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Preharvest factors affecting physiological disorders of fruit

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Abstract

Development of disorders during postharvest ripening and storage of fruit depends on a range of preharvest factors. The most obvious of these is maturity of fruit at harvest. However, a number of other factors may be just as important in ripening-related disorders and in determining how fruit respond to low temperatures or other imposed postharvest conditions. Fruiting position on the tree and fruit temperature history are two of the most important of these factors. In apples, position strongly influences fruit mineral contents, and consequently incidence of postharvest disorders such as bitter pit. This positional effect may reflect pollination and cropping effects, or more direct differences in flow of minerals and water into developing fruit. In both apples and avocado fruit, we have shown that high temperatures experienced by fruit on the tree can influence the response of those fruit to low and high postharvest temperatures. Specific disorders such as watercore in apples and chilling injury in avocado can also be related to fruit exposure to sunlight and high temperatures; disorders such as scald in apples may be related to frequency of low temperature exposure over the season. Identification of preharvest factors raises the possibility of producing fruit with less predisposition to postharvest disorders.

Keywords: Apples; Bitter pit; Chilling injury; Heat treatments; Postharvest disorders; Preharvest factors; Superficial scald; Watercore

1. Introduction

There are few postharvest disorders of fruits which are completely independent of preharvest factors. Even incidence of disorders induced specifically by storage conditions such as low temperature or high CO_2 will be modified by preharvest environmental conditions and orchard practice. In terms of general postharvest product quality, this preharvest impact is implicit in the use of maturity indices for optimizing harvest times. Some preharvest factors may be effective through influencing fruit maturity. However, many direct effects of growing conditions and fruit development on postharvest disorder incidence may be quite independent.

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In attempting to understand the relationships between fruit development and postharvest quality it is useful to divide disorders into those which are predetermined on the tree and those which are specifically induced by storage conditions yet modified by preharvest factors. The division may be somewhat artificial, although still useful, in that some disorders are in both categories.

2. Predetermined disorders

A number of fruit disorders, whilst recognized as postharvest problems, do not always require specific postharvest conditions in order to be expressed, and may be closely associated with the later stages of fruit development and ripening. Storage conditions (e.g. low temperatures, controlled atmospheres) may be used to ameliorate or delay disorder development or, in some cases, they can result in greater disorder expression.

In some well-studied disorders, such as bitter pit in apples (Ferguson and Watkins, 1989), the preharvest factors have been relatively well-defined. In others, they are largely still speculative. The factors affecting fruit development are mostly associated with either positional effects on the tree, or the environment. Examples of these are the interplay between position and nutrition, and responses of fruit to temperature changes or extremes.

2.1. Mineral nutrition, fruit position and crop load

Calcium is the nutrient most commonly associated with postharvest disorders. In bitter pit in apple fruit, almost all preharvest factors which influence incidence of the disorder can be directly or indirectly related to calcium nutrition of the fruit. The only exception may be maturity. The reason for the higher incidence of bitter pit in less mature fruit is not clear, but is perhaps related to subsequent rates of ripening (Ferguson and Watkins, 1989).

A number of preharvest factors are associated with movement of calcium into the developing fruit (Table 1). Apart from pollination, these are associated largely with relationships between fruit development, position on the tree, and the dynamics of nutrient flow in relation to leaves on the fruiting wood. Even where a very strong relationship between light crop load, low fruit calcium concentration and high bitter pit incidence is found (Ferguson and Watkins, 1992), the reason for this relationship may still lie in the position, leaf area and wood age of the fruiting site (Volz et al., 1993). Whilst we still do not have a clear reason for these positional effects, they will be associated with the ability of the spur and bourse leaves to draw calcium into the fruiting wood (Lang and Volz, 1993). The net result of these factors is that growers can minimize the risk of bitter pit incidence through appropriate orchard practice, and prediction schemes can be developed to segregate lines of high risk fruit.

Preharvest calcium nutrition of other fruits such as papaya and tomatoes has also been linked with subsequent postharvest quality and disorders. In papayas, low mesocarp calcium concentrations have been linked with fruit softening (Qiu

Table 1
Preharvest factors associated with increased incidence of bitter pit in apple fruit

Preharvest factors associated with high bitter pit incidence	Reference
Low fruit Ca at harvest	Ferguson and Watkins, 1989
High fruit Mg and K at harvest	Ferguson and Watkins, 1989
Low crop load/low fruit Ca/high fruit K	Ferguson and Watkins, 1992; Volz et al., 1993
Large fruit volume and weight/low fruit Ca	Ferguson and Watkins, 1989
Poor pollination/low seed number/low fruit Ca	Bramlage et al., 1990; Tomala and Dilley, 1990; Brookfield et al., 1996; Volz et al., 1996b
Low spur/bourse leaf area/low fruit Ca	Jones and Samuelson, 1983; Proctor and Palmer, 1991; Volz et al., 1994, 1996a
Fruiting wood age and terminal or lateral positions	Schumacher et al., 1980; Volz et al., 1994
High position on tree/low fruit Ca	Jackson et al., 1971; Ferguson and Triggs, 1990

et al., 1995), and in tomatoes blossom end rot has been associated with low calcium and high potassium fertilization of tomato plants (Ho et al., 1993). In these examples, as with bitter pit, the interplay between nutrient transport, water relations and fruit growth provides the basis for disorder susceptibility.

The influence of fruiting position and crop load characteristic of calcium-related disorders in apple fruit has also been shown with stonefruit. Incidence of mealiness and flesh browning in peaches has been found to be higher in fruit from trees with low crop loads, and higher in fruit from shaded, inner canopy positions (Crisosto et al., 1997). As more information is assembled, crop load and fruiting position seem to have as strong an effect on a range of storage disorders as any environmental influence. The two factors may be closely linked in terms of water and nutrient supply to the fruit.

2.2. Temperature and carbohydrate physiology

Watercore in apple fruit may be the most obvious disorder associated with dysfunction in carbohydrate physiology. It is a disorder which is often found on the tree and can decrease during storage or ripening (Marlow and Loescher, 1984). Incidence is associated with an increase in sorbitol in the extracellular volume of the fruit, and is likely to result from poor or dysfunctional transport of sorbitol into the cell. Although it is a generic disorder in some apple cultivars (e.g. 'Fuji'), it does occur in others such as 'Cox's Orange Pippin'. Low levels of watercore may disappear during low temperature storage, and for some cultivars the affected fruit may subsequently develop internal breakdown (Perring, 1971). In terms of preharvest factors, the main influences include fruit maturity, fruit calcium levels, at least in the early development of the disorder (Bowen and Watkins, 1997), and fruit temperatures. Preharvest factors associated with other disorders, such as light crop loads, may also be associated with high watercore incidence (Faust et al., 1969). The disorder is thought to be of two types; the first is associated with late harvest and advanced maturity. Low temperatures during fruit maturation can exacerbate this type of watercore, such an effect occurring independent of fruit maturity (Yamada et al., 1994). Observations on 'Fuji' fruit in the USA suggest that there is greater incidence after a cooler growing season (Fallahi et al., 1997). The second type of watercore can be related to exposure of fruit to high temperatures on the tree, before fruit maturation (Faust et al., 1969; Fig. 1). Even in temperate regions, apple fruit flesh temperatures under direct sunlight can reach in excess of 40°C (Ferguson et al., 1998). Frequent exposure of apple fruit to such temperatures will result in damage such as sunburn (Bergh et al., 1980) and loss of texture (Tustin et al., 1993), as well as increases in generic disorders such as watercore. The differences between these high and low temperature effects may relate to long-term effects where low temperatures are influential, and short-term effects with high localized temperatures developed in exposed fruit, where incidence has been related to exposure (Fig. 1). Again, fruit position in relation to water and nutrient supply underlies disorder development.

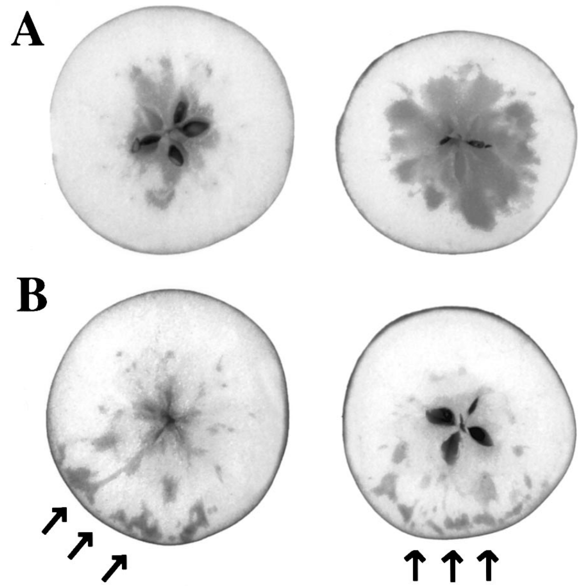

Fig. 1. Watercore in 'Cox's Orange Pippin' fruit. Fruit were picked at commercial harvest (February 1998). (A) Symptoms associated with the core area and not related to exposed sides of the fruit. (B) Symptoms located on the exposed side of the fruit only. Arrows indicate direction of maximum exposure to direct sunlight when the fruit were on the tree.

A disorder with many similarities to watercore is translucence in pineapple. This occurs before harvest, and can increase if fruit are stored (Rohrbach and Paull, 1982). Translucence has been related to high nitrogen, and high radiation, temperatures and rainfall during growth (Soler, 1994; Paull and Reyes, 1996). It also is more common in large fruit, a finding which suggests that it is related to fruit growth rates, and water and carbohydrate supply. High rainfall and the consequences on fruit growth also increase incidence of skin cracking disorders, such as found in cherries (Sekse, 1995), apples (Opara et al., 1997) and tomatoes (Whaley and Scott, 1997).

3. Storage disorders

The response of fruit to imposed storage conditions, principally low temperature, low O_2 and high CO_2, may well depend on preharvest growing conditions. In terms of specific disorders, there are a range of low temperature disorders which can be connected back to the condition of the fruit at harvest. Responses to altered gas concentrations in storage may be associated with maturity, cropping factors, skin and gas diffusion properties.

To prevent the occurrence of many of these disorders, one strategy has been to modify the storage condition which is responsible for inducing the disorder (e.g. raise storage temperature, reduce atmospheric CO_2 concentrations). However, this may sacrifice positive benefits from that storage condition. Knowledge of those preharvest factors which modify fruit responses to a storage condition is therefore important in optimizing product storage quality.

3.1. Low temperature disorders

Preharvest factors influencing postharvest chilling injury are mostly those to do with temperatures experienced during fruit development. Chilling injury of tomatoes (Lurie et al., 1993; Sabehat et al., 1996) and avocados (Woolf et al., 1995) can be reduced by heat treatments applied directly after harvest. By analogy, exposure to high temperatures on the tree, particularly close to or at harvest, may induce tolerance to low temperatures in postharvest storage. Flesh temperatures of avocado fruit growing in New Zealand, exposed to direct sunlight on the tree, frequently exceed 35°C (Woolf et al., 1999). These exposed fruit had lower levels of chilling injury than fruit from shaded parts of the tree, when stored at 0°C. Many fruits, not only tropical and subtropical, but also those growing under temperate conditions with relatively low (below 30°C) air temperatures (e.g. apples; Ferguson et al., 1998), can experience flesh temperatures in the range shown to be effective as postharvest heat treatments (35–45°C). We might expect in the future, therefore, to find more examples of chilling tolerance associated with preharvest high fruit temperatures.

One of the most studied postharvest disorders associated with low temperatures is superficial scald. This is a skin disorder linked to autoxidation of α-farnesene to conjugated trienes. It only develops after long-term cold storage, and it has been defined as a chilling injury (Watkins et al., 1995). At a physiological level, there are preharvest factors which predispose the fruit to the disorder (Emonger et al., 1994; Bramlage and Weis, 1997). The most direct relationship may be between greater incidence of scald in less mature fruit with low antioxidant to α-farnesene and conjugated triene ratios. High phosphate, low calcium and high potassium contents of fruit have been associated with increased scald incidence, although there is no clear direct physiological link. High nitrogen nutrition has also been associated with increased incidence, and there may be more direct connections between nitrogen and α-farnesene levels (Emonger et al., 1994). The shaded parts of fruit tend to develop scald more readily, suggesting a link with light intensity or temperature, and as with the heat effects just described, there is evidence that long-term temperature experience may influence subsequent development. From analysis of results collected over several years from four countries, Bramlage and Weis (1997) have concluded that reduced scald susceptibility in 'Delicious' apples can be related to relatively high amounts of preharvest low temperature exposure, rainfall and sunshine. Late season high temperatures resulted in higher susceptibility. The physiological reasons for these accumulated effects are not fully understood.

Some whole fruit and green plant tissues have been shown to withstand postharvest low temperatures better when conditioned by preharvest exposure to temperatures which are low, but above those which induce injury. Examples include grapefruit, sweet peppers and sweet basil shoots (Lang and Cameron, 1997, and citations therein). These results suggest some similarity between the effects of preharvest high and low temperature conditioning on tolerance to low temperature. There are suggestions that heat shock proteins induced by high temperatures have a role in both subsequent high and low temperature tolerance (Sabehat et al., 1996). Perhaps it is possible that proteins specifically induced by low temperature, and associated with tolerance, may have a longer-term effect.

3.2. Gas-related disorders

Fruit stored under controlled or modified atmosphere conditions are often subject to a range of disorders largely related to high CO_2 and/or low O_2 concentrations (Kader, 1997; Kupferman, 1997). In apples, the injury can be expressed both as internal browning (e.g. 'Braeburn') and as a skin disorder (e.g. 'Empire') (Watkins et al., 1997). There is considerable variation in incidence among seasons, regions and orchard lines, independent of maturity effects (Lidster et al., 1990; Watkins et al., 1997; Volz et al., 1998). Apples developing low O_2 injury, as a skin and/or internal disorder, can also show variation in susceptibility (Lau et al., 1987). Whilst there is a general presumption that preharvest factors are involved in susceptibility, there are not many examples of clear explanations for preharvest effects. For instance, the internal browning disorder found in 'Braeburn' apple fruit has been associated with high CO_2 and low O_2 concentrations within the fruit. It will occur on the tree and in air storage, indicating preharvest development or predisposition; disorder incidence is increased by CA storage (Kupferman, 1997; Lau, 1997; Elgar et al., 1998a). There is a strong harvest date effect on incidence, in common with many apple storage disorders, with later harvested fruit being more susceptible (Lau, 1997). However, a more specific preharvest factor not associated with maturity, is crop load, where light crop loads produce fruit with greater susceptibility (Elgar et al., 1998b). The reasons for this effect, so common with many disorders, are not understood. Watkins et al. (1997) have linked crop load, preharvest temperatures, and harvest date both with fruit respiration and skin permeance, and with more direct effects in predisposing fruit to CO_2 injury, but the physiological bases for these connections remain to be found.

4. Predicting disorder incidence

If preharvest development of predisposition to postharvest disorders is understood, then orchard practices which reduce risk can be developed (see Fig. 2). An additional benefit, particularly for marketing, is that such knowledge may provide the means for predicting potential incidence. If this can be done, then lines of products at high risk can be handled appropriately. Prediction can be based either on significant relationships between preharvest factors and postharvest disorder incidence, or on premature expression of the disorder by artificial means. The former have been the most successful.

Preharvest nutritional factors, such as those contributing to the strong calcium/bitter pit relationship, have formed the basis for commercial disorder prediction schemes which have been in use in New Zealand and other countries for some years (Ferguson and Watkins, 1989). While very significant biological relationships have been found, preharvest factors other than calcium alone have been introduced in order to make the prediction scheme more precise. In New Zealand, for 'Cox's Orange Pippin' and 'Braeburn' fruit, this has involved incorporating magnesium and potassium levels, crop load, and fruit size (see Table 1). Nutrient levels, fruit

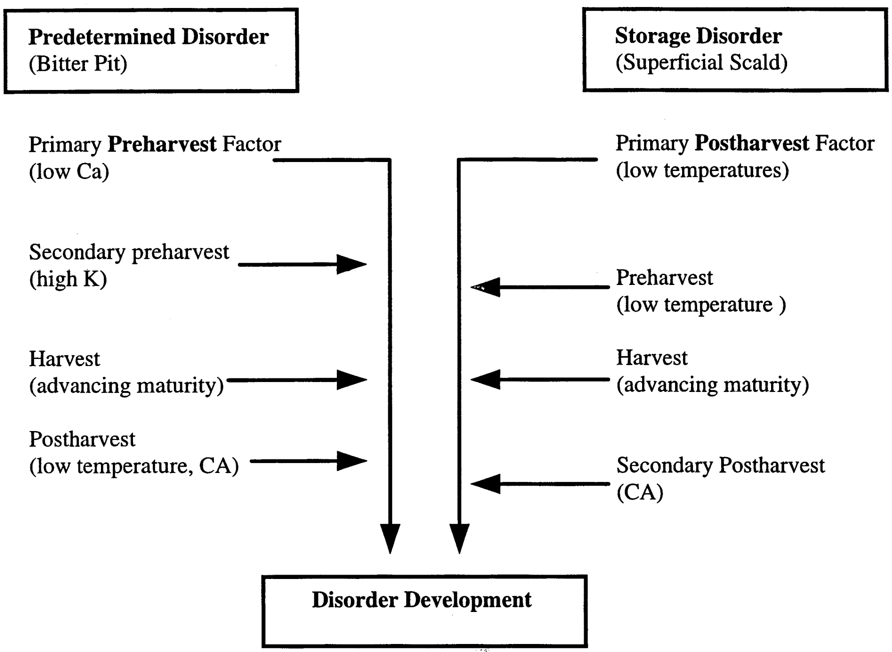

Fig. 2. Model of postharvest disorder development in relation to preharvest factors. Predetermined disorders are those which will develop either at late stages of maturity on the tree or during postharvest ripening. Storage conditions will modify incidence. Storage disorders are those which are specifically induced by storage conditions such as low temperature or high CO_2, but where severity of incidence may be modified by preharvest factors. Bitter pit and superficial scald are used as examples.

weight and density, have continued to be used and developed as preharvest factors in developing predictive systems for internal breakdown and bitter pit in apples (e.g. Wolk et al., 1998).

Preharvest environmental factors are being used to develop prediction schemes for scald in apples. Within a climatic location, temperature and maturity account for most of the measured variation in scald incidence (Bramlage and Weis, 1997). Any practical predictive system is likely to involve measurement of number of hours or days below critical temperatures over the growing season, frequent exposure to low temperatures being necessary to ensure a reduction in later scald development. Similar attempts to use preharvest temperature records to predict disorders are being made with pineapple translucence (Paull and Reyes, 1996), and the internal browning disorder in 'Braeburn' apples (Lau, 1997; unpublished New Zealand data).

5. Conclusion

Preharvest factors which may predispose fruit for subsequent disorder development are dominated by position of the fruit on the tree, characteristics of the fruiting site, crop load, mineral and carbohydrate nutrition of the developing fruit, water relations, and response to temperatures. Expression of disorders which are the direct result of storage conditions, such as low temperature and high CO_2, will still be modified by similar factors (Fig. 2). An understanding of these factors allows modification of fruit development to optimize storage quality, and development of methods for predicting disorder risk.

References

Bergh, O., Franken, J., Zyl, E.J., van Kloppers, F., Dempers, A., 1980. Sunburn on apples—preliminary results of an investigation conducted during the 1978/79 season. Deciduous Fruit Grower 30, 8–22.

Bowen, J.H., Watkins, C.B., 1997. Fruit maturity, carbohydrate and mineral content relationships with watercore in 'Fuji' apples. Postharvest Biol. Technol. 11, 31–38.

Bramlage, W.J., Weis, S.A., 1997. Effects of temperature, light and rainfall on superficial scald susceptibility in apples. HortScience 32, 808–811.

Bramlage, W.J., Weis, S.A., Greene, D.W., 1990. Observations on the relationships among seed number, fruit calcium and senescent breakdown in apples. HortScience 25, 351–353.

Brookfield, P.L., Ferguson, I.B., Watkins, C.B., Bowen, J.H., 1996. Seed number and calcium concentrations of 'Braeburn' apple fruit. J. Hortic. Sci. 71, 265–271.

Crisosto, C.H., Johnson, R.S., DeJong, T., Day, K.R., 1997. Orchard factors affecting postharvest stone fruit quality. HortScience 32, 820–823.

Elgar, J.H., Burmeister, D.M., Watkins, C.B., 1998a. Storage and handling effects in a CO2-related internal browning disorder of 'Braeburn' apples. HortScience 33, 719–722.

Elgar, J.H., Watkins, C.B., Lallu, N., 1998b. Harvest date, blush and crop load effects in a carbon dioxide-related storage injury of 'Braeburn' apple. HortScience (in press).

Fallahi, E., Conway, W.S., Hickey, K.D., Sams, C.E., 1997. The role of calcium and nitrogen in postharvest quality and disease resistance of apples. HortScience 32, 831–835.

Emonger, V.E., Murr, D.P., Lougheed, E.C., 1994. Preharvest factors that predispose apples to superficial scald. Postharvest Biol. Technol. 4, 289–300.

Faust, M., Shear, C.B., Williams, M.W., 1969. Disorders of carbohydrate metabolism of apples. Bot. Rev. 35, 169–194.

Ferguson, I.B., Triggs, C.M., 1990. Sampling factors affecting the use of mineral analysis of apple fruit for prediction of bitter pit. New Zealand J. Crop Hortic. Sci. 18, 147–152.

Ferguson, I.B., Watkins, C.B., 1989. Bitter pit in apple fruit. Hortic. Rev. 11, 289–355.

Ferguson, I.B., Watkins, C.B., 1992. Crop load affects mineral concentrations and incidence of bitter pit in 'Cox's Orange Pippin' apple fruit. J. Am. Soc. Hortic. Sci. 117, 373–376.

Ferguson, I.B., Snelgar, W., Lay-Yee, M.., Watkins, C.B., Bowen, J.H., 1998. Expression of heat shock protein genes in apple fruit in the field. Aust. J. Plant Physiol. 25, 155–163.

Ho, L.C., Belda, R., Brown, M., Andrews, J., Adams, P., 1993. Uptake and transport of calcium and the possible causes of blossom-end rot in tomato. J. Exp. Bot. 44, 509–518.

Jackson, J.E., Sharples, R.O., Palmer, J.W., 1971. The influence of shade and within-tree position on apple fruit size, colour and storage quality. J. Hortic. Sci. 46, 277–287.

Jones, H.G., Samuelson, T.J., 1983. Calcium uptake by developing apple fruits. II. The role of the spur leaves. J. Hortic. Sci. 58, 183–190.

Kader, A.A., 1997. A summary of CA requirements and recommendations for fruits other than apples and pears. Proceedings of the 7th International CA Research Conference, 13–18 July 1997, University of California, Davis, CA, vol. 3, pp. 1–34.

Kupferman, E., 1997. Summary of CA and MA storage and shipping conditions for pome fruits. Controlled atmosphere storage of apple. Proceedings of the 7th International CA Research Conference, 13–18 July 1997, University of California, Davis, CA, vol. 2, pp. 1–30.

Lang, A, Volz, R.K., 1993. Leaf area, xylem cycling and Ca status in apples. Acta Hortic. 343, 56–58.

Lang, D.L., Cameron, A.C., 1997. Pre- and postharvest temperature conditioning of greenhouse-grown sweet basil. HortScience 32, 114–116.

Lau, O.L., 1997. Influence of climate, harvest maturity, waxing, O2 and CO2 on browning disorders of 'Braeburn' apples. Proceedings of the 7th International CA Research Conference, 13–18 July 1997, University of California, Davis, CA, vol. 2, pp. 132–137.

Lau, O.L., Yastremski, R., Meheriuk, M., 1987. Influence of maturity, storage procedure, temperature, and oxygen concentration on quality and disorders of 'McIntosh' apples. J. Am. Soc. Hortic. Sci. 112, 93–99.

Lidster, P.D., Blanpied, G.D., Prange, R.K., 1990. Controlled atmosphere storage of commercial fruits and vegetables. Agriculture Canada Publication 1947/E Communications Branch, Agriculture Canada, Ottawa, Ontario, Canada.

Lurie, S., Klein, J.D., Watkins, C.B., Ross, G.S., Boss, P.K., Ferguson, I.B., 1993. Prestorage heat treatments of tomatoes prevent chilling injury and reversibly inhibit ripening. Acta Hortic. 343, 283–285.

Marlow, G.C., Loescher, W.H., 1984. Watercore. Hortic. Rev 6, 189–251.

Opara, L.U., Studman, C.J., Banks, N.H., 1997. Fruit skin splitting and cracking. Hortic. Rev. 1, 217–262.

Paull, R.E., Reyes, M.E.Q., 1996. Preharvest weather conditions and pineapple fruit translucency. Sci. Hortic. 66, 59–67.

Perring, M.A., 1971. Watercore in apples. Report East Malling Research Station for 1970, pp. 161–162.

Proctor, J.T., Palmer, J.W., 1991. The role of the spur and bourse leaves of three apple cultivars on fruit set, growth and calcium content. J. Hortic. Sci. 66, 275–282.

Qiu, Y., Nishina, M.S., Paull, R.E., 1995. Papaya fruit growth, calcium uptake, and fruit ripening. J. Am. Soc. Hortic. Sci. 120, 246–253.

Rohrbach, K.G., Paull, R.E., 1982. Incidence and severity of chilling induced internal browning of waxed 'Smooth Cayenne' pineapple. J. Am. Soc. Hortic. Sci. 107, 453–457.

Sabehat, A., Weiss, D., Lurie, S., 1996. The correlation between heat-shock protein accumulation and persistence and chilling tolerance in tomato fruit. Plant Physiol. 110, 531–537.

Schumacher, R., Frankhauser, F., Stadler, W., 1980. Influence of shoot growth, average fruit weight and diaminozide on bitter pit. In: Atkinson, D., Jackson, J.E., Sharples, R.O., Waller, W.M. (Eds.), Mineral Nutrition of Fruit Trees. Butterworths, London, pp. 83–91.

Sekse, L., 1995. Fruit cracking in sweet cherries (*Prunus avium* L.). Some physiological aspects—a mini review. Sci. Hortic. 63, 135–141.

Soler, A., 1994. Enzymatic characterization of stress induced translucence of pineapple flesh in the Ivory Coast. Acta Hortic. 334, 295–304.

Tomala, K., Dilley, D.R., 1990. Some factors influencing the calcium level in apple fruits. Acta Hortic. 274, 481–486.

Tustin, D.S., Watkins, C.B., Cashmore, W.M, Brookfield, P.L., 1993. Sources of variation in fruit quality of 'Braeburn' apple at harvest and after storage. HortScience 28, 446 (abstract).

Volz, R.K., Tustin, D.S., Ferguson, I.B., 1996. Mineral accumulation in apple fruit as affected by spur leaves. Sci. Hortic. 65, 151–161.

Volz, R.K., Tustin, D.S., Ferguson, I.B., 1996. Pollination effects on fruit mineral composition, seeds and cropping characteristics of 'Braeburn' apple trees. Sci. Hortic. 66, 169–180.

Volz, R.K., Biasi, W.V., Grant, J.A., Mitcham, E.J., 1998. Prediction of controlled atmosphere-induced flesh browning in 'Fuji' apple. Postharvest Biol. Technol. (in press).

Volz, R.K., Ferguson, I.B., Bowen, J.H., Watkins, C.B., 1993. Crop load effects on mineral nutrition, maturity, fruiting and tree growth of 'Cox's Orange Pippin' apple. J. Hortic. Sci. 68, 127–137.

Volz, R.K., Ferguson, I.B., Hewett, E.W., Woolley, D.J., 1994. Wood age and leaf area influence fruit size and mineral composition of apple fruit. J. Hortic. Sci. 69, 385–395.

Watkins, C.B., Bramlage, W.J., Cregoe, B.A., 1995. Superficial scald of 'Granny Smith' apples is expressed as a typical chilling injury. J. Am. Soc. Hortic. Sci. 120, 88–94.

Watkins, C.B., Burmeister, D.M., Elgar, H.J., Liu, F.W., 1997. A comparison of two carbon dioxide-related injuries of apple fruit. Proceedings of the 7th International CA Research Conference, 13–18 July 1997, University of California, Davis, CA, vol. 2, pp. 119–124.

Whaley, C.L.E., Scott, J.W., 1997. Environmental and physiological effects on cuticle cracking in tomato. J. Am. Soc. Hortic. Sci. 122, 797–801.

Wolk, W.D., Lau, O.L., Neilsen, G.H., Drought, B.G., 1998. Factors and time of sample collection for correlating storage potential of 'McIntosh', 'Spartan', and 'Golden Delicious' apples. J. Am. Soc. Hortic. Sci. 123, 104–109.

Woolf, A.B., Watkins, C.B., Bowen, J.D., Lay-Yee, M., Maindonald, J.H., Ferguson, I.B., 1995. Reducing external chilling injury in stored 'Hass' avocados with dry heat treatments. J. Am. Soc. Hortic. Sci. 120, 1050–1056.

Woolf, A.B., Bowen, H.J., Ferguson, I.B., 1999. Preharvest exposure to the sun influences postharvest responses of 'Hass' avocado fruit. Postharvest Biol. Technol. (in press).

Yamada, H., Ohmura, H., Ara, C., Terui, M., 1994. Effect of preharvest fruit temperature on ripening, sugars, and occurrence of watercore in apples. J. Am. Soc. Hortic. Sci. 119, 208–1214.