester, the Effe-gi firmness tester, and the Electronic Pressure tester (1, 5, 122). However, since it is advantageous to measure apple firmness with a reliable, non-destructive method, different techniques based on mechanical resonance (1, 2, 4, 10, 37, 48, 75, 191, 194), vibrational excitation (155), spectrophotometric reflectance (168), or chlorophyll fluorescence (14, 55) have been reported. Despite this experimental work, there are still no

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commercial applications of nondestructive methods for measuring apple firmness in sorting machines (6).

Preharvest Factors Affecting Apple Firmness

a. Genetic material

Most postharvest quality characteristics, including fruit firmness, are genetically controlled and thus may vary with cultivar (19). For example, apples ranging in firmness from 76.5 N for 'Granny Smith' to 56.3 N for 'McIntosh' can be found in Quebec supermarkets during February to June (140).

The strain within a particular cultivar can also influence fruit firmness. For example, standard-type 'McIntosh' strains (e.g. 'Redmax' and 'Marshall') tend to be 4.5 N firmer than the spur-type strains (e.g. 'Macspur' and 'Hartenhof'), both at harvest and after storage (52). DeEll and Prange (52) also found that 'Stewart Cortland' tended to be firmer than 'Redcort,' 'Hartcort,' 'H53-A12-10,' and 'Sheffield' after long-term storage, although there were no differences at harvest.

Fallahi et al. (68) evaluated 26 strains of 'Delicious' and found 'Apex,' 'Hardispur,' 'Redspur,' 'Silverspur,' 'Starkrimson,' and 'Starkspur Supreme' fruit to be among the firmest at harvest. 'Hardi-Brite Spur' fruit were found to be the softest after storage, while 'Rose Red' fruit had lower firmness than most other strains at harvest and after storage. 'August Red,' 'Hardi-Brite Spur,' and 'Starking' fruit had the greatest firmness loss after storage, whereas 'Silverspur,' 'Spured Royal,' 'Starkrismon,' and 'Starkspur Supreme' had the least firmness loss. The difference among strains was 7% at harvest and 20% after storage, and there appeared to be no general advantage of either spur or standard growth habit trees. Generally, the difference in flesh firmness among strains of a cultivar is not as great as differences among cultivars.

Rootstocks may have an effect on apple firmness, but this tends to vary with cultivar and/or strain. Rootstock M.26 produced softer apples than Seedling, M.1, MM.106, M.7 and OAR.1 at most harvest times, whereas OAR.1 produces firmer apples, although not consistently (69). Autio (11) examined the effect of nine rootstocks on 'Delicious' and found a consistent effect of rootstock on fruit size, and fruit size was covaried with flesh firmness and calcium. He concluded that the main effect of rootstock on apple storability was related to maturity and calcium levels. Regardless of rootstock, harvest time or storage conditions, the cultivar 'Granny Smith' produced firmer apples than those of 'Greenspur' (60). This was thought to be due to the relatively high calcium content and low nitrogen:calcium ratio found in 'Granny Smith.' However, apples from M.26 rootstocks were firmer than apples from MM.111, and no significant difference was found in the calcium content of these apples (60). The effect of rootstock on firmness is minor and varies from site to site (12). In the NC-140 1984 planting of 'Delicious' on 15 rootstocks the difference between the firmest to least firm was 4% in MA, 8% in IN and 12% in CA. When values were averaged across sites, there was less than 1% difference between the most firm and least firm due to rootstock.

b. Nutrient management

1. Calcium (Ca). Although there is little doubt that the Ca content of an apple is directly related to the development of bitter-pit (58, 148), a physiological disorder, there are conflicting reports as to the relationship between Ca content and apple fruit firmness. For example, apple firmness has been shown to be independent of whole fruit mineral composition (47); however, Webster (202) demonstrated that the Ca content of fair and poor quality 'McIntosh' apples was consistently lower than the amount of Ca associated with good keeping quality apples (200 ppm Ca dry weight basis in cortex (flesh), and 500 ppm dry weight basis in peel). Bramlage et al. (30) measured 'McIntosh' fruit firmness at harvest time and found it increased slightly with increased flesh Ca concentration. Ben (16) found a high positive correlation between Ca concentration and the firmness of 'Jonagold' apples.

Similarly, there have been inconsistent results pertaining to the use of calcium chloride ($CaCl_2$) sprays to improve apple fruit firmness. Preharvest $CaCl_2$ sprays neither influence the Ca content of 'Delicious' (47, 156) and 'York Imperial' apples (87), nor the fruit firmness of 'Delicious' (156) and 'Anna' apples (64). A 3-year study on 'Delicious' and 'Golden Delicious' apples affirmed that three to five preharvest sprays of 3.64 to 5.45 kg of $CaCl_2$ per 400 gallons per acre from early June to late August did not affect the firmness of these apples (156). The firmness of 'McIntosh' apples was not affected by preharvest sprays of $CaCl_2$, $Ca(H_2PO_4)_2$, 'Seniphos' ($Ca(H_2PO_4)_2$), 'Stopit' ($CaCl_2$), and 'THIS Calcium' ('Top Cal,' a polyphenolic acid chelate of Ca) (32).

On the other hand, 'Golden Delicious' apples sprayed individually until runoff with 0.11% $CaCl_2$ over a 9-week period prior to harvest were 9.45 N firmer than untreated apples at harvest, as well as after 9 weeks of storage (166). 'Golden Delicious' fruit firmness was correlated positively with calcium concentration in the fruit at harvest, as well as after storage (172). Ingle and D'Souza (97) showed that preharvest calcium chloride sprays (4.4 kg•ha–1, applied eight times at 2week intervals starting 19 days after full bloom) increased the firmness of 'Nittany' apples for two consecutive years, as did Stopit (9.34 $L{\bullet}ha^{-1}$) when applied 19 days after full bloom. Raese and Drake (164) reported an increased flesh firmness of 2.7 to 3.6 N in 'Delicious' apples to which preharvest $CaCl_2$ sprays were applied, while the fruit firmness of 'Golden Delicious' increased by more than 2.25 N with the highest rate of $CaCl_2$ (1.8 kg per 378 L of H_2O), but in only one of the three locations studied. However, these results have some inconsistencies even though the study was conducted for 5 years, e.g. one year at one particular location, fruit firmness and Ca concentration were higher in the control apples than in those from the $CaCl_2$ sprayed 'Delicious' trees (164). 'Cox's Orange Pippin' apples treated with $Ca(NO_3)$ have been shown to be firmer than untreated fruit after storage at 3°C for 6 weeks followed by 1 week at ambient temperature (200). Such results may be due to the presence of an autoregulatory system of Ca level in mature apple fruit (113).

In other reports, preharvest Ca sprays seem to be effective only when applied at very high frequencies (e.g. 18 times during the growing season), or at very high rates (a single $CaCl_2$ spray of 90 lbs per acre, 2 weeks before harvest) that would damage apple skin (156, 204). Sprays of 2.5 to 5% $CaCl_2$ do not cause fruit damage in 'Spartan,' while resulting in increased fruit Ca content (145). Mason (145) reported that $CaCl_2$ sprays applied closer to harvest were more effective in increasing Ca content in 'Spartan' apples than sprays applied earlier in the season.

In summary, as Siddiqui and Bangerth (184, 185) reported, it appears that preharvest applications of $CaCl_2$ may not always result in increased fruit firmness at harvest but may increase firmness retention during storage. On one hand, Ca delayed apple softening by delaying the degradation of cell wall polymers (172) and was important in maintaining cell-to-cell adhesion (160). Fruit not treated with Ca has been shown to soften during storage, as cell walls separate and eventually swell (160). Another theory is that apples with high Ca content also have low respiration rates and thus longer storage life, compared to low-Ca fruit (183). Cooper and Bangerth (43) suggested that apple firmness could be determined not only by high Ca but also by low Ca concentrations, since these two states may lead to the same results via different pathways. For instance, 'Baldwin' apples with less than 700 ppm Ca were 7.4 to 9.9 N firmer and considerably less waxy than ones that had more than 700 ppm Ca (29). Although the data is conflicting, it seems prudent to maintain or increase fruit Ca levels because the evidence is clear that disorders such as bitterpit, cork spot and internal breakdown are reduced, and firmness sometimes increased.

2. Nitrogen (N). N application did not appear to directly influence apple fruit firmness. For example, N application did not affect the firmness of 'Gala' apples (153). Similarly, fertilization with NPK-micro fertilizers did not seem to affect the firmness of 'Summerred' apples at harvest or after storage (67).

However, N-application could influence apple fruit firmness indirectly. Bramlage et al. (31) showed that high-N fruit were larger, softer, more prone to preharvest drop, and were more likely to develop physiological disorders in storage. Increasing fruit size was correlated negatively with firmness at harvest and after storage in 'McIntosh' (143) and 'Starkspur Golden Delicious' apples (70). N concentration was also correlated negatively with fruit firmness of 'Jonagold' apples (16).

*3. **Boron (B)***. The use of B sprays also did not appear to directly influence apple fruit firmness. Granelli et al. (80) found that the application of an experimental fertilizer known as urea-B (20-0-0, $7B_2O_3$) on two different orchards in Italy had no effect on the fruit firmness of eight apple cultivars. Peryea and Drake (157) also reported that B had no effect on the firmness of 'Starking Delicious' apples when applied as a single mid-July spray (0, 11.3, or 22.6 g B per tree).

*4. **Phosphorus (P)***. Phosphate compounds ($NH_4H_2PO_4$, KH_2PO_4, $CaH_4(PO_4)_2$, and $NH_4H_2PO_4$) applied to 'McIntosh' as foliar sprays resulted in increased fruit firmness of the same magnitude as postharvest Ca dips (144, 146, 147, 203). For 'Jonagold' apples, P concentration was positively correlated with fruit firmness (16).

In a 4-year study, Bramlage et al. (33) determined the relationships between Ca, K, P, Mg, and N concentrations in 'McIntosh' apples at harvest and the fruit quality after storage. Fruit firmness at harvest or after storage does not appear to be correlated with any of these elements.

c. Fruit size

Blanpied et al. (25) reported that large apple fruit were generally softer than small fruit. However, Johnson (99) illustrated that focusing on fruit size alone was likely an over-simplification since fruit size relates to both cell number and cell size. Early thinning during cell division resulted in larger fruit that were firmer. A recent very controlled study in a controlled environment facility found no differences in firmness between large and small fruit (Tustin, personal communication).

d. Bioregulators

Apple trees are sprayed with bioregulators in order to control vegetative growth, hasten or delay ripening, delay apple abscission, or to simply enhance apple quality characteristics. Cytokinins, sprayed at full bloom or post-bloom, increased flesh firmness of mature apples on M.7, MM.106, or M.26 rootstocks at harvest, but only fruit treated with CPPU (N-(2-chloro-4-pyridyl)-N'-phenylurea, also known as fenclopyr, KT-30, 4-PU and CN-11-3183) or thidiazuron maintained the firmness benefit after storage (82). When CPPU was applied to 'Delicious' apple trees at concentrations ranging from 0 to 50 $mg{\bullet}L^{-1}$ at full-bloom or full-bloom plus 2 weeks, flesh firmness of treated fruit increased linearly with increasing concentration (45). 'Delicious' apples treated with CPPU and stored for 7 months at 1°C were firmer than non-treated fruit, whereas 'Empire' fruit firmness was not affected by the application of CPPU (45). 'Golden Delicious' firmness however, was not influenced by the application of post-bloom gibberellin sprays (133).

Repeated applications of NAA at concentrations of 5 to 20 $mg{\bullet}L^{-1}$ did not affect the firmness of 'Campbell Redchief Delicious'/MM.111 apples at harvest or after 4 months of storage (142). Greene (83) found that NAA-treated (10 ppm) 'McIntosh'/M.7 apples were softer than the non-treated fruit at harvest, as well as after 20 weeks of storage.

The use of SADH (succinic acid 2,2-dimethyl hydrazide, AlarTM, B-9, daminozide) resulted in increased fruit firmness of 'Delicious' (13) and 'McIntosh' (66), in addition to its primary use of providing preharvest drop control (44, 66). 'McIntosh' apples from trees treated with SADH, CEPA (2-chloroethylphosphonic acid) or NAA (naphthaleneacetic acid), alone or in combination, had decreased fruit firmness between the 6th and 10th day after harvest; however, when CEPA+NAA was used, firmness was reduced during the preharvest stage (159). Only SADH-treated apples were firmer than the non-treated fruit overall. Edgerton and Blanpied (63) showed that although the increased flesh firmness induced by the application of SADH was reduced by ethephon, NAA or fenoprop (2, 4, 5-trichlorophenoxypropionic acid) treatments, apples were still firmer than those on non-treated trees. However, others found that when ethephon was applied to SADH-treated trees, fruit were softer than the controls (86). Excessive fruit firmness loss also resulted from application of 1000 $mg{\bullet}L^{-1}$ SADH and 250 $mg{\bullet}L^{-1}$ ethephon in combination with 20 $mg{\bullet}L^{-1}$ of either NAA or fenoprop (85).

The recent withdrawal of SADH from the American and Canadian market resulted in major problems for the apple industry (83). The market witnessed the emergence of several different products aiming to produce the same effects as SADH. It has been reported that paclobutrazol gives similar results as SADH with respect to fruit characteristics (65). Apples from 'Spartan' trees treated with paclobutrazol maintained greater firmness than untreated apples after 7 months of storage at 0°C (197).

Aminoethoxyvinylglycine (AVG, ReTainTM) improved 'McIntosh' fruit firmness at harvest by 2.25 to 4.5 N (83). However, no difference in firmness was found between the AVG-treated or untreated apples after 20 weeks of storage. AVG applied to 'McIntosh' apple trees in Nova Scotia and New Brunswick improved fruit firmness in New Brunswick (56), and treated apples were firmer than untreated fruit after 6 months in controlled atmosphere (CA) storage (57). Retain has consistently provided preharvest drop control, but results with firmness have been inconsistent.

Other materials such as preharvest sprays of lysiphosphatidylethanolamine (LPE, 100 $mg{\bullet}L^{-1}$) have potential to delay firmness loss in 'McIntosh' apples (72). However, results from Nova Scotia suggest that there were no obvious benefits from LPE application on 'McIntosh' apples (51). 'Ralls' and 'Starking' apples had increased firmness when treated with 500 and 1000 $mg{\bullet}L^{-1}$ Polaris (glyphosine) compared to the non-treated fruit (206). The effects of antitranspirants on apple firmness were also studied. Sprays of Vapor Gard (poly-1-p-1-methene-8-9-diyl), Wilt Pruf NCF (di-1-p-menthene), emulsifiable A-C polyethylene, and Plyac (octyl phenoxy polyethoxy ethanol) at concentrations of 0.5, 1, and 2% applied 14 days before harvest, resulted in increased fruit size but reduced firmness of 'Starkrimson Delicious' apples (149). Thus, of the chemical growth regulators available today, none can be counted on to consistently improve firmness.

e. Other cultural practices

Other cultural practices, such as crop density, root and tree pruning, flower and fruit thinning, trunk scoring, and trunk ringing have also been evaluated for their effects on apple fruit firmness. 'Gala' apples were firmer from trees with a small crop load, compared to fruit from trees with a heavy crop load (153). In Ohio studies, Schupp and Ferree (177, 178) reported increased fruit firmness at harvest when apple tree roots were pruned. However, in Switzerland no change in fruit firmness was recorded when trees were root-pruned at bloom (176).

Johnson (99) found that removal of all but the axillary flowers or fruitlets within 37 days after full bloom increased fruit firmness of 'Cox's Orange Pippin' in two out of 3 years. This increase in firmness occurred even though fruit were larger, less dense, and lower in Ca (factors usually associated with a decrease in firmness). In more recent work, Johnson (100) identified the period of 5 to 15 days after bloom as the critical time to influence fruit firmness through thinning. This firmness benefit was maintained during storage in 2% O_2 and <1% CO_2, but not in air or 1.25% O_2 and <1% CO_2.

Positions in the tree canopy of 'Delicious' (35) and 'Golden Delicious' (74) had little effect on fruit firmness. In a comparison of six tree canopy forms of 'Granny Smith' the greenest and firmest fruit occurred in inner canopy regions (198). However, Blanpied et al. (25) indicated apples harvested from inner-shaded zones within the tree canopy were softer than apples from outer zones. Hirst et al. (96) evaluated fruit firmness of 'Granny Smith' which had light excluded during the growing season by bags applied at different times and for different periods, and found only a very small (2.9 N) increase due to light exclusion. The variable results from these studies show that fruit firmness cannot be easily manipulated by cultural practices, such as pruning and training, which can have large influences on canopy light environment, fruit size, and yield.

Trunk scoring of 'Delicious' apple trees 19 days after full bloom resulted in reduced fruit firmness, whereas similar trunk scoring of 'Cortland' had no effect on apple firmness (84). Trunk scoring or ringing of 'Macspur McIntosh'/M.7 trees as late in the growing season as 3 weeks before harvest retarded loss of flesh firmness before harvest and during subsequent storage at 0.5°C for 19 weeks (66). Branch ringing of 'Granny Smith' apple trees 25 or 50 days before harvest did not influence fruit firmness at harvest or after 30 days of cold storage (78).

Water management also plays a role in determining apple fruit firmness. Fruit from non-irrigated 'Gala' apple trees were firmer than those from irrigated trees (153), whereas drip irrigation had no impact on the firmness of 'Summered' apple fruit (67).

Organically grown 'McIntosh' apples were perceived by sensory panelists to be firmer at harvest compared to conventionally grown 'McIntosh' (49). However, this perception appeared to be lost after storage and there were no significant differences in measured fruit firmness (using a penetrometer). DeEll and Prange (49) found no significant differences in firmness between organically and conventionally 'Cortland' apples at harvest or after storage, as perceived by sensory panelists or determined by a penetrometer. Thus, although many cultural practices can have a small influence on firmness, none had a large or entirely consistent influence.

Postharvest Factors Affecting Apple Firmness

a. Maturity at harvest

Maturity at harvest can affect the postharvest quality of apples. In many cases, variability in the maturity of fruit on a tree makes it necessary to harvest more than once (95). Generally, fruit firmness was greater on early harvest dates, as opposed to late ones. Fruit firmness of 'Starkspur Golden Delicious' apples produced on six different rootstocks decreased with later harvest dates (69). However, no differences in fruit firmness were found after 6 months of storage for any harvest date

Some apple cultivars (e.g. 'Golden Delicious,' 'Redchief' and 'Jonathan') showed decreased fruit firmness with later harvest dates (7, 175), while others (e.g. 'Granny Smith,' 'Starking Delicious') were not affected by harvest date (181, 190). 'Granny Smith' maintained high fruit firmness after 6 months of CA storage, irrespective of the harvest date (190), whereas 'Starking Delicious' fruit exhibited firmness loss during 5 to 6 months of storage, regardless of harvest date and the location (181). 'Neiplings Early Stayman,' 'Double Red Rome,' and 'Law Red Rome Beauty' cultivars had a tremendous decrease in fruit firmness after 6 months of CA storage, with the highest firmness values at the latest harvest time (190).

Maturity at harvest can also affect the rate at which apples soften during storage. Early harvested 'Cox's Orange Pippin' apples had greater firmness retention during air or CA storage at 0°C than late harvested apples (192). 'Virginia Gold' apples had a considerably lower softening rate in storage than 'Golden Delicious' (0.15 N and 0.27 N per day, respectively) when harvested at a starch index of 3 (using the Ontario 'Golden Delicious' starch index of 1 to 9) (102). Later harvests result in continuous fruit firmness loss in 'Jonathan' apples (175).

Although ethylene production of apples was associated with increased maturity, fruit firmness was not necessarily related to ethylene production (79, 88, 98). For example, 'PA14-238' and 'D101-110' produced very little ethylene (<10 $L\bullet kg^{-1}\bullet h^{-1}$) at harvest and during 86 days of storage at 41°C; however, 'PA14-238' fruit remained firm while 'D101-110' softened during storage (88). It was reported that fruit softening in the latter genotype was generally not dependent on ethylene production. Another apple selection, 'NJ55,' produced considerable amounts of ethylene but remained as firm as 'PA-14-238' after storage (88).

b. Pre-storage treatments

1. Calcium (Ca). Postharvest calcium applications can influence the firmness retention of apples. 'Spartan' fruit firmness improved by 3.76 N when the fruit were dipped in a 4% $CaCl_2$ solution after harvest (146). The Ca content of 'Delicious' fruit improved after dipping in a 4% $CaCl_2$ solution, and the rate of firmness loss during storage under ambient conditions for 60 days was significantly reduced (150).

In addition to dipping, vacuum-infiltration and pressure-infiltration of Ca into apples can be used to retain fruit firmness (36, 172, 179). 'Fuji' and 'Jonathan' apples, but not 'Tsugaru,' had increased firmness retention during storage at 4°C for 1 to 7 months and an additional 1 to 2 weeks at 20°C, when vacuum or pressure infiltrated with up to 6% $CaCl_2$ (40 and 80 kPa, respectively) but not after dipping (36). $CaCl_2$ (1, 2, or 4 %), whether used in pressure or vacuum-infiltration or as a dip, increased Ca concentration in the peel of 'Fuji' apples and resulted in increased fruit firmness retention (154). In 'Jonathan' apples, but not in 'Fuji,' firmness increased with increasing Ca concentration (0, 2, 4, 6%), and was highest with vacuum infiltration (36). 'Fuji' apples, but not 'Jonathan,' had greater fruit firmness with higher infiltration force (100 or 48 kPa for pressure and vacuum infiltration, respectively) (36). 'Liaofu' apples had greater firmness when vacuum-infiltrated with 2 to 6% $CaCl_2$ at –0.07 MPa for 1 min, as compared to non-treated apples (205).

Postharvest pressure infiltration of $CaCl_2$ was effective in increasing the Ca concentration of 'Golden Delicious' apples, and consequently maintaining their firmness under laboratory (172, 173) and commercial conditions (42). Sams and Conway (173) compared the storage potential of Ca-treated fruit to that of fruit stored in CA storage, and found that the firmness of fruit with high flesh Ca concentrations and those stored in CA were similar. 'Delicious' apples retained more firmness when pressure-infiltrated for 2 min with a solution of 8% $CaCl_2$ (25% firmer than non treated apples), but results were not as great as with 'Golden Delicious,' which softens quickly in storage (40, 172).

Ca uptake in harvested fruit varied enormously with apple cultivar, as well as with different orchards and growing seasons for a given cultivar. Conway and Sams (39) reported that 4% $CaCl_2$ infiltration was optimal for 'Golden Delicious,' while Abbott et al. (3) reported that 4% $CaCl_2$ concentration was harmful to 'Golden Delicious' and thus recommended a 2% solution. This difference was thought to be due either to the use of $CaCl_2$ with different percent of impurities or to maturity differences between apples in the two studies (3). Ca uptake in 'Golden Delicious' was greater than in 'Delicious' fruit and therefore, 'Golden Delicious' was more likely to respond to Ca infiltration (125).

'Delicious' apples from trees on M.9 rootstock were more permeable to $CaCl_2$ and were firmer after 6 months of storage, than those from trees on M.26 (150). Since some cultivars, such as 'Golden Delicious,' were very susceptible to skin injury, the use of optimal $CaCl_2$ concentration for maintaining fruit firmness may be difficult to achieve. For example, Saftner et al. (171) recommended pressure infiltration of 'Golden Delicious' apples with 0.14 to 0.20 $\mu\bullet L^{-1}$ solutions of $CaCl_2$, although higher concentrations maintained better fruit firmness. Moreover, proper sanitation measures should be observed, otherwise fruit decay could occur faster than without pressure-infiltration (42).

The Ca source also played a role in effects on apple fruit firmness. Although the firmness of 'Golden Delicious,' 'McIntosh,' 'Mutsu,' 'Red Rome,' and 'Winesap' apples were correlated positively to tissue Ca content for all $CaCl_2$ and Stopit treatments, apples treated with Stopit were firmer than those treated with $CaCl_2$ (15). The infiltration of 'Cox's Orange Pippin' apple tissue with calcium acetate ($Ca(C_2H_3OH2O)•2H_2O$) was thought to partially reverse the softening that results from delayed harvesting and storage (air or 1.25% O_2 and 1% CO_2 at 3.5°C) (189).

One method to increase Ca infiltration without having to increase $CaCl_2$ concentration or the applied pressure gradient is to add surfactants or thickeners to the infiltration solution. Ca infiltration was greatest when 'Golden Delicious' apples were pre-treated with the organosilicone surfactants SilwetL-77 or SilwetL-7604 (170). Dipping 'Golden Delicious' apples in 0.2% (w/v) methylene chloride before Ca pressure infiltration resulted in the highest flesh Ca concentration and greatest fruit firmness (83.3 N, compared to 46.8 N for non-treated apples), but also had the greatest fruit injury (167). In the same study, pre-treatment with Triton X-100 increased the Ca content of apples, as well as fruit firmness (74.9 N).

The use of 0.2 or 0.3% Keltrol, a food thickener, with a 4% $CaCl_2$ dip solution increased Ca uptake and the firmness of 'Stayman' and 'McIntosh' apples by increasing the effect of $CaCl_2$ (90, 144, 147). The Ca concentration of 'McIntosh' apples dipped in $CaCl_2$ with Ketrol was 2.5 to 3-fold more than untreated apples after 5 or 6 months of cold storage (144).

*2. **Heat.*** Apple immersion in hot water was originally aimed at reducing losses caused by postharvest pathogens (34, 182). Hot air later became a more popular method of heat treatment because hot water resulted in increased tissue breakdown (162). Exposing apples to temperatures above 35°C improved firmness retention during storage (106, 107, 137). Exposing 'Spartan' and 'Golden Delicious' apples to 38°C for 4 to 6 days before storage at –1°C for 4 to 7 months improved firmness retention, compared to those not preheated (162). Klein et al. (110) found that the best heat treatment for 'Anna' or 'Granny Smith' apples was exposure to 38°C for 4 days; however, this treatment was comparable to exposing 'Anna' and 'Granny Smith' apples to 46°C for 12 hours or to 42°C for 24 hours (108). Crispiness and sweetness of 'Golden Delicious' apples heated for 4 days at 38°C and stored for a week at 20°C or 0°C were greater than those of unheated apples (136).

Not all apple cultivars respond positively to pre-storage heating. For example, the pre-storage heating of 'McIntosh' apples at 38 to 40°C for 1 to 3 days resulted in firmness reduction (38). Dipping heat-treated apples in a $CaCl_2$ solution tends to increase the effect of heating on firmness (138). It appeared that Ca and heat treatments act in a synergistic way to retain apple fruit firmness after 5 months of storage, compared to non-treated or non-heated Ca-dipped fruit (109). Conway et al. (41) reported that heat treatments of 'Golden Delicious' apples, either alone or in combination with $CaCl_2$, improved firmness retention (80 N), followed by fruit infiltration with 2% or 4% $CaCl_2$ (70 N) and untreated controls (66 N). Although such heated fruit were firmer and had a harder texture, they were less crisp than those not heated. 'Golden Delicious' apples were the firmest when pressure-infiltrated with 4% Ca (84 N), followed by those heat-treated for 4 days at 38°C and then pressure-infiltrated with 4% Ca (76 N), heat-treated only (71 N), and finally those untreated (60 N) (174).

*3. **1-methylcyclopropene.*** The novel gaseous compound 1-methylcyclopropene (1MCP), an inhibitor of ethylene action, has been recently shown to improve apple firmness retention. Fan et al. (71) showed that 1-MCP inhibited softening of 'Fuji,' 'Gala,' 'Ginger Gold,' 'Jonagold,' and 'Delicious' apples. Rupasinghe et al. (169) found 'McIntosh' and 'Delicious' apples which had been treated at harvest with 1-MCP for 18 hours at 20°C and stored for 60 and 120 days in air at 0°C and 90-95% RH to be 13.5 to 18 N firmer than those not treated. However, such results have not been consistent year to year, and seem to vary with cultivar. 'McIntosh' apples treated with 1-MCP (0.6 $\mu L \bullet L^{-1}$) at harvest during the following season (1998-99) and stored for 70 days in air at 0°C and 90-95% RH showed only 4.5 to 9 N better firmness retention, while 'Cortland' and 'Empire' apples treated the same were 18 to 22.5 N firmer after storage than non-treated apples (DeEll and Murr, unpublished data). Ontario-grown 'Jonagold,' 'Mutsu,' and 'Fuji' treated with 1-MCP were also 9 to 13.5 N firmer than non-treated apples after air storage, and firmness benefits were still evident after an additional 1 or 2 weeks at 20°C in all cultivars evaluated. Despite the benefits of CA storage on apple firmness, the use of 1-MCP in combination with CA greatly improved firmness retention in 'McIntosh,' 'Cortland,' and 'Empire' apples after storage and during simulated marketing of 1 or 2 weeks at 20°C (DeEll and Murr, unpublished data).

Temperature and treatment duration are two important factors governing the efficacy of 1-MCP. 'Cortland' apples treated with 1-MCP at 3°C showed improved firmness retention with at least 9 h of treatment, whereas those treated with 1-MCP at either 13 or 23°C showed improved firmness retention with at least 6 h of treatment (DeEll and Murr, unpublished data). On the other hand, 'Empire' apples treated with 1-MCP showed improved firmness retention with only 3 h of treatment regardless of temperature, but those treated at 3°C for 3 h no longer had the full firmness advantage after an additional 7 days at 20°C (DeEll and Murr, unpublished data). Watkins et al. (201) also found that the efficacy of 1-MCP was affected by cultivar and storage conditions, and thus concluded that successful commercial implementation will require more understanding of such relationships.

*4. **Other compounds.*** Other chemicals sometime help to maintain the firmness of apples during storage, even though this may not be their primary use. Diphenylamine (DPA) is generally used at a concentration of 3000 $mg \bullet L^{-1}$ as a postharvest dip for 'Granny Smith' apples to control storage scald, a physiological disorder characterized by diffuse browning of the skin (139). The firmness of these DPA-treated apples was greater by 1.5 N after 6 months of cold storage plus 1 week at 20°C, as compared to non-treated apples.

'Golden Delicious' apples pressure-infiltrated with 0.25 to 1.0 mM spermine, a polyamine, were 2.7 to 6.7 N firmer than water-treated controls, while 'McIntosh' apples were 2.2 to 5.3 N firmer than the controls when subjected to the same treatments (112). A sucrose fatty acid polyester (SPE), SemperfreshTM, improved firmness retention of 'Granny Smith' apples stored for 60 days in ambient air at 0°C, when applied with wax (61). Coating early or late harvested 'Granny Smith' apples with 0.75 or 1.5 % SemperfreshTM resulted in slightly better firmness retention after cold storage for 4 to 5 months (104). Diazocyclopentadiene (DACP) resulted in increased firmness retention of 'Delicious' apples (73 N, compared to 46 N for non-treated apples) after 30 days of air storage at 21°C (20, 21).

c. Storage conditions

*1. **Temperature.*** Temperature is the single most important factor governing the maintenance of postharvest quality, and the importance of using low temperatures to maintain apple fruit firmness cannot be overstated. Rapid cooling after harvest can greatly improve firmness retention in apples during storage. Harvesting triggers an increase in respiration and hastens ripening, and therefore, any delays in cooling after harvest can result in reduced storage-life (129). 'McIntosh' apples have been shown to soften as much as 20 times faster at 21°C than at 0°C (129), and hence apples should be refrigerated even for short-term storage. Furthermore, apples soften about twice as fast at 4°C than at 0°C, and about three times as fast at 15°C than at 4°C (91). Recommended storage temperatures are always the compromise of good firmness retention and the induction of low-temperature disorders. Some cultivars were more susceptible to softening than others when cooling was delayed. For example, fruit firmness of 'Stayman' and possibly 'Rome Beauty' (46), 'McIntosh' (22, 196), and 'Golden Delicious' (119), was affected negatively by the delay, whereas 'Jonared' (46) and 'Spartan' (124) may not be affected.

*2. **Controlled-atmosphere (CA) storage.*** Many apple cultivars stored under CA conditions have reduced loss firmness and shelf-life. Blanpied and Smock (23) found that high flesh firmness of 'McIntosh' apples was correlated positively with low temperature, low O_2 and high CO_2 levels. 'McIntosh' apples retained greater firmness in CA storage of 2.5 to 3.0% O_2 and 2.5% CO_2 (23, 62, 161). CA storage reduced fruit firmness loss in 'Novaspy,' 'Nova Easygro,' 'Prima,' 'Macfree,' 'Priscilla,' and 'Moira,' although it did not extend the storage life of the three latter cultivars (50). CA-stored (1.5% or 3.5% O_2, 1.5 to 4% CO_2) 'Nittany' apples were firmer than those held in cold storage (0 to 2°C in air) (97). Mealiness of 'Delicious' apples was hastened by CO_2 in the storage atmosphere (76).

*3. **Ultra-low oxygen CA.*** Reducing the O_2 level in storage from 3 to 0.7% improved firmness retention of 'Fuji' apples (9). Maintenance of the maximum firmness for this cultivar was attained in CA storage of 0.7% O_2 and 0% CO_2 at 0.5°C, or 0.7 to 1% O_2 and 1% CO_2 and at 2.5°C (9). The storage of 'Delicious' apples in 1% O_2, irrespective of the CO_2 level (0 to 15%), resulted in good overall quality fruit (8). The regime of 0.7% O_2 and 1.0% CO_2 used initially to reduce the development of superficial scald in apples during storage, also improved fruit firmness retention (120). 'Imperial Double Red Delicious' and 'Granny Smith' apples retained better firmness when stored in 1% O_2 and 1% CO_2, compared to cold storage in air at 0°C with 90 to 95% RH or modified atmosphere in polyethylene bags at 0°C (141). On the other hand, 'Cortland' fruit firmness was insensitive to low O_2 or high CO_2 levels in CA storage (54). 'Novamac' fruit firmness decreased in storage, whether in standard CA conditions (2.5% O_2, 4.5%CO_2) or in low O_2 CA (1.5% O_2, 1.5%CO_2) (50). 'Bramley's Seedling' apples softened rapidly when stored in ultra-low O_2 (0.4-1% O_2, 0% CO_2) for 100 days (101). 'McIntosh' apples stored in 1.0% O_2 and 1.5% CO_2 were 25.7 N firmer after 7 months of storage at 2.8°C than those stored in 3% O_2 and 5% CO_2, the standard commercial atmospheres (126). Retention of 'McIntosh' fruit firmness in low O_2 atmospheres has been reported for storage at 0 to 4°C (27, 59, 103, 118, 123, 126, 128, 135).

'Golden Delicious' and 'Delicious' apples stored in 1.0 to 1.5% O_2 and 1.0 to 1.9% CO_2 at 0 to 0.5°C with 90 to 92% RH for 6 to 10 months, maintained greater fruit firmness than apples stored in standard commercial atmospheres of 2.5% O_2 and 1 to 1.5% CO_2 at 0 to 1°C (117). 'Golden Delicious' apples had higher firmness when stored under ultra-low O_2 conditions (1%) than fruit stored in conventional CA conditions (3% O_2, 3% CO_2) (28). However, Sitton and Patterson (186) found that the fruit firmness of 'McIntosh' and 'Golden Delicious' fruit was not affected by high CO_2 or low O_2, and that 'Delicious' apples were slightly firmer in a high-CO_2 storage (14%). Ben-Arie et al. (17) reported that fruit softening of 'Golden Delicious' and 'Jonathan' apples was retarded by increasing CO_2 concentration from 0 to 20% and decreasing O_2 from 15 to 3%; fruit hardly softened at 20% CO_2, irrespective of the O_2 concentration. 'Golden Delicious,' but not 'Jonathan,' had retained fruit firmness following storage. DeEll and Prange (53) reported that 'Delicious' fruit firmness after CA storage plus 7 days at 0°C in ambient air, was highest when the apples were stored previously in ultra-low O_2 conditions (0.7% O_2 and 0% CO_2.)

The firmness of 'Spartan' apples stored in 1.0% O_2 and 2.0% CO_2 at 0°C for 6 to 9 months was greater than those kept in commercial CA of 2.5% O_2 and 2.0% CO_2 (116). However, 'Spartan' apples stored for 6 months at 0°C in standard CA (2.5%

O_2, 4.5% CO_2) plus 1 week at 0°C in ambient air were firmer than those stored under low O_2 (1.5% O_2, 1.5% CO_2) or ultra-low O_2 (0.7% O_2, no CO_2), because of the sensitivity of these apples to low O_2 and the resulting internal breakdown (53).

'Starking Delicious' apples stored in 1% O_2 and 1% CO_2 for 7 to 8 months were firmer than those in standard commercial CA storage (180). Firmness was greatest in 'Idared' apples after CA storage plus 7 days at 0°C in ambient air, when the fruit were previously stored for in 0.7% O_2 and 0% CO_2, followed by 1.5% O_2 and 1.5% CO_2, and finally standard CA (53). 'Bramley' fruit firmness decreased when fruit were stored for 100 days in low O_2 (0.2-1%) without CO_2 (101). Storing 'Jonagold' apples for 169 days at 0.5 to 1°C in an atmosphere of 1% O_2 and 1.5 to 2% CO_2 resulted in crisper fruit than apples stored under standard CA (94). The best 'Gala' fruit firmness was obtained when fruit were stored at 0 to 1°C in atmospheres of <2% O_2 (18). 'Aroma' apples had better firmness retention in 2% O_2 and 2% CO_2, compared to 3% O_2 and 3% CO_2 or cold storage at –2°C with 88% RH (89). Firmness of 'Elstar,' 'Jonagold' and 'Cox's Orange Pippin' apples was affected positively by storage under ultra-low O_2 conditions (152). Therefore, ultra-low oxygen can improve fruit firmness retention in a wide range of apple cultivars.

*4. **Low ethylene CA.*** The presence or absence of ethylene in storage rooms affects apple fruit firmness differently depending on cultivar and storage conditions. A low level of ethylene (1 $mL \cdot L^{-1}$) in the storage room tended to increase the softening of 'McIntosh' and 'Cox's Orange Pippin' apples stored at 3.3°C, whereas 'Delicious,' 'Golden Delicious,' and 'Idared' apples stored at 0°C were not affected by low levels of ethylene (199). Some studies suggest that ethylene removal from CA chambers can result in increased firmness retention of 'McIntosh' apples (24, 77, 81). Lougheed et al. (134) reported that a relationship with 'McIntosh' fruit firmness and ethylene occurred often, although it was not always obvious. It seems that low ethylene treatments with CA conditions of 3% O_2 and 5% CO_2 resulted in firmer 'McIntosh' fruit compared to those stored only in CA (127). However, low O_2 or low ethylene treatments are equally effective when apples are treated with SADH (84, 130). Removal of ethylene in an atmosphere of 1.25% O_2 and 2% CO_2 for 'Cox's Orange Pippin' (187) and 3% O_2 and 5% CO_2 for 'Golden Delicious' (114) reduced apple softening. However, flesh firmness of 'Cox's Orange Pippin' apples was not affected by ethylene removal when the storage atmosphere was 0.5 to 2% O_2 in flowing gas streams, as compared to the static system (188).

Ethylene removal from storage atmospheres of 1.5% O_2 and 1.5% CO_2 at 1.5°C for 'Golden Delicious,' 'Delicious,' and 'Spartan' or 2.2% O_2 and 5.0% CO_2 at 1.7°C for 'McIntosh' did not increase firmness retention (118). Furthermore, low ethylene storage of 'Belle de Boskoop' apples was not recommended (193). In summary, ethylene removal positively enhanced fruit firmness of some cultivars, but had little or no effect on others. Therefore, the commercial use of low ethylene CA will be cultivar dependant.

*5. **Rapid CA.*** Rapid CA establishment (short loading time and rapid reduction of storage O_2 to 2.5%) maximized the storage life of 'Golden Delicious' and 'McIntosh' apples (46), and to a lesser extent 'Spartan' and 'Delicious' apples (115). A rapidly established 1.0% O_2 and 1.0 to 1.5% CO_2 atmosphere improved firmness retention of 'Golden Delicious,' 'Delicious,' and 'Spartan' apples at 0.5°C and 'McIntosh' at 3.0°C (118). 'Spartan' apples stored in 1.0% to 2.5% O_2 with 'rapid CA' establishment were firmer than those with 'slow CA,' immediately after removal from storage. However, this effect was lost after an additional storage period of 28 days in 0°C air and 7 days at 20°C air (116). If storage rooms can be loaded quickly, very rapid establishment of CA conditions appears to benefit fruit firmness retention.

Concluding Remarks

Apple fruit firmness was affected by both preharvest and postharvest factors. The main preharvest factor affecting apple fruit firmness is the genetic material, with nutrient management, bioregulators, and other cultural practices contributing small but significant benefits. Fruit firmness is mainly under genetic control, with major contributions through cultivar and strain. For example, the cultivar 'Granny Smith' is inherently firmer than 'McIntosh,' and within 'McIntosh' the standard-type are firmer than the spur-type. Rootstock can also influence fruit firmness, due to its ability to control fruit yield and size. Nutrient management, particularly Ca, plays a role in apple fruit firmness. There are conflicting reports about the relationship between Ca content and fruit firmness. Preharvest applications of $CaCl_2$ do not always result in increased fruit firmness at harvest, but they may increase firmness retention during storage. Nitrogen affects apple fruit size and thus, influences firmness indirectly. 'McIntosh' and 'Starkspur Golden Delicious' fruit firmness decreases with increasing fruit size. Phosphate compounds increase 'McIntosh' and 'Jonagold' fruit firmness, whereas boron does not appear to affect fruit firmness. Bioregulators, such as cytokinins, may increase flesh firmness at harvest when sprayed at full or post bloom. However, only fruit sprayed with CPPU or thidiazuron tend to retain this firmness benefit after storage. On the other hand, gibberellins do not appear to influence apple fruit firmness. NAA-treated fruit may be softer than the non-treated apples both at harvest and after storage, whereas SADH and paclobutrazol, which are no longer available for commercial use, tend to increase apple firmness. None of the commercially available bioregulators consistently improve fruit firmness.

Postharvest factors affecting apple firmness vary from maturity at harvest to pre-storage treatments and storage conditions, and generally have a much larger effect than the preharvest cultural factors. Early harvest dates tend to favor fruit firmness and affect the rate at which apples soften during storage. Dipping apples in a $CaCl_2$ solution tends to improve firmness retention, while vacuum- and pressure-infiltration tend enhance the effect. Storage conditions are one of the most important postharvest factors influencing fruit firmness. Low temperatures are crucial for maintaining apple firmness and rapid cooling after harvest can greatly improve firmness retention during storage. CA storage, especially ultra-low oxygen CA, improves firmness retention of apples. In addition, rapid CA establishment further improves the storage life of apples. Given the genetic limitations of fruit firmness imposed by the cultivar, the postharvest factors, particularly the rapid imposition of low temperatures, have the greatest effect on apple firmness.

Literature Cited

1. Abbott, J. A. 1994. Firmness measurement of freshly harvested 'Delicious' apples by sensory methods, sonic transmission, Magness-Taylor, and compression. 1994. J. Amer. Soc. Hort. Sci. 119:510-515.
2. Abbott, J. A., G. S. Bachman, R. F. Childers, J. V. Fitzgerald, and F. J. Matusik. 1968. Sonic technique for measuring texture of fruits and vegetables. Food Technol. 22:635-646.
3. Abbott, J. A., W. S. Conway, and C. E. Sams. 1989. Postharvest calcium chloride infiltration affects textural attributes of apples. J. Amer. Soc. Hort. Sci. 114:932-936.
4. Abbott, J. A., and L. A. Liljedahl. 1994. Relationship of sonic resonant frequency to compression tests and Magness-Taylor firmness of apples during refrigerated storage. Trans. ASAE 37:1211-1215.
5. Abbott, J. A., A. E. Watada, and D. R. Massie. 1976. Effe-gi, Magness-Taylor, and Instron fruit pressure testing devices for apples, peaches, and nectarines. J. Amer. Soc. Hort. Sci. 101:698-700.
6. Abbott, J. A., R. Lu, B. L. Upchurch, and R. L. Stroshine. 1997. Technologies for nondestructive evaluation of fruits and vegetables. Hort. Rev. 20:1-120.
7. Ait-Oubahou, A., M. El-Otmani, Y. Charhabaili, J. Fethi, et M. Bendada. 1995. Effet de la date de cueillette et du traitement au calcium en post-récolte sur la qualité des pommes en conservation, p. 57-64. In: Ait-Oubahou, A. and M. El-Otmani (eds.), Postharvest Physiology, Pathology and Technologies Horticultural Commodities:

Recent Advances, Institut Agronomique et Vétérinaire Hassan II, Agadir, Morocco.
8. Anderson, R. E. 1967. Experimental storage of Eastern-grown 'Delicious' apples in various controlled atmospheres. Proc. Amer. Soc. Hort. Sci. 91:810-820.
9. Argenta, L. C., A. Brackmann, and M. Mondardo. 1994. Postharvest quality of apples stored at different temperatures and CO_2 and O_2 concentrations. Revista Brasileira de Fisiologia Vegetal 6:121-126.
10. Armstrong, P., H. R. Zapp, and G. K. Brown. 1990. Impulsive excitation of acoustic vibrations in apples for firmness determination. Transactions of the ASAE 33:1353-1359.
11. Autio, W. R. 1991. Roostocks affect ripening and other qualities of 'Delicious' apple. J. Amer. Soc. Hort. Sci. 116:378-382.
12. Autio, W. R. 1996. Rootstock effects ripening, color and shape of 'Starkspur Supreme Delicious' apples in the 1984 NC-140 Cooperative Planting. Fruit Var. J. 50(1):45-53.
13. Bartram, R. D., K. L. Olsen, and M. W. Williams. 1971. Influence of summer application of succinic acid-2, 2 dimethylhydrazide on firmness of 'Delicious' apples in storage. HortScience 6:240-241.
14. Beaudry, R. M., N. Mir, J. Song, P. Armstrong, W. Deng, and E. Timm. 1997. Chlorophyll fluorescence: a nondestructive tool for quality measurements of stored apple fruit, p. 56-66. In: Proc. Sensors for Nondestructive Testing: Measuring the Quality of Fresh Fruits and Vegetables. NRAES, Ithaca, New York.
15. Beavers, W. B., C. E. Sams, W. S. Conway, and G. A. Brown. 1994. Calcium source affects calcium content, firmness, and degree of injury of apples during storage. HortScience 29:1520-1523.
16. Ben, J. 1997. Effect of the concentration of mineral constituents in apples on their postharvest quality and storage performance II. Relations between the concentration of mineral constituents in apples and some factors determining their quality. Folia Hort. 9:51-57.
17. Ben-Arie, R., A. Levine, L. Sonego, and Y. Zutkhi. 1993. Differential effects of CO_2 at low and high O_2 on the storage quality of two apple cultivars. Acta Hort. 326:165-174.
18. Bender, R. J. 1989. Controlled atmosphere storage of apples, cv. 'Gala,' in southern Brazil. Acta Hort. 258:221-223.
19. Beverly, R. B., J. G. Latimer, and D. A. Smittle. 1993. Preharvest physiological and cultural effects on postharvest quality, p. 73-98. In: Shewfelt, R. L. and S. E. Prussia (eds.), Postharvest Handling: a System Approach. Academic Press, Inc., London.
20. Blankenship, S. M., and E. C. Sisler. 1993a. Response of apples to diazo-cyclopentadiene inhibition of ethylene binding. Postharvest Biol. Technol. 3:95-101.
21. Blankenship, S. M., and E. C. Sisler. 1993b. Use of diazocyclopentadiene to block ethylene action in plants and flowers. Acta Hort. 343:215-216.
22. Blanpied, G. D. 1975. The effect of cooling rate on the market quality of 'McIntosh' apples. Proc. Am. Soc. Hort. Sci. 70:58-70
23. Blanpied, G. D., and R. M. Smock. 1961. Two factorial experiments on controlled atmospheric storage of 'McIntosh' apples. Proc. Amer. Soc. Hort. Sci. 78: 3542.
24. Blanpied, G. D., O. Cadun, and T. Tamura. 1972. Ethylene in apple and pear experimental CA chambers. J. Amer. Soc. Hort. Sci. 97:207-209.
25. Blanpied, G. D., W. J. Bramlage, D. H. Dewey, R. L. Labelle, L. M. Massey, Jr., G. E. Mattus, W. C. Stiles, and A. E. Watalla. 1978. A standardized method for collecting apple pressure test data. Bul. 74 Cornell Expt. Sta.
26. Bourne, M. C. 1980. Texture evaluation of horticultural crops. HortScience 15:713.
27. Bourne, M. L., and D. H. Dewey. 1980. Very low oxygen for the storage of 'McIntosh' apples. HortScience 15:424 (abstr.).
28. Brackmann, A. 1989. Effect of different CA conditions and ethylene levels on the aroma production of apples. Acta Hort. 258:207- 214.
29. Bramlage, W. J., M. Drake, and J. H. Baker. 1974. Relationships of calcium content torespiration and postharvest condition of apples. J. Amer. Soc. Hort. Sci. 99:376-378.
30. Bramlage, W. J., M. Drake, and J. H. Baker. 1979. Changes in calcium level in apple cortex tissue shortly before harvest and during postharvest storage. Commun. Soil Sci. Plant Anal. 10:417-426.
31. Bramlage, W. J., M. Drake, and W. J. Lord. 1980. The influence of mineral nutrition on the quality and storage performance of pome fruits grown in North America. Acta Hort. 92:29-40.
32. Bramlage, W. J., M. Drake, and S. A. Weis. 1985a. Comparisons of calcium chloride, calcium phosphate, and a calcium chelate as foliar sprays for 'McIntosh' apple trees. J. Amer. Soc. Hort. Sci. 110:786-789.
33. Bramlage, W. J., S. A. Weis, and M. Drake. 1985b. Predicting the occurrence of poststorage disordres of 'McIntosh' apples from preharvest mineral analyses. J. Amer. Soc. Hort. Sci. 110:493-498.
34. Burchill, R. T. 1964. Hot water as a possible post-harvest control of Gloesporium rots of stored apples. Plant Pathol. 13:106-107.

35. Campbell, R. J., and R. P. Marini. 1992. Light environment and time of harvest affect 'Delicious' apple fruit quality characteristics. J. Amer. Soc. Hort. Sci. 117:551-557.
36. Chang, K. H., and J. K. Byun. 1991. Differences in the storage potential of apple cultivars caused by various postharvest calcium infiltration methods. J. Korean Soc. Hort. Sci. 32:335-339.
37. Chen, H., and J. de Baerdemaeker. 1993. Effect of apple shape on acoustic measurements of firmness. J. Agr. Eng. Res. 56:253-266.
38. Chiu, H. J. 1984. Effects of pre-storage and storage treatments of brown core development in 'McIntosh' apples. Acta Hort. 157:135-142.
39. Conway, W. S., and C. E. Sams. 1983. Calcium infiltration of 'Golden Delicious' apples and its effect on decay. Phytopathol. 73:1068-1071.
40. Conway, W. S., and C. E. Sams. 1987. The effects of postharvest infiltration of calcium, magnesium, or strontium on decay, firmness, respiration, and ethylene production in apples. J. Amer. Soc. Hort. Sci. 112:300-303.
41. Conway, W. S., C. E. Sams, C. Y. Wang, and J. A. Abbott. 1994a. Additive effects of postharvest calcium and heat treatment on reducing decay and maintaining quality in apples. J. Amer. Soc. Hort. Sci. 119:49-53.
42. Conway, W. S., C. E. Sams, G. A. Brown, W. B. Beavers, R. B. Tobias, and L. S. Kennedy. 1994b. Pilot test for the commercial use of postharvest pressure infiltration of calcium into apples to maintain fruit quality in storage. HortTechnol. 4:239-243.
43. Cooper, T., and F. Bangerth. 1976. The effect of Ca and Mg treatments on the physiology, chemical composition and bitter-pit development of 'Cox's Orange' apples. Scientia Hort. 5:49-57.
44. Cummins, J. N., R. L. LaBelle, and W. J. Kender. 1982. Effects of post-bloom alar sprays on 'Spigold' apples. Fruit Var. J. 36:18-21.
45. Curry, E. A., and D. W. Greene. 1993. CPPU influences fruit quality, fruit set, return bloom, and preharvest drop of apples. HortScience 28:115-119.
46. D'Souza, M. C., and M. Ingle. 1989. Effect of delayed cooling on the poststorage flesh firmness of apples. J. Food Sci. 54:493-494.
47. Davenport, J. R., and F. J. Peryea. 1990. Whole fruit mineral element composition and quality of harvested 'Delicious' apples. J. Plant Nutr. 13:701-711.
48. De Baerdemaeker, J. 1989. The use of mechanical resonance measurements to determine fruit texture. Acta Hort. 258:331-339.
49. DeEll, J. R., and R. K. Prange. 1992a. Postharvest quality and sensory attributes of organically and conventionally grown apples. HortScience 27:1096-1099.
50. DeEll, J. R., and R. K. Prange. 1992b. Postharvest quality and storage of scab-resistant apple cultivars. HortTechnol. 2:352-358.
51. DeEll, J. R., and R. K. Prange. 1993. Update on apple storage research at Kentville, p. 75-79. 130th Annual Report of the Nova Scotia Fruit Growers' Association.
52. DeEll, J. R., and R. K. Prange. 1994. Maturity and storage requirements of 'McIntosh' and 'Cortland' strains, p. 86-87. 131st Annual Report of the Nova Scotia Fruit Growers' Association.
53. DeEll, J. R., and R. K. Prange. 1995. Ultra-Low oxygen (ULO) storage to control scald in 'Idared,' 'Spartan' and 'Delicious' apples, p. 82-84. 132nd Annual Report of the Nova Scotia Fruit Growers' Association.
54. DeEll, J. R., and R. K. Prange. 1998. Disorders in 'Cortland' apple fruit are induced by storage at 0° C in controlled atmosphere. HortScience 33:121-122.
55. DeEll, J. R., R. K. Prange, and D. P. Murr. 1997. Chlorophyll fluorescence as an indicator of apple fruit firmness, p. 67-73. In: Proc. Sensors for Nondestructive Testing: Measuring the Quality of Fresh Fruits and Vegetables. NRAES, Ithaca, New York.
56. DeLong, J. M. 1996. Preliminary results with the new stop drop RetainTM, p. 104-107. 133rd Annual Report of the Nova Scotia Fruit Growers' Association.
57. DeLong, J. M., R. K. Prange, and C. G. Embree. 1997. RetainTM and apple quality, p. 15. 134th Annual Report of the Nova Scotia Fruit Growers' Association.
58. DeLong, W. A. 1936. Variations in the chief ash constituents of apples affected with blotchy cork. Plant Physiol. 11:453-456.
59. Dewey, D. H., and M. L. Bourne. 1982. Low oxygen CA storage of 'McIntosh' apples. Proc. 3rd Natl. Controlled Atmosphere Res. Conf. 1:101-107.
60. Drake, S. R., F. E. Larsen, and S. S. Higgins. 1993. Greenspur on selected rootstocks - a better green. Good Fruit Grower 44(17):75-77.
61. Drake, S. R., J. K. Fellman, and J. W. Nelson. 1987. Postharvest use of sucrose polyesters for extending the shelf-life of stored 'Golden Delicious' apples. J. Food Sci. 52:1283-1285.
62. Eaves, C. A., F. R. Forsyth, J. S. Leefe, and C. L. Lockhart. 1964. Effect of varying concentrations of oxygen with and without CO_2 on senescent changes in stored 'McIntosh' apples grown under two levels of nitrogen fertilization. Can. J. Plant Sci. 44:458-465.

63. Edgerton, L. G., and G. D. Blanpied. 1970. Interactions of succinic acid 2,2-dimethylhydrazide, 2-chloroethylphosphoric acid and auxins on maturity, quality and abscission of apples. J. Amer. Soc. Hort. Sci. 95:664-666.
64. El-Ansary, M. M., H. M. Ayaad, and F. El-Morshed. 1992. The effect of spraying and post-harvest treatment with calcium chloride on the fruit quality changes of 'Anna' apples during cold storage at 4C. Acta Agronomica Hungarica 41:209-213.
65. Elfving, D. C., C. L. Chu, E. C. Lougheed, and R. A. Cline. 1987. Effects of daminozide and paclobutrazol treatments on fruit ripening and storage behavior of 'McIntosh' apple. J. Amer. Soc. Hort. Sci. 112:910-915.
66. Elfving, D. C., E. C. Loughheed, and R. A. Cline. 1991. Daminozide, root pruning, trunk scoring, and trunk ringing effects on fruit ripening and storage behavior of 'McIntosh' apple. J. Amer. Soc. Hort. Sci. 116:195-200.
67. Ericsson, N. A. 1993. Quality and storability in relation to fertigation of apple trees cv. 'Summerred.' Acta Hort. 326:73-83.
68. Fallahi, E., B. R. Simons, J. K. Fellman, M. A. Longstroth, and W. M. Colt. 1994. Tree growth and productivity and postharvest fruit quality in various strains of 'Delicious' apple. J. Amer. Soc. Hort. Sci. 119:389-395.
69. Fallahi, E. T., D. G. Richardson, and M. N. Westwood. 1985. Quality of apple fruit from a high density orchard as influenced by rootstocks, fertilizers, maturity, and storage. J. Amer. Soc. Hort. Sci. 110:71-74.
70. Fallahi, E., W. S. Conway, K. D. Hickey, and C. E. Sams. 1997. The role of calcium and nitrogen in postharvest quality and disease resistance of apples. HortScience 32:831-835.
71. Fan, X., S. M. Blankenship, and J. P. Mattheis. 1999. 1-Methylcyclopropene inhibits ethylene ripening. J. Amer. Soc Hort. Sci. 124:690-695.
72. Farag, K., and J. P. Palta. 1990. Use of lysophosphatidylethanolamine, a natural lipid, as an aid for fruit ripening and improving keeping quality, p. 135-137. In: Proc. 17th Annual Meeting of the Plant Growth Regulat. Soc. Amer.
73. Fédération des Producteurs de Pommes du Québec (FPPQ). 1996. Guide aux producteurs et emballeurs, saison 1995-1996. Plan de la commercialisation de la pomme du Québec.
74. Ferree, D. C. 1989. Influence of orchard management systems on spur quality, light, and fruit within the canopy of 'Golden Delicious' apple trees. J. Amer. Soc. Hort. Sci. 114:869-875.
75. Finney, Jr., E. E. 1970. Mechanical resonance within red 'Delicious' apples and its relation to fruit texture. Trans. ASAE 23:177-180.
76. Fisher, D. V. 1939. Storage of 'Delicious' apples in artificial atmospheres. Proc. Amer. Soc. Hort. Sci. 37:459-462.
77. Forsyth, F. R., C. A. Eaves, and H. J. Lightfoot. 1969. Storage quality of 'McIntosh' apples as affected by removal of ethylene from the storage atmosphere. Can. J. Plant Sci. 49:567-572.
78. Gatti, R., and G. Gil. 1982. RegulaciÛn de la madurez de manzanas cv Granny Smith con ethephon y anilladura. Ciencia e Investig. Agraria 9:27-36.
79. Graell, J., I Recasens, J. Salas, and M. Vendrell. 1993. Variability of internal ethylene concentration as a parameter of maturity in apples. Acta Hort. 326:277-284.
80. Granelli, G., V. Ughini, and A. Minguzzi. 1989. Harvest and postharvest apple quality influenced by boron application. Acta Hort. 258:405-412.
81. Granger, R. L., and G. L. Rousselle. 1984. Effect of ethylene removal by alumina/potassium permanganate on 'McIntosh' apples in regular and controlled atmosphere storages. Acta Hort. 157:57-64.
82. Greene, D. W. 1993. A comparison of the effects of several cytokinins on apple fruit set and fruit quality. Acta Hort. 329:144-146.
83. Greene, D. W. 1996. AVG: a new preharvest drop control compound for apples. Proc. 101st Annual Meeting of the Massachusetts Fruit Growers' Association 102: 79-84.
84. Greene, D. W., and W. J. Lord. 1978. Evaluation of scoring, limb spreading and growth regulators on growth, yield, and fruit quality of 'Delicious' and 'Cortland'apple trees. Amer. Soc. Hort. Sci. 103:208-210.
85. Greene, D. W., W. J. Lord, and F. W. Southwick. 1973. Effects of SADH (Alar), ethephon and preharvest drop control chemicals on quality of 'McIntosh' apples. Proc. 79th Annual Meeting of the Massachusetts Fruit Growers' Association 79:112-119.
86. Greene, D. W., W. J. Lord, F. W. Southwick, and W. J. Bramlage. 1972. Interactions of SADH (Alar), ethephon and preharvest drop control chemicals on quality of 'McIntosh' apples. Proc. 78th Annual Meeting of the Massachusetts Fruit Growers' Association 78:85-91.
87. Greene, G. M., and C. B. Smith. 1980. The influence of calcium chloride rate and spray method on the calcium concentration of apple fruits. Acta Hort. 92:316317.
88. Gussman, C. D., J. C. Goffreda, and T. J. Gianfagna. 1993. Ethylene production and fruit-softening rates in several apple fruit ripening variants. HortScience 28:135-137.

89. Haffner, K. E. 1993. Storage trials of 'Aroma' apples at the agricultural University of Norway. Acta Hort. 326:305-313.
90. Hardenburg, R. E., and R. E. Anderson. 1979. Effects of postharvest calcium and other chemical treatments on softening, scald, bitter pit and breakdown of stored apples. Bulletin de l'Institut International du Froid 59:1132.
91. Hardenburg, R. E., A. E. Watada, and C. Y. Wang. 1986. The commercial storage of fruits, vegetables, and florist and nursery stocks. USDA Agriculture Handbook Number 66.
92. Harker, F. R., and I. C. Hallett. 1992. Physiological changes associated with development of mealiness of apple fruit during cool storage. HortScience 27:1291-1294.
93. Harker, F. R., R. J. Redgwell, I. C. Hallett, and S. H Murray. 1997. Texture of fresh fruit. Horticulture Reviews 20:121-224.
94. Herregods, M., and G. Goffings. 1993a. The storage of 'Jonagold' apples in U.L.O. - circumstances. Acta Hort. 343:148-154.
95. Herregods, M., and G. Goffings. 1993b. Variability in maturity, quality and storage ability of 'Jonagold' apples on a tree. Acta Hort. 326:59-64.
96. Hirst, P. M., D. J. Tustin, and I. J. Warrington. 1990. Fruit color responses of 'Granny Smith' apples to variable light environments. N.Z. J. Crop Hort Soc. 18:205-214.
97. Ingle, M., and M. C. D'Souza. 1989. Storage of 'Nittany' apples. Proc. 5th Intl. Controlled Atmosphere Res. Conf. 1:237-245.
98. Jobling, J., W. B. McGlasson, P. Miller, and J. Hourigan. 1993. Harvest maturity and quality of new apple cultivars. Acta Hort. 343:53-55.
99. Johnson, D. S. 1992. The effect of flower and fruit thinning on the firmness of 'Cox's Orange Pippin' apples at harvest and after storage. J. Hort Sci. 67:95-101.
100. Johnson, D. S. 1994. Influence of time of flower and fruit thinning on the firmness of 'Cox's Orange Pippin' apples at harvest and after storage. J. Hort. Sci. 69:197-203.
101. Johnson, D. S., C. J. Dover, and K. Pearson. 1993. Very low oxygen storage in relation to ethanol production and control of superficial scald in 'Bramley's' seedling apples. Acta Hort. 326:175-182.
102. Kamath, O. C., M. M. Kushad, and J. A. Barden. 1992. Postharvest quality of 'Virginia Gold' apple fruit. Fruit Var. J. 46:87-92.
103. Kapotis, G., E. C. Loughheed, and S. R. Miller. 1982. Low-oxygen storage-can it be? Proc. 3rd Natl. Controlled Atmosphere Res. Conf. 1:121-129.
104. Kerbel, E. L., F. G. Mitchell, A. A. Kader, and G. Mayer. 1989. Effects of 'Semperfresh' coating on postharvest life, internal atmosphere modification and quality maintenance of 'Granny Smith' apples. Proc. 5th Intl. Controlled Atmosphere Res. Conf. 1:247-254.
105. Khan, A.A. and J.F.V. Vincent. 1993. Compressive stiffness and fracture properties of apple and potato parenchyma. J. Test. Stud. 24:423-435.
106. Klein, J. D., J. Henzon, P. L. Irwin, S. Lurie, and N. Ben-Shalom. 1993. Studies on the mechanism of firmness retention of heat-treated apples. Acta Hort. 343:209-211.
107. Klein, J. D., and S. Lurie. 1990. Prestorage heat treatment as a means of improving postharvest quality of apples. J. Amer. Soc. Hort. Sci. 115:265-269.
108. Klein, J. D., and S. Lurie. 1992. Prestorage heating of apple fruit for enhanced postharvest quality: interaction of time and temperature. HortScience 27:326328.
109. Klein, J. D., and S. Lurie. 1994. Time, temperature, and calcium interact in scald reduction and firmness retention in heated apples. HortScience 29:194-195.
110. Klein, J. D., S. Lurie, and R. Ben-Arie. 1990. Quality and cell wall components of 'Anna' and 'Granny Smith' apples treated with heat, calcium, and ethylene. J. Amer. Soc. Hort. Sci. 115:954-958.
111. Knee, M. 1973. Polysaccharide changes in cell walls of ripening apples. Phytochemistry 12:1543-1549.
112. Kramer, G. F., C. Y. Wang, and W. S. Conway. 1991. Inhibition of softening by polyamine application in 'Golden Delicious' and 'McIntosh' apples. J. Amer. Soc. Hort. Sci. 116:813-817.
113. Kubik, M, L. Michalczuk, and T. Malinowski. 1991. Does externally applied Ca influence endogenous Ca accumulation in apple fruit? Fruit Sci. Rpt. 18:716.
114. Lange, E., and J. Fica. 1984. Response of 'Golden Delicious' apples to low oxygen storage, ethylene removal and to short term high CO_2 treatment before storage in 5% CO_2 + 3% O_2. Fruit Sci. Rpt. 11:113-121.
115. Lau, O. L. 1983a. Storage responses of four apple cultivars to a 'rapid CA' procedure in commercial controlled atmosphere facilities. J. Amer. Soc. Hort. Sci. 108:530-533.
116. Lau, O. L. 1983b. Effects of storage procedures and low oxygen and carbon dioxide atmospheres on storage quality of 'Spartan' apples. J. Amer. Soc. Hort. Sci. 108:953-957.
117. Lau, O. L. 1985. Storage procedures, low oxygen, and low carbon dioxide atmospheres on storage quality of 'Golden Delicious' and 'Delicious' apples. J. Amer. Soc. Hort. Sci. 110:541-547.
118. Lau, O. L. 1989. Responses of British Columbia-grown apples to low-oxygen and

low-ethylene controlled atmosphere storage. Acta Hort. 258:107-114.

119. Lau, O. L., and N. E. Looney. 1982. Improvement of fruit firmness and acidity in controlled atmosphere stored 'Golden Delicious' apples by a rapid O_2 reduction procedure. J. Amer. Soc. Hort. Sci. 107:531-534

120. Lau, O. L., and R. Yastremski. 1993. The use of 0.7% storage oxygen to attenuate scald symptoms in 'Delicious' apples: effect of apple strain and harvest maturity. Acta Hort. 326:183-189.

121. Lau, O. L., R. Yastremski, and M. Meheriuk. 1986. Influence of maturity, storage procedure, temperature, and oxygen concentration on quality and disorders of 'McIntosh' apples. J. Amer. Soc. Hort. Sci. 111:93-99.

122. Lehman-Salada, L. 1996. Instrument and operator effects on apple firmness readings. HortScience 31:994-997.

123. Lidster, P. D. 1982. Low oxygen atmospheres to maintain apple quality in storage. Proc. 3rd Natl. Controlled Atmosphere Res. Conf. 1:109-120.

124. Lidster, P. D., and S. W. Porritt. 1978. Influence of maturity and delay of storage on fruit firmness and disorder in 'Spartan' apple. HortScience 13:253-254.

125. Lidster, P. D., and S. W. Porritt. 1978. Some factors affecting uptake of calcium by apples dipped after harvest in $CaCl_2$ solution. Can. J. Plant Sci. 58:35-40.

126. Lidster, P. D., F. R. Forsyth, and H. J. Lightfoot. 1980. Low oxygen and carbon dioxide atmospheres for storage of 'McIntosh' apples. Can. J. Plant Sci. 60:299301.

127. Lidster, P. D., H. J. Lightfoot, and K. B. McRae. 1983. Fruit quality and respiration of 'McIntosh' apples in response to ethylene, very low oxygen and carbon dioxide storage atmospheres. Scientia Hort. 20:81-83.

128. Lidster, P. D., K. B. McRae, and K. A. Sanford. 1981. Responses of 'McIntosh' apples to low oxygen storage. J. Amer. Soc. Hort. Sci. 106:159-162.

129. Lidster, P. D., P. D. Hildebrand, L. S. Bérard, and S.W. Porritt. 1988. Commercial storage of fruits and vegetables. Agriculture Canada Publication 1532/E.

130. Liu, F. W., and L.-J. Ci. 1986. Responses of daminozide-sprayed 'McIntosh' apples to various concentrations of oxygen and ethylene in simulated CA storage. J. Amer. Soc. Hort. Sci. 111:400-403.

131. Liu, F. W., and M. M. King. 1978. Common evaluation of 'McIntosh' apple firmness. HortScience 13:162-163.

132. Looney, N. E. 1968. Inhibition of apple ripening by succinic acid, 2,2-dimethyl hydrazide and its reversal by ethylene. Plant Physiol. 43:1133-1137.

133. Looney, N. E., R. L. Granger, C. L. Chu, L. N. Mander, and R. P. Pharis. 1992. Influences of gibberellins A4, A4+7 and A4+iso-A7 on apple fruit quality and tree productivity. II. Other effects on fruit quality and importance of fruit position within the fruit canopy. J. Hort. Sci. 67:841-847.

134. Lougheed, E. C., E. W. Franklin, S. R. Miller, and J. T. A. Proctor. 1973. Firmness of 'McIntosh' apples as affected by Alar and ethylene removal from the storage atmosphere. Can J. Plant Sci. 53:317-322.

135. Lougheed, E. C., J. T. A. Proctor, and S. R. Miller. 1980. Low oxygen storage of three apple cultivars. HortScience 15:4240 (abstr.).

136. Lurie, S., and A. Nussinovitch. 1996. Compression characteristics, firmness, and texture perception of heat treated and unheated apples. Intl. J. Food Sci. Technol. 31:1-5.

137. Lurie, S., and J. D. Klein. 1990. Heat treatment of apples: differential effects on physiology and biochemistry. Physiol. Plant. 78:181-186.

138. Lurie, S., and J. D. Klein. 1992. Calcium and heat treatments to improve storability of 'Anna' apples. HortScience 27:36-39.

139. Lurie, S., J. Klein, and R. Ben-Arie. 1989. Physiological changes in diphenylamine-treated 'Granny Smith' apples. Israel J. Bot. 38:199-207.

140. Malenfant, D. 1998. Enquîte détaillants : la qualité a sa place, p. 11-14. In: Proc. Clinique Pomme, Journées Horticoles Régionales, Saint-Rémi, Québec.

141. Manseka, V. S., and M. Vasilakakis. 1993. Effect of stage of maturity, postharvest treatments and storage conditions on superficial scald and quality of apples. Acta Hort. 326:213-224.

142. Marini, R. P., R. E. Byers, and D. L. Sowers. 1993. Repeated applications of NAA control preharvest drop of 'Delicious' apples. J. Hort. Sci. 68:247-253.

143. Marmo, C. A., W. J. Bramlage, and S. A. Weis. 1985. Effects of fruit maturity, size, and mineral concentrations on predicting the storage life of 'McIntosh' apples. J. Amer. Soc. Hort. Sci. 110:499-502.

144. Mason, J. L. 1976. Calcium concentration and firmness of stored 'McIntosh' apples increased by calcium chloride solution plus thickner. HortScience 11:504-505.

145. Mason, J. L. 1979. Increasing calcium content of calcium-sensitive tissue. Commun. Soil Sci. Plant Anal. 10:349-371.

146. Mason, J. L., B. G. Drought, and J. M. McDougald. 1974. Effect of a calcium chloride dip on senescent breakdown, firmness and calcium concentration in 'Spartan' apple. HortScience 9:596.

147. Mason, J. L., J. J. Jasmin, and R. L. Granger. 1975. Softening of 'McIntosh' apples reduced by a post-harvest dip in calcium chloride solution plus thickener. HortScience 10:524-525.
148. Meheriuk, M., R. K. Prange, P. D. Lidster, and S. W. Porritt. 1994. Postharvest disorders of apples and pears. Agriculture Canada Publication 1737/E.
149. Miller, S. S. 1979. Effect of preharvest antitranspirant sprays on the size and quality of 'Delicious' apples at harvest. J. Amer. Soc. Hort. Sci. 104:204-207.
150. Mir, N. A., J. N. Bhat, and A. R. Bhat. 1993. Effect of calcium infiltration on storage behavior of red 'Delicious' apples. Indian J. Plant Physiol. 36:65-66.
151. Nova Scotia Intake Guidelines. 1995. Intake standards. Nova Scotia Fruit Growers' Association.
152. Oosterhaven, K. 1995. The taste of ULO-stored apples can be influenced. Fruitteelt Den Haag 85(41):14-15.
153. Opara, L. U., C. J. Studman, and N. H. Banks. 1997. Physico-mechanical properties of 'Gala' apples and stem-end splitting as influenced by orchard management practices and harvest date. J. Agr. Eng. Res. 68:139-146.
154. Park, S. H., and C. U. Lee. 1996. Effect of postharvest calcium infiltration on firmness, pectin content and occurrence of Botryosphaeria dothidea in apple fruits. J. Korean Soc. Hort. Sci. 37:81-86.
155. Peleg, K. 1993. Comparison of non-destructive and destructive measurement of apple firmness. J. Agr. Eng. Res. 55:227-238.
156. Peryea, F. J. 1991. Preharvest calcium sprays and apple firmness. Good Fruit Grower 42(13):12-15.
157. Peryea, F. J., and S. R. Drake. 1991. Influence of mid-summer boron sprays on boron content and quality indices of 'Delicious' apple. J. Plant Nutr. 14:825840.
158. Pirmoradian, M., and M. Babalar. 1995. Effect of rootstock and postharvest application of $CaCl_2$ during storage of Red Delicious apple on ethylene production and some qualitative factors. Iranian J. Agr. Sci. 26:69-76.
159. Plich, H., and E. S. Hegazi. 1978. Hormonal control of fruit maturation and ripening. I. The effect of growth regulators on ethylene production and acid phosphatase activity in apple fruits. Acta Hort. 80:409-417.
160. Poovaiah, B. W., G. M. Glenn, and A. S. N. Reddy. 1988. Calcium and fruit softening: physiology and biochemistry. Hort. Rev. 10:107-152.
161. Porritt, S. W. 1966. The effect of oxygen and low concentrations of carbon dioxide on the quality of apples stored in controlled atmosphere. Can. J. Plant Sci. 46:317-321.
162. Porritt, S. W., and P. D. Lidster. 1978. The effect of pre-storage heating on ripening and senescence of apples during cold storage. J. Amer. Soc. Hort. Sci. 109:5357.
163. Prange, R. K., M. Meheriuk, E. C. Lougheed, and P. D. Lidster. 1993. Harvest and storage, p. 64-69. In: Producing apples in eastern and central Canada. Agriculture Canada, Publication 1899/E.
164. Raese, J. T., and S. R. Drake. 1993. Effects of preharvest calcium sprays on apple and pear quality. J. Plant Nutr. 16:1807-1819.
165. Reeve, R.M. 1953. Histological investigations of texture in apples. II. Structure and intercellular spaces. Food Res. 18:604-617.
166. Riley, R. G., and P. E. Kolattukudy. 1976. Effect of treatment with calcium ion-containing formulations on the firmness of 'Golden Delicious' apples. HortScience 11:249-251.
167. Roy, S., W. S. Conway, J. G. Buta, A. E. Watada, C. E. Sams, and W. P. Wergin. 1996. Surfactants affect calcium uptake from postharvest treatment of 'Golden Delicious' apples. J. Amer. Soc. Hort. Sci. 121:1179-1184.
168. Ruiz-Altisent, M., P. Barreiro, and J. L. Garcia. 1994. Non-destructive quality measurement and modelling in fruits. Intl. Agrophysics 8:445-453.
169. Rupasinghe, H. P. V., D. P. Murr, G. Paliyath, and L. Skog. 2000. Inhibitory effect of 1-MCP on ripening and superficial scald development in 'McIntosh' and 'Delicious' apples. J. Hort. Sci. Biotechnol. 75:271-276.
170. Saftner, R. A., J. G. Buta, W. S. Conway, and C. E. Sams. 1997. Effects of surfactants on pressure infiltration of calcium chloride solutions into 'Golden Delicious' apples. J. Amer. Soc. Hort. Sci. 122:386-391.
171. Saftner, R. A., W. S. Conway, and C. E. Sams. 1998. Effect of postharvest calcium chloride treatments on tissue water relations, cell wall calcium levels and postharvest life of 'Golden Delicious' apples. J. Amer. Soc. Hort. Sci. 123:893-897.
172. Sams, C. E., and W. S. Conway. 1984. Effect of calcium infiltration on ethylene production, respiration rate, soluble polyuronide content, and quality of 'Golden Delicious apple fruit. J. Amer. Soc. Hort. Sci. 109:53-57.
173. Sams, C. E., and W. S. Conway. 1993. Postharvest calcium infiltration improves fresh and processing quality of apples. Acta Hort. 326:123-129.
174. Sams, C. E., W. S. Conway, J. A. Abbott, R. J. Lewis, and N. Ben-Shalom. 1993. Firmness and decay of apples following postharvest pressure infiltration of calcium and heat treatment. J. Amer. Soc. Hort. Sci. 118:623-627.

175. Sass, P., P. Meresz, T. Lov·sz, P. L·szlÛ, and I. Moln·r-Perl. 1993. Effect of picking date on the apple storage quality. Acta Hort. 343:61-62.
176. Schumaher, R., F. Fankhauser, and W. Stadler. 1986. Influence of growth regulators, ringing and root cutting on apple quality and physiological disorders. Acta Hort. 179:731-742.
177. Schupp, J. R., and D. C. Ferree. 1987. Effect of root pruning at different growth stages on growth and fruiting of apple trees. HortScience 22:387-390.
178. Schupp, J. R., and D. C. Ferree. 1988. Effects of root pruning at four levels of severity on growth and yield of 'Melrose'/M.26 apple trees. J. Amer. Soc. Hort. Sci. 113:194-198.
179. Scott, K. J., and R. B. H. Wills. 1979. Effects of vacuum and pressure infiltration of calcium chloride and storage temperature on the incidence of bitter pit and low temperature breakdown of apples. Austral. J. Agr. Res. 30:917-928.
180. Sfakiotakis, E., N. Niklis, G. Stavroulakis, and T. Vassiliadis. 1993a. Efficacy of controlled atmosphere and ultra-low oxygen low ethylene storage on keeping quality and scald control of 'Starking Delicious' apples. Acta Hort. 326:191-202.
181. Sfakiotakis, E., G. Naonos, G. Stavroulakis, and M. Vassilakakis. 1993b. Effect of growing location, harvest maturity and ventilation during storage on ripening and superficial scald of 'Starking Delicious' apples. Acta Hort. 326:231-235.
182. Sharples, R. O. 1967. The effect of postharvest-heat treatment on the storage behavior of 'Cox's Orange Pippin' apple fruits. Ann. Appl. Biol. 59:401-406.
183. Shear, C. B., and M. Faust. 1975. Preharvest nutrition and postharvest physiology of apples, p. 35-42. In: Haard, N. F. and D. K. Salunkhe (eds.), Postharvest Biology and Handling of Fruits. AVI Publication Inc., West Port, Connecticut.
184. Siddiqui, S., and F. Bangerth. 1995a. Effect of pre-harvest application of calcium on flesh firmness and cell-wall composition of apples - influence of fruit size. J. Hort. Sci. 70:263-269.
185. Siddiqui, S., and F. Bangerth. 1995b. Differential effect of calcium and strontium on flesh firmness and properties of cell walls in apples. J. Hort. Sci. 70:949-953.
186. Sitton, J. W., and M. E. Patterson. 1992. Effect of high-carbon dioxide and low-oxygen controlled atmospheres on post-harvest decays of apples. Plant Dis. 76:992-995.
187. Stow, J. R. 1988. The effects of high carbon dioxide pre-treatments and ethylene removal on the storage performance of apples cv. 'Cox's Orange Pippin.' Scientia Hort. 35:89-97.
188. Stow, J. R. 1989. Effects of oxygen concentration on ethylene synthesis and action on stored apple fruits. Acta Hort. 258:97-106.
189. Stow, J. 1993. Effect of calcium ions on apple softening during storage and ripening. Postharvest Biol. Technol. 3:1-9.
190. Testoni, A., and P. E. Zerbini. 1989. Picking time and quality in apple storage. Acta Hort. 258:445-454.
191. Tu, K., J. de Baerdemaeker, R. Deltour, and T. de Barsy. 1996. Monitoring postharvest quality of 'Granny Smith' apple under simulated shelf-life conditions: destructive, nondestructive and analytical measurements. Intl. J. Food Sci. Technol. 31:267-276.
192. Tu, K., K. Waldron, L. Ingham, T. de Barsy, and J. de Baerdemaeker. 1997. Effect of picking time and storage conditions on 'Cox's Orange Pippin' apple texture in relation to cell wall changes. J. Hort. Sci. 72:971-980.
193. Van Schaik, A. C. R., and H. A. M. Boerrigter. 1989. The effects of low ethylene storage in 1% and 3% oxygen on the quality of apples cv. 'Belle de Boskoop.' Acta Hort. 258:69-79.
194. Verreydt, J., E. Schrevens, J. Keulemans, J. de Baerdemaeker, and F. Vervaeker. 1993. Evolution of quality parameters of 'Jonagold' apples by means of non-destructive methods. Acta Hort. 343:63-66.
195. Vincent, J. F. V. 1989. Relationship between density and stiffness of apple flesh. J. Sci. Food Agr. 47:443-462.
196. Walsh, C. S. 1978. The effect of delayed storage, slow cooling, and polyethylene box liners on 'McIntosh breakdown. HortScience 13:534-536.
197. Wang, C. Y., and G. L. Steffens. 1987. Postharvest responses of 'Spartan' apples to preharvest paclobutrazol treatment. HortScience 22:276-278.
198. Warrington, I. J., C. J. Stanley, D. S. Tustin, P. M. Hirst, and W. M. Cashmore. 1996. Light transmission, yield distribution and fruit quality in six tree canopy forms of 'Granny Smith' apple. J. Tree Fruit Prod. 1(1):27-54.
199. Watada, A. E. 1986. Effects of ethylene on the quality of fruits and vegetables. Food Technol. 40(5):82-85.
200. Watkins, C. B., E. W. Hewett, C. Bateup, A. Gunson, and C. M. Triggs. 1989. Relationships between maturity and storage disorders in 'Cox's Orange Pippin' apples as influenced by preharvest calcium or ethephon sprays. New Zealand J. Crop Hort. Sci. 17:283-292.

201. Watkins, C. B., J. F. Nock, and B. D. Whitaker. 2000. Responses of early, mid and late season apple cultivars to postharvest application of 1-methylcyclopropene (1-MCP) under air and controlled atmosphere storage conditions. Postharvest Biol. Technol. 19:17-32.
202. Webster, D. H. 1978. Soft McIntosh and calcium content of apple fruit tissue. The Canadian Horticulture Council Report, Ottawa.
203. Webster, D. H., and P. D. Lidster. 1986. Effects of phosphate sprays on 'McIntosh' apple fruit and leaf composition, flesh firmness and susceptibility to low-temperature disorders. Can. J. Plant Sci. 66:617-626.
204. Weis, S. A., M. Drake, W. J. Bramlage, and J. H. Baker. 1980. A sensitive method for measuring changes in calcium concentration in 'McIntosh' apples demonstrated in determining effects of foliar calcium sprays. J. Amer. Soc. Hort. Sci. 105:346-349.
205. Yang, C. X., M. X. Gao, and K. W. Yang. 1991. Effect of postharvest calcium treatment on apple quality and K ion leakage. J. Fruit Sci. 8:201-204.
206. Zhang, Y. H., B. S. Cheng, and S. F. Yu. 1992. Effects of preharvest leaf spray with Polaris on physiological characteristics of postharvest apples. J. Shandong Agri. Univ. 23(2):119-124.

Journal American Pomological Society 55(1):27-33 2001

Performance of Primocane-fruiting Raspberries Grown in the Greenhouse

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Abstract

Seven cultivars of primocane-fruiting raspberries (*Rubus idaeus* L.) were grown for three years in a greenhouse in Simcoe, Ontario. Red raspberry cultivars 'Autumn Bliss,' 'Autumn Britten,' 'Caroline,' 'Heritage,' 'Polana,' and 'Summit,' and the yellow raspberry, 'Anne,' were compared for berry yield, fruit quality, and earliness and consistency of fruiting. Two types of propagules of 'Autumn Britten' were used, tissue-cultured and vegetative, and these behaved similarly with the exception of fruiting consistency in the first harvest season. 'Polana' yielded the most, 'Autumn Britten' produced the largest berries, and 'Summit' and 'Heritage' ranked highest for total fruit quality. Early and consistent fruiting patterns were exhibited by 'Polana,' 'Autumn Britten' and 'Summit.'

Introduction

Greenhouses have been used to produce crops such as tomatoes and cucumbers in the off-season for many years. Recently, off-season production of raspberries has been commercially developed in northern Europe (3) and may have potential in northern North America due to the limited growing season and short post-harvest life of raspberries.

Summer bearing and primocane fruiting raspberry cultivars can be grown in greenhouses where primocane fruiting canes can produce at least two crops in a twelve-month period (2). Primocane fruiting raspberries generally fruit on the tip of the primocane in late summer and fall, while the basal portion bears a summer crop the following year (5). All primocane fruiting raspberries will produce fruit on new primocanes without chilling of the initial root buds (5). Some cultivars, such as 'Summit,' fruit readily without vernalization while with others, such as 'Heritage,' fruiting is delayed (5, 6).

This study evaluates the performance of seven primocane fruiting raspberry cultivars in the greenhouse over a three-year

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