FACTORS INFLUENCING THE SUSCEPTIBILITY OF APPLES TO BRUISING

This thesis is presented in partial fulfilment of
the requirements of the degree of
Doctor of Philosophy
in
Horticultural Science
at
Massey University, Palmerston North,
New Zealand.

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1997

ABSTRACT

Financial returns to New Zealand orchardists could be increased if bruise damage to apples and its visual consequences were reduced. Comprehension of the variability of susceptibility to the bruising of apples associated with either preharvest, harvest or postharvest influences is fundamental to reducing bruise damage. Standard impacts to apples have been generated in many ways and bruise severity has generally been represented as bruise volume per unit energy. In this study bruise severity was represented by a) the diameter of a bruise generated by a sphere of mass and radius of curvature similar to that of apples and whose impact energy (0.32 *J*) was similar to apple-apple collisions that occurred during grading or b) the damage that apples incurred by grading in a standard manner. Bruise colour was also measured and visual differences between dark and light brown 'Granny Smith' bruised tissue were associated with a 5° difference in hue angle, as measured by a Minolta chromameter.

In 1990 from a survey of 'Granny Smith' orchards it was determined that the range in bruise diameter of individual fruit was 17% (fruit mass range; 0.157-0.207 kg) and in 1991 was 63% (fruit mass range; 0.098-0.278 kg). The between-season difference in mean bruise diameter was 2.8%. Over the two years it was found that bruise diameter of fruit from orchards producing either the most or least bruise susceptible fruit differed by an average of 6.5%. In 1991 bruise diameter generated from a standard impact was related to grader damage (R^2 = 0.49) and the slope of this relationship indicated that small increases in bruise diameter equated to large increases in grader damage. In both years the most bruise susceptible fruit had higher levels of tissue phosphorus, calcium and nitrogen than least susceptible fruit. In one year of the survey bruise diameter was positively related to apple calcium content and apple mass with grader damage positively related to phosphorus content.

In a within-orchard study between-tree variation in bruise diameter of 'Royal Gala' (11%) exceeded that of 'Granny Smith' (4%). Bruise diameter of least bruise susceptible fruit was more consistently related to starch index, soluble solids, fruit mass and firmness than bruise diameter of the most susceptible fruit. Harvesting 'Granny Smith' and 'Royal Gala' early rather than later in the season resulted in bruise diameter reductions of 5% and 21% respectively. Within-tree position of apples did not consistently influence susceptibility to bruising in either variety. Foliar sprays of calcium ($CaCl_2$) and phosphorus (H_3PO_4) did not influence fruit mineral contents or susceptibility to bruising. Apples from non-irrigated 'Braeburn' trees had smaller bruise diameters (6%), less calcium and tended to have more dry matter than apples from normally irrigated trees.

'Golden Delicious' apples harvested later in the day were less susceptible to bruise damage (7.3%) than those harvested early in the morning; elevated temperatures and reduced water status were identified as causative factors. As temperature increased from 0 to 20°C susceptibility to bruising showed a non-linear reduction. Bruise diameter and grader damage reduced 5% and 24% respectively when 'Granny Smith' apples were bruised at 20°C rather than when bruised at 0°C. If 'Royal Gala' were cooled to 2°C and then rewarmed to 20°C they sustained 36% less grader damage than if graded immediately after harvest. Useful reductions in grader damage (25%) were achieved by holding freshly harvested 'Royal Gala' at ambient temperatures for one day before grading. Storing the bruise susceptible cultivar 'Splendour' apples for 54 h at 20°C before bruising resulted in a 9% reduction in bruise diameter. A 24 h delay in pre-cooling of 'Royal Gala' was associated with a 0.5% weight loss and a 3% reduction in bruise diameter; delays of more than 24 h before pre-cooling were associated with enhanced ripening and greater weight loss but no measurable change in susceptibility to bruising.

In the 1991 survey, there were large between-orchard differences in hue angle of bruised 'Granny Smith' apple tissue (16°) and light brown bruise tissue was associated with higher fruit nitrogen content ($R^2 = 0.55$). Between-tree differences in hue angle of bruised tissue from 'Royal Gala' apples were large (15°) but with 'Granny Smith' were insignificant. Differences in bruised tissue colour due to enhanced maturity or within-tree position in both cultivars were not consistent. Cool storing 'Splendour' for 414 h before bruising appeared to increase bruise lightness.

ACKNOWLEDGEMENTS

I have been most fortunate to have had such excellent supervision throughout my PhD studies. My Chief supervisor, ENZA Professor Nigel Banks, provided academic and personal support at all times. Nigel easily established a friendly yet stimulating atmosphere for all those in the Postharvest Group and his tireless work ethic has been an incentive to all of his students.

Professor Errol Hewett, my second supervisor constructively reviewed my written work and generated inspiration at all levels. His attention to detail as well as being able to see the wider picture has been of considerable value. Dr Ian Gordon provided assistance regarding the numerous statistical queries resulting from this study.

To all of the staff and students associated with the Postharvest Group, I add without hesitation, my time at the Department of Plant Science at Massey University has been enjoyable and stimulating.

The manager of the FCU, Shane Max provided assistance and generated enthusiasm that was greatly appreciated. There have been too many apple and kiwifruit orchardists and packhouse managers to thank individually. These dedicated people provided valuable assistance and generated discussions that have been of immense value. A valuable contribution came from Tessa Mills which formed the basis of the irrigation study.

An important thank you goes to ENZA and the New Zealand Kiwifruit Marketing Board whose funding made these studies possible.

To my two children, Shanan and Jeane, thank you for showing patience and understanding.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	bruise area (mm^2)
AA	ascorbic acid
°C	degrees Centigrade
CRI	cell roundness index
CV	coefficient of variation
d	bruise diameter (mm)
d_1	major bruise diameter (mm)
d_2	minor bruise diameter (mm)
DSP	deformation at skin puncture (mm)
E	Energy (*J*)
EC	Enzyme Nomenclature
ENZA	New Zealand Apple and Pear Marketing Board
FCU	Fruit Crops Unit
Fig	Figure
g	gram
g	gravitational constant (9.81 m/s^2)
H	drop height (m)
H_1	rebound height (m)
h	bruise depth (mm)
h	hour
ISO	European International Organisation for Standardization
kPa	kilopascal
kg	kilogram
L	litre
LS	lower south tree position
M	mass (kg)
m	metre
ml	millilitre
mm	millimetre
N	Newton
n	number

nm	nanometre
NZ	New Zealand
P	perimeter (mm)
PPF	photosynthetic photon flux (μmol·s^{-1}·m^{-2})
PPO	polyphenol oxidase
R	radius of apple (mm)
R^2	coefficient of determination
r	correlation coefficient
S	inner bruise boundary area (mm^2)
s	seconds
SED	standard error of the difference
UK	United Kingdom
UN	upper north tree position
USA	United States of America
V	bruise volume (mm^3)
V_1	bruise volume (mm^3); Chen and Sun (1981)
V_2	bruise volume (mm^3); Holt and Schoorl (1977)
x	height of bruise above contact plane (mm)
χ^2	chi squared

CHAPTER ONE
INTRODUCTION

Large quantities of New Zealand (NZ) grown apples are rejected because bruising exceeds export quality standards thereby causing significant reductions in potential revenue. Two strategies could be implemented to reduce such damage and improve returns to growers. The first would be to improve the engineered aspects of apple handling systems so that fruit were subjected to fewer and less severe impacts during handling. A second strategy would be to identify and then manipulate factors that influence susceptibility of apples to bruise damage, thereby minimising the consequences of damaging influences. Whilst the potential benefits of the first strategy are immediately obvious, the links between pre- and postharvest conditions and susceptibility to bruising, and the extent that they could be manipulated under typical NZ growing conditions and harvesting systems, have to be identified. In a United Kingdom (UK) study, Johnson and Dover (1990) indicated there were no firm views on the effects of preharvest factors on bruise susceptibility although orchardists considered this to be a high priority for research. Preliminary discussions indicated that NZ orchardists also supported research in this area, which became the focus of this study.

Both fruit grading specialist staff and consumers use bruise visibility to assess apple suitability either for export or consumption. If visible evidence of apple bruise damage could be reduced by the manipulation of management factors, this might be expected to reduce the number of fruit rejected at the packhouse and by consumers.

Previous studies on the susceptibility of apples to bruise damage have used methods that are usually only loosely related to the type of damage that apples incur during harvesting and grading. These studies have usually employed bruise severity indices that are characterised by large variation which makes small differences between treatment groups difficult to detect. Furthermore, the relationship between bruise severity indices and the actual damage that apples incur during harvesting and grading practices does not appear to have been addressed by other researchers. There would be considerable value in determining how closely variation in measures of bruise susceptibility might predict likely damage that apples would incur during grading.

There are many physical attributes of apple tissue that are probably cultivar dependent but are also influenced by growing conditions or management inputs that could be associated with susceptibility to bruising. These include fruit mass, skin thickness, size and shape of cells in the epidermis, hypodermis and parenchyma as well as intercellular spaces, fruit firmness, starch contents, tissue density, stage of maturity and turgor pressure. As a fruit grows and matures on a tree and then later ripens and loses water after harvest in coolstore, the relative importance of the contribution of each attribute to energy absorption and damage changes. Comprehension of characteristics and dynamics of the resistance that apple tissue offers to impact damage would be important as it would give an understanding of the likely outcomes of apple treatments aimed at reducing susceptibility to bruising.

Anecdotal evidence which has been supported by preliminary research work suggests that some orchard lines of fruit are more sensitive to bruise damage than others. The reasons for such variation may be difficult to identify because of the diversity of growing conditions and the number of variable inputs associated with the production of apples from a particular orchard. It would be desirable to identify the extent of between-orchard variation for several seasons. Initial survey work could be used to provide indications as to where further research efforts to manipulate bruise susceptibility should be directed.

There are many preharvest factors that potentially could be manipulated to influence apple composition and structure and as a consequence perhaps influence susceptibility to bruising: rootstocks and planting density, fertilizer applications, ground cover management, pruning/canopy management, thinning, foliar sprays and irrigation intensity are the more obvious factors. The strong influence of mineral contents on apple characteristics (Marcelle, 1995) clearly offers an attractive approach to investigate because of the potential for growers to manipulate them by sprays and fertilizers.

Calcium is known to influence membrane permeability and strength of cell wall and intercellular bonding (Ferguson, 1984). Fruit phosphorus concentration has been negatively associated with cell volume (Letham, 1969), firmness and storage disorders (Webster and Lidster, 1986), and has also been associated with cell strength (Martin *et al.* 1965). Development of bruise colour is a result of polyphenol oxidase (PPO) activity on phenolics released from the ruptured cell walls in damaged tissue. The potential influence of apple mineral contents on the activity of the enzymatic browning substrates and, as a consequence, final bruise colour is not known. Investigating potential associations between mineral composition of apples and susceptibility to bruising as well as the influence of the application of foliar sprays could provide evidence on the role of the mineral content of apples in determining the sensitivity of apple tissue to bruising and effects on bruise colour. Johnson and Dover (1990) expected to find a relationship between fruit mineral content and susceptibility to bruising. However, in a long term survey of UK 'Bramley's Seedling' apple growers, this group found no consistent relationship between the endogenous fruit mineral content and bruise susceptibility. An alternative survey approach may be to compare groups of least and most bruise susceptible apples from a number of orchards.

Irrigation intensity is another management input that could be manipulated: apples maturing on trees under reduced or nil irrigation programmes would be expected to have lower water content than apples developing under adequate water supplies. It seems likely that apples harvested from trees subjected to differing irrigation programmes would have different responses to impact. Whilst Durand (1990) indicated that reduced irrigation of apple trees produced fruit that were less susceptible to bruising, no data were provided to quantify such effects.

Potential within-tree influences on fruit attributes are considerable and are primarily a result of variable light interception which has been studied by a number of researchers (Tustin *et al.* 1988; Campbell and Marini, 1992). The type, size, location and age of fruiting wood have also been shown to influence fruit composition. Based on this it would seem reasonable to expect that within-tree location of apples would influence fruit attributes in a manner that could affect sensitivity to impact damage.

The time of day that fruit are harvested may also influence their susceptibility to bruising. As temperatures rise during the day, leaves transpire and water losses may not be replaced by root supplies quickly enough and water may be drawn from the fruit to maintain leaf stomatal function. Thus, through a combined effect of increased temperature and lower water potential, fruit harvested later in the day may be less susceptible to bruising than those harvested early in the morning at low temperatures and higher water potential. Should this supposition be correct then choosing the time of day that harvesting operations are undertaken would be a relatively simple strategy to reduce bruise damage.

Once apples are harvested, a series of interactions between turgor, temperature and rate of ripening come into play to determine susceptibility to bruising. Freshly harvested apples may lose water quickly if placed in low humidity storage environments. Such an effect is likely to reduce bruise susceptibility and this has been suggested by Johnson and Dover (1990) as a possible strategy to reduce bruise damage. The extent that water loss may be used to reduce susceptiblity to bruising is governed by the New Zealand Apple and Pear Marketing Board's (ENZA, 1994) packing and coolstore criteria which are presumably designed to minimise the negative effects that excess water loss and ripening have on postharvest quality.

The firmness of coolstored apple tissue has been shown to be influenced by temperature (Bourne, 1982) and firmness has been occasionally associated with susceptibility to bruising. Elucidation of the temperature effect on susceptibility to the bruising of apples at harvest, or soon after, may provide information that could be used by orchardists in their efforts to reduce bruise damage.

Temperature of storage influences rate of ripening which is also important in determining susceptibility to bruising. As the middle lamella and cell walls begin to break down, cells are likely to be less able to transfer impact energy before rupturing. The point at which each of the three above mentioned influences can be maximised to reduce susceptibility to bruising without detrimentally influencing apple quality is of interest to those involved in postharvest storage and grading of the fruit.

Until the extent of between-orchard and within-orchard variability has been determined the scope to manipulate management inputs other than foliar sprays and irrigation programmes is limited. However, real possibilities exist to manipulate harvest and postharvest factors thought to be associated with the bruise susceptibility of apples. It would be of benefit to the NZ apple industry if these key factors were identified and quantified.

The objectives of this thesis were to:

- define a measure of bruise severity with low variance which was related to the damage that apples incur during postharvest handling

- define the variability in susceptibility to bruising and bruise colour apparent on a between-year, between-season, between-orchard, between-tree and within-tree basis

- investigate the possibilities to manipulate susceptibility to bruising by application of foliar sprays, reduced irrigation and harvest time during the day

- investigate postharvest opportunities to manipulate fruit temperature, storage time and rate of ripening to reduce the susceptibility of fruit to impact damage.

To systematically accomplish the above objectives this thesis was developed as follows. Chapter Two reviews current literature pertaining to apple bruising and bruise colour where a plant physiology rather than an engineering approach is adopted. General materials and methods are outlined in Chapter Three. As several experiments differed slightly, further specific details are provided in each chapter as required. The development of new methods is described in Chapter Four where various bruise severity indexes and the damage that apples incur during grading were critically examined. Determining an appropriate method of measuring bruise colour differences is also described. Chapter Five explores preharvest variation in susceptibility to bruising by way of a two-year orchard survey, a within-orchard study of two apple cultivars including harvest date, between-tree and within-tree considerations as well as determining the effect of irrigation on susceptibility to bruising. The relationship between a bruise severity index and the damage that apples incur during grading is also explored. The value of harvesting apples at different times of the day, the effect of temperature, storage time and ripening are explored in Chapter Six. Chapter Seven, the general discussion, evaluates results presented in the earlier chapters in the light of current knowledge and their implication for both bruise susceptiblity studies and industry. It also outlines further research possibilities identified through conducting this programme.

CHAPTER TWO

FACTORS INFLUENCING SIZE AND COLOUR OF APPLE BRUISES

2.1 Introduction

According to the European International Organisation for Standardization (ISO) quality can be defined as "the degree in which the whole characteristics of a product meets the requirements that spring from the goals of use". Quality has become the single most important factor leading to business success in markets (Shewfelt and Prussia, 1993). Kader (1983) defined quality of fruit and vegetables as "the combination of attributes or properties that give value in terms of human food". Because of strong international sales competition for horticultural produce, factors that may improve quality of produce delivered to markets are continually being researched. Attributes of any produce or product that are used to characterise quality should be easily detected or measured, so that they can be expressed quantitatively and evaluated objectively. To ensure suitable quality for NZ export apples is attained, the marketing arm of the New Zealand Apple and Pear Marketing Board (ENZA NZ International) has described minimum standards for quality attributes considered essential for market success.

Apple mass, maturity, firmness, soluble solids, and skin colour are all attributes that contribute in various ways to quality. At harvest, an apple could comply for these attributes but could still be rejected if excessively bruised during postharvest handling procedures. If an apple accumulates more than 100 mm^2 of visible skin bruising it should be rejected for export (ENZA, 1994); damage of this type resulted in a financial loss of approximately NZ$8 million to NZ growers of 'Granny Smith' apples in 1991 (Banks *et al.* 1992). In that year 'Granny Smith' comprised a large proportion of the total fruit exported and Klein (1987) ranked this variety as one of the moderately bruise susceptible apple cultivars when compared to other NZ grown apples. Had losses caused by bruising of other, more bruise susceptible cultivars that are exported been evaluated, then the financial loss would have been considerably greater. There are several other implications of excessive bruising that impinge on orchardists marketing options. The variety 'Splendour' was keenly sought after by consumers but has been withdrawn from export by ENZA because of its susceptiblity to bruising. Bruised apples rejected for export are sold to processors for substantially lower financial returns. Unfortunately such apples contribute to the concentration of off-flavours in juice and dried fruit products. It is clear that financial returns to NZ apple orchardists are significantly reduced by excessive bruising.

Compression and impact damage to apples, sufficient to cause bruising occur during harvesting, grading, packing and transport operations. Shewfelt and Prussia (1993) advocate a systems-approach to solving postharvest problems. By applying this theory to the typical handling system, identification of potential areas for reduction of bruising may result.

Several studies have identified the causes and incidence of apple bruising during harvesting and grading in NZ, the United States of America (USA) and Australia (Bollen and Dela-Rue, 1990; Studman, 1990; Banks, 1991; Brown *et al.* 1993; Crisosto *et al.* 1993; Dodds *et al.* 1994). Generally these studies have identified that grading speed and grader design contribute significantly to the bruise damage that occurs. A typical NZ export apple handling system has approximately eleven distinct operations (Fig. 2.1). ENZA identified that apples of count size 88 and 100 were bruised during transit, and Heap (1994) identified that tray design was responsible. Apart from this size range, NZ apples generally arrive at overseas warehouses bruise free (Robertson, pers comm. 1992). Quality attributes including bruise damage are evaluated both on entry and exit from overseas warehouses (Step 8) and poor quality fruit are generally discounted for sale or rejected; few fruit are rejected entirely because of excessive bruising. It is therefore possible to conclude that at the grading operation (Step 3) excessively bruised fruit are identified and rejected.

Research into the influence of grading machinery on bruising (Banks, 1991; Bollen and Dela Rue, 1990), cushioning materials (Studman *et al.* 1994),

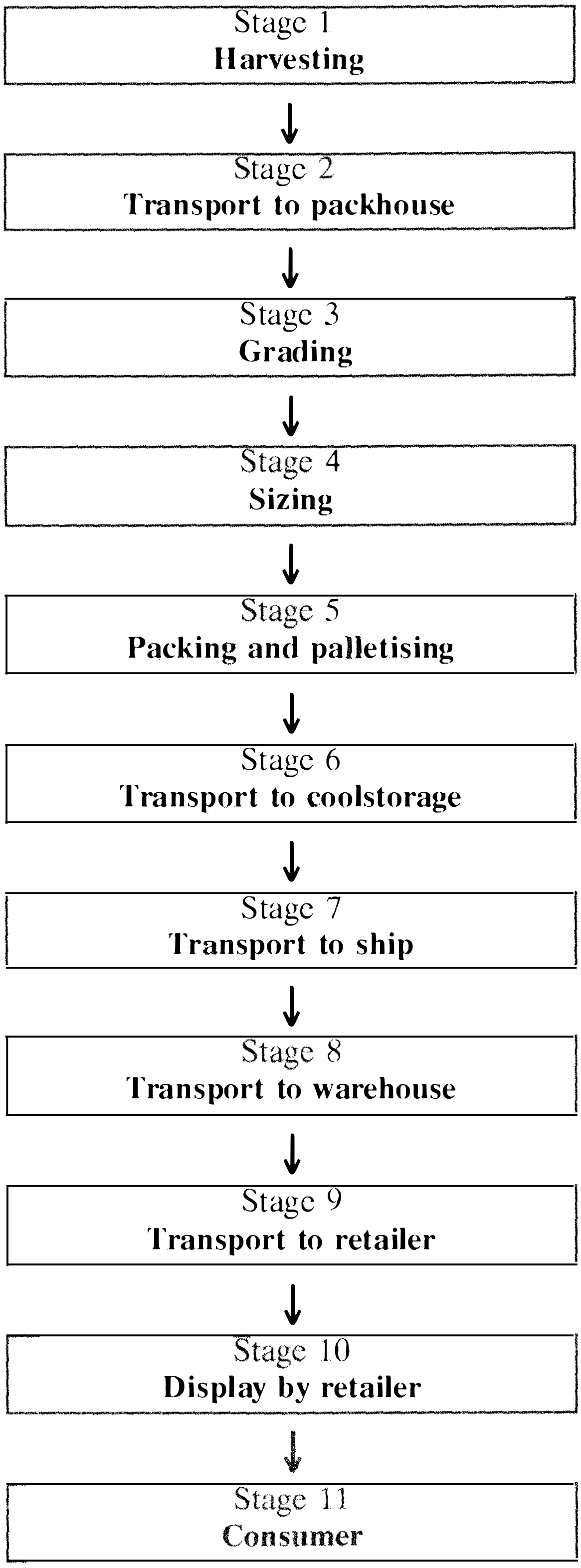


Fig. 2.1 Handling stages applicable to NZ export apples (modified from Shewfelt *et al.* 1987).

packaging types (Heap, 1994) and transport (Maindonald and Finch, 1986) has identified potential improvements to systems and equipment.

Whilst improving handling techniques is important in reducing bruise damage to apples, Johnson and Dover (1990) reported that bruise susceptibility varies more within a year than between years. This observation suggests that there may be scope to manipulate factors that reduce bruise susceptibility thereby making the fruit less prone to damage. Despite adopting a systems-approach to identify approaches to reducing bruise damage, Shewfelt and Prussia (1993) did not consider manipulation of bruise susceptibility as a possible solution.

There are preharvest, harvest and postharvest factors that could be manipulated by orchardists or packhouse operators that may reduce bruise damage. This Chapter reviews previous research related to methods of assessing bruise susceptibility and also examines the opportunity to manipulate production, harvest or storage factors to reduce apple susceptibility to mechanical damage and its undesirable visual consequences.

2.2 What is a bruise ?

Mohsenin (1986) defined bruising as damage to plant tissue by external forces causing alterations to the physical and/or eventual chemical (colour, flavour, texture) attributes of the crop. Apples can be bruised whilst still on the tree and anywhere in the harvesting, grading, packaging and marketing chain. Packhouse grading specialists and consumers perceive severity of bruising by the degree of tissue deformation and visible browning which depends on bruise size, bruise colour and background skin colour.

Unless bruises that occur during grading are recognised by skin indentation, they are often not identified by grading specialists. Therefore, Shewfelt's (1986) description of bruising as "latent damage" ie. damage incurred at one step in a postharvest system but not apparent until a later step, is accurate. The practical implications of this fact are that every effort should be made to reduce the incidence of bruising at harvest, grading and during later handling operations.

It is clear that the engineering approach to bruising has been to design handling systems that are less predisposed to damage fruit. However, if the potential kinetic energy of fruit or energy from other mechanical sources that is generated during handling operations exceeds levels that can be absorbed by engineered devices (cushioning, packaging, shock absorbers), then energy is transferred to fruit. Whilst the fruit can absorb some energy without damage, generally, absorbed energy is dissipated by tissue failure. Apple tissue failure depends on the type, severity and duration of energy transfer (Pitt, 1992):

- Impacts - these usually occur during harvesting and grading and are caused by fruit-fruit collisions or by fruit hitting other hard objects.

- Vibration, friction and abrasion - such damage usually occurs during transportation.

- Compression - usually a result of overloading of field bins or poor packaging.

For similar amounts of energy absorbed, impact-generated bruise volumes on apples were approximately 40% smaller than those resulting from compression (Holt and Schoorl, 1977). Substantiating this observation, Rodriguez *et al.* (1990) determined that there were clear differences in tissue response to impact and compression damage. However, impacts are the most prevalent cause of apple damage during handling operations in NZ (Banks, 1991) and for this reason have been researched in more detail.

Generally, different apple cultivars each have their own characteristic cell packing arrangement, stage of maturity and ripening, and therefore display variable responses to impact damage. Knowledge of cell dynamics and physiology assists in appreciating the causes of variation in tissue sensitivity to bruising and these are described in the following section.

2.3 Bruise development

The causes of tissue failure have been intensively researched by engineers in attempts to quantify, and facilitate prediction of, bruise damage. It is clear that apple tissue shows viscoelastic properties (Sommers, 1965) defined as "a combined solid-like and liquid behaviour in which the stress-strain relationship is time dependent" by Mohsenin (1970). The intercellular bonds and movement of cell contents through the cell wall constitute the viscous component (Frey-Wyssling, 1952; Preston, 1955; Pitt, 1992). The elastic component arises from the incompressibility of the cell fluid and the elasticity of cell walls. The time-dependent properties of the structure result from changes in the plasticity of the cell wall and intercellular pectin bonds, the permeability of the plasmalemma and the degree of movement of unbound extra-cellular fluid (Pitt, 1992) as ripening proceeds. Stress (Newtons per m^2) has been described as the components of internal force that act through a given plane at the point at which the stress is applied. Strain (mm per mm) has been described as the unit change due to force in the size or shape of a body referred to its original size or shape. By the application of various test techniques it is possible to measure stress and strain to develop a range of definitions relating to the mechanical properties of fruit and vegetable tissue; these lie outside the scope of this work. Because of the complex interactions of cultivar effects, variable fruit mass, size, maturity, type and shape of impacting surface, impact velocity, height of fall, temperature and water status of fruit tissue, definitive models predicting bruising have not yet been developed.

Pitt (1992) suggested that whilst further work on the technical understanding of tissue failure and impact dynamics could be undertaken, it was important that current knowledge was practically applied to reduce bruise damage to horticultural produce. This philosophy is fundamental to the physiological investigations that are described in the following chapters.

2.3.1 Mechanisms of tissue failure

Holt and Schoorl (1977) described apple tissue and the dissipation of energy during impact as: "an orderly arrangement of liquid filled spherical cells bounded by viscoelastic membranes with air filled interstitial spaces. On initial compression, cells are deformed into ellipsoids under stress distribution similar to an elastic sphere. Further compression would result in cell wall fracture i.e. cells bursting in regions of high shearing stress. Distortion and bursting of cells explains the energy dissipative system".

This description, for completeness requires the addition of several factors that are important influences in the transfer of energy to apple tissue. It must be added that:

- Whilst cell walls do have elastic properties their elasticity modulus (which decreases during ripening) is not high, particularly when prestressed by high turgor pressure (Nilsson *et al.* 1958). Thus, turgor pressure is important in determining the point at which the cell wall's elastic capacity is exceeded.

- Cell interstitial spaces vary in size between cultivars and the stage of ripening and are usually filled with air and solutes (Vincent, 1989; Pitt, 1992). Therefore, the potential of cells to deform or be displaced when compressed varies considerably both between and within cultivars.

- The strength of intercellular bonding determines whether these bonds slip or are broken during impact. The relative strength of intercellular bonding and the cell wall (not cell wall strength alone) are key factors in determining the efficiency of the apple's energy dissipative system and eventual type of structural failure.

An improved comprehension of the mechanisms of tissue failure can be derived by considering the four tissue characteristics that Pitt (1992) observed to be associated with tissue resilience to bruise damage.

2.3.1.1 Initial turgor pressure

As cells absorb water they stretch, become turgid and compress against each other increasing the strength of intercellular bonding. Such action decreases the capability of the cell to be displaced or to utilise the small elastic potential of the walls when impacted. Highly turgid cells are pre-stressed and are more sensitive to external loading than less turgid cells (Pitt and Chen, 1983).

Diurnal fluctuations in fruit diameter occur while fruit are still on the tree (pears, Klepper, 1968; apples, Jones and Higgs, 1982 and Higgs and Jones, 1985; immature apples, Lang, 1990; peaches, Berger and Selles, 1993). If evaporative demands exceed leaf and trunk reserves then water is drawn from the fruit which results in fruit volume changes. Apple diameter begins to reduce mid-morning and reaches a minimum soon after peak leaf transpiration (about mid-day). In the early evening, as evaporative demands decrease, apple diameter returns to early morning levels. The fluctuations of up to 2% of fruit volume are assumed to be directly related to cell turgor (Lang, pers comm. 1993). Therefore, harvesting at mid-day or soon after when cell turgor is lowered may be a procedure that could be used to decrease the susceptibility of apples to bruise damage.

Various postharvest storage conditions could be used to influence water status of apples. Johnson and Dover (1990) suggested that reductions in fruit turgor by manipulating storage conditions after harvest could be used to reduce bruise susceptibility of fruit prior to grading. Garcia *et al.* (1995) reduced the weight of freshly harvested ‘Golden Supreme’ and ‘Golden Delicious’ apples by less than 1% after 16 h storage in low humidity (35-40%; at 20-25°C). After applying standard impacts, a small but significant reduction in bruise volume (about 5%) was measured on these apples when compared to controls. A similar experiment using stored fruit gave inconsistent results presumably because any weight loss critical to reducing apple bruise susceptibility had been lost before starting the experiment.

2.3.1.2 Plasma membrane hydraulic permeability

Plasma membranes are permeable to water and are either less permeable or effectively impermeable to various solutes. Cell contents are incompressible (Pitt, 1992) and therefore the ability of the membranes to allow liquids to pass through them, thereby relieving strain when subjected to external loading, may influence membrane breaking point. Potentially damaging impacts usually take about 5 - 10 milli-seconds (Garcia *et al.* 1988) and the ability of the membranes to convey water content outside the cell in this time may be limited (Nilsson *et al.* 1958). As fruit go from climacteric to post-climacteric, membrane viscosity and permeability increase (Lurie and Ben-Arie, 1983) and modifications in cell shape may occur as turgor decreases (Stow, 1989). Therefore, after periods in store, the increased permeability of the plasma membrane should contribute to reduce the tendency of cells to rupture at the moment of impact.

2.3.1.3 Viscoelasticity of the cell wall

Viscoelasticity encompasses most cell wall mechanical properties (Pitt, 1992) and relates primarily to their plastic and elastic properties. Immature fruit cell walls are more elastic than plastic. Such fruit cells are still expanding and the growth stage, which is driven by turgor pressure, is facilitated by relaxation of intercellular bonds (Cosgrove, 1993). As fruit ripen, cell walls become thinner, particularly in the vicinity of the middle-lamella (Ben-Arie *et al.* 1979), and more plastic (Ruiz, 1990) and are therefore more likely to rupture rather than stretch during impact. Generally, if fruit are exposed to higher levels of radiant energy during growth they tend to contain more fibre (Pitt, 1992). This might be expected to increase cell stiffness and reduce the susceptibility of cells to impact damage.

The viscoelastic properties of cell walls are reduced as temperatures decrease (Britton *et al.* 1987). At colder temperatures cell walls become stiffer and more brittle (Nelson and Mohsenin, 1968) and are therefore more susceptible to bruising damage. It is becoming increasingly common to coolstore or CA-store apples in bulk prior to grading, but the influence of fruit temperature at the time of grading on susceptiblity to bruising does not appear to have been quantified under NZ growing conditions. Based on the above argument it would seem likely that bruise damage may be reduced if coolstored apples were rewarmed immediately prior to grading.

Intercellular spaces can account for up to 30% of fruit volume and different apple cultivars may have similar cell sizes yet widely different proportions of intercellular spaces (Baumann and Henze, 1983; Vincent, 1989). Different cell packing arrangements of cultivars are likely to be reflected in variable tissue responses to damaging impacts.

The cell walls and interlamella layers constitute 1 - 3% of the fresh apple weight and impart rigidity to the whole structure. Cell wall rupture was considered to be the most important tissue failure mechanism in bruise development by Pitt and Davis (1984). This statement was based on the belief that cell wall rupture was required for enzymatic browning to occur. However, Rodriguez *et al.* (1990) determined that cell wall rupture was not essential for the initiation of enzymatic browning. This group suggested that disorganisation of membranes was sufficient to cause enzymes and substrates to leak thereby causing browning.

2.3.1.4 Viscoelasticity of the middle lamella

The middle lamella structure changes as fruit soften (Ben-Arie et al. 1979; Stow, 1989) chemical bonds within the middle lamella have been loosely likened to a 'sticky gel' (Jarvis, 1984). The strength of these bonds assists in determining the energy absorbing characteristics of apple tissue. Immature fruit have intercellular bonds that are strong and impact energy is dissipated through the whole fruit structure. Later as fruit ripen, cells enlarge, their walls become thinner and the volume of interstitial spaces increases leading to less cell-cell contact (Johnson and Dover, 1990). Therefore, more impact energy is dissipated at the site of impact generating larger areas of damaged tissue.

The viscoelastic properties of the middle lamella are reduced by lower temperatures (Britton *et al.* 1987) and therefore potential movement of the middle lamella during impact would be reduced and more energy would be absorbed by the cell wall. As a consequence, at lower temperatures, more cell walls would rupture rather than cell-cell bonds.

Transfer of energy to apple tissue is affected by all four of these fruit tissue components all of which are mutually dependent at the moment of impact. Whilst the susceptiblity of apple tissue to bruising is determined by the integration of the resistance of cells to rupture and the resistance of cells to separate, the location of each cell within the impact zone is also important. Cells in the centre of the impact zone are likely to separate and rupture, whilst those cells in the outer zone may show either type of damage depending on turgor and maturity. Lapsley *et al.* (1992) observed that mechanical deformation of non-mealy apples resulted in cell wall rupture, while mealy apple showed disintegration of tissue through individual intact cells or cell agglomerates. The relative importance of the mechanisms of tissue failure are dependent on inherent structural characteristics, ripening effects, turgor and the temperature of the apple tissue.

Other important influences on apple tissue response to impact include various growing conditions. Pitt (1992) identified cell size and number as important variables in this respect, both of which have been shown to display between-season variation (Smith, 1950). Garcia *et al.* (1988) observed that fruit with a dense, juicy pulp and low air-space volume were susceptible to deep bruises, whilst fruit with a high volume of air-space between the cells develop bruises that were wider and closer to the skin. Variation in skin thickness and strength (Mohsenin *et al.* 1962; Clevenger and Hamann, 1968), cell size and shapes in the epidermis, hypodermis, parenchyma and intercellular spaces are also likely to be associated with variation in tissue strength (Vincent, 1989; Ruiz, 1990; Patocka, 1992). Fruit firmness (Johnson and Dover, 1990), starch contents and density (Klein, 1987) have also been associated with tissue strength, but the association between susceptibility to bruising and these attributes has been variable. For instance Klein (1987) found a correlation between fruit density and fruit firmness (r = 0.46), but neither of these attributes were significantly correlated with bruise diameter or volume.

2.3.2 Physiological processes involved in browning

Impacts sufficient to rupture the cell wall usually damage cell membranes; both events have been reported to be essential to provide a mix of cellular components that lead to the development of the characteristic brown colour of bruised apple tissue (Diehl *et al.* 1979; Pitt, 1992). On the other hand Rodriguez *et al.* (1990) suggested that cell tonoplast rupture, and not necessarily cell rupture, was the cause of enzymatic browning.

Within several hours of being damaged, apple tissue generally develops a characteristic brown colour. Membrane (mainly thylakoid) disruption releases the copper-containing mono-oxygenase, polyphenol oxidase (PPO; EC 1.14.18.1) which becomes active when subjected to a change in pH, or when exposed to various cations (Valero and Garcia Carmona, 1992). In its activated form, PPO has two distinct enzyme functions (Oszmianski and Lee, 1990) which act on various phenols located primarily in the vacuole:

- the *o*-hydroxylation of monophenols to *o*-diphenols

- the mono-oxygenation of *o*-diphenols resulting in the production of *o*-quinones which polymerise in a non-enzymatic reaction to brown melanin pigments that stabilise by linkage to proteins.

It is clear that phenolics play a major role in the browning reaction. Amiot *et al.* (1992) reported that apple cortical tissue generally contains three classes of phenolics:

- Hydroxy-cinnamic acid derivatives such as chlorogenic acid, caffeoyl, coumaroyl and feruloyl, all of which react with PPO. Chlorogenic acid is a natural substrate for PPO action and the products from this reaction co-oxidise other substances (Oszmianski and Lee, 1990). Chlorogenic acid therefore plays a prominent role in the browning reaction. Phenols can constitute 1.2% of fresh apple weight (Trejo-Gonzalez and Soto-Valdez, 1991).

◆ Flavan-3-ols such as epicatechin and procyanidin. PPO activity on these compounds is enhanced in the presence of chlorogenic acid (Oszmianski and Lee, 1990) and the products are more intensely coloured compounds than those of chlorogenic acid (Rouet-Mayer *et al.* 1990).

◆ Flavanols such as anthocyanins have also been implicated in bruise discolouration (Ingle and Hyde, 1968). Anthocyanins have been associated with the intensification of red apple skin colours and appear to decrease in concentration from the skin to the third layer of cells (Mazza and Miniati, 1993). After cell disruption anthocyanins are subject to enzymatic degradation by an endogenic anthocyanase from which evolves two products (Markakis, 1982):

- release of aglycone from anthocyanin which spontaneously converts to colourless derivatives
- a product resulting from the action of PPO on anthocyanins in the presence of *o*-diphenols.

Though they are poor substrates, anthocyanins can also be directly acted upon by PPO (Markakis, 1982) and may also form complexes with phenolics to produce the yellow or brown pigments often seen in bruised apple tissue (Mazza and Miniati, 1993). Ascorbic acid (AA), metal ions and pH of the fruit tissue affect the stability of the anthocyanins (Markakis, 1982) and therefore their contribution to colour intensity. Seniphos a mineral mixture (calcium, phosphorus and nitrogen) has been shown to enhance anthocyanin content and delay ripening when compared to ethephon treatment (Larrigaudiere and Pinto, 1996).

Zocca and Ryugo (1975) indicated that bruise colour was related to PPO activity. However, according to Vamos-Vigyazo (1981), both level of enzymatic activity and substrate content determine whether browning rates of a fruit of a given cultivar correlate with PPO activity or polyphenol content. More recently, Amiot *et al.* (1992) determined that the degree of browning was related to the ratio of hydrocinnamic acid derivatives and flavan-3-ols as well as PPO activity. The velocity of the enzymatic reaction contributed to the extent of the final pigmentation but tissue pH and AA concentration also played an influential role. Amiot *et al.* (1992) concluded that PPO activity was not as important as the quantity of degraded phenolics which are generated by co-oxidation of phenolics by degraded phenolics as well as by enzyme activity in determining bruise colour. He also suggested that to reduce enzymatic browning, apple cultivars with low chlorogenic and flavan-3-ols contents should be selected.

2.3.3 Bruise colour development.

Different researchers have reported that apple bruises do not reach their maximum discolouration until 3-4 h (Hyde and Ingle, 1968; Samim and Banks, 1993a), 12 h (Klein, 1987) or 12 weeks (Prussia *et al.* 1986) after impact. Ingle and Hyde (1968) observed that 50% of browning occurred within 30 minutes of bruising with no further change after about 3 h. The rate of discolouration was roughly linear for the first 60 minutes and then decreased sharply. In a study of bruise colour changes with time, Samim and Banks (1993a) found that to assess bruises at their most intense degree of discolouration, they should be allowed to develop for a period of 4-14 h before sectioning and measuring. Depending on the objective of measuring bruise colour, it appears that measurements could be made at any time provided intervals between bruising and measuring are accurately replicated.

There are considerable varietal, as well as within-fruit, differences in the concentration of compounds responsible for bruise colour (Nadudvari-Markus and Vamos-Vigyazo, 1984).

2.4 Bruise severity

Bruise diameter, area and volume are all measures of bruise severity. Bruise dimensions are best measured about 4-14 h after bruising, by which time the bruised tissue has browned and is clearly distinguishable from undamaged tissue (Ingle and Hyde, 1968; Samim and Banks, 1993a).

2.4.1 Bruise size

Variation in bruise size for a given impact energy occurs between cultivar, orchard, season, stage of maturity and storage conditions (Johnson and Dover, 1990). Bruise size can be represented by linear dimension, area or volume.

2.4.1.1 Linear dimensions

Bruise diameter (d) and depth (h) are primary measurements that are made to evaluate bruise size. Bruise diameter is easily measured with micro-callipers and has been used by a number of researchers (Hyde and Ingle, 1968; Sekse and Opedal, 1993) to represent bruise severity. With red skinned cultivars it may be difficult to determine the bruise perimeter and there is merit in bisecting the bruise on the intact fruit and measuring diameter on exposed halves (Figs. 2.2 and 2.3).

2.4.1.2 Area

Bruise surface area (A) is the measure which is most closely related to that used by industry and consumers to determine if an apple satisfies required standards. ENZA (1994) stipulates an export apple should not have more than 100 mm^2 of accumulated bruise area whilst consumers may differ in what they consider is acceptable (Opara *et al.* 1991).

Pang *et al.* (1992) considered that, when two apples collided, the resultant bruise was ellipsoidal in shape and calculated bruise area using the following formula:

where d_1 and d_2 were the major and minor diameters.

Zhang *et al.* (1992) used surface area of the inner bruise boundary of the bruise (S) in an attempt to reduce the multiplication of errors associated with the calculation of bruise volume.

$$S = \pi\left(\frac{d^2}{4} + h^2\right) \qquad \text{.......... 2.2}$$

For definition of terms see Fig. 2.2.

2.4.1.3 Volume

Many researchers determine bruise volume (V) to quantify bruise severity. Klein (1987) excavated bruised tissue and measured its mass. However, this method could be very time consuming.

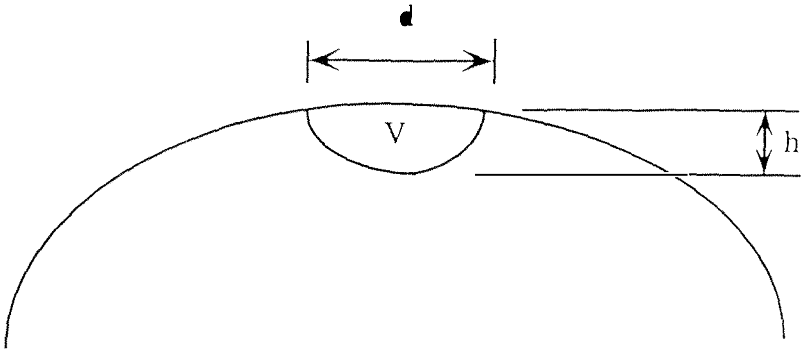


Fig. 2.2 A cross section of an idealised bruise showing the symbols used by Mohsenin (1970).

Calculation of bruise volume requires a measure of bruise width and depth and a simple procedure of measurement and calculation of bruise volume was developed by Mohsenin (1970). A cut was made longitudinally to the calyx and stem of the apple through the centre of a bruise to expose equal halves (Fig. 2.2), and measurements taken of *d* and *h*. He assumed the shape of a bruise was spherical and utilised the following volume equation:

$$V=\frac{\pi d}{24}(3h^2+4d^2) \qquad \text{.......... 2.3}$$

Holt and Schoorl (1977) assumed that the shape of the bruise was spherical above and below the contact plane (Fig 2.3). In addition to *d* and *h* the following measurements were taken:

- height of bruise above the contact plane (x)
- total bruise depth ($h + x$)
- radius of the apple (R)

on each half of the bruise (Fig. 2.3).

The height x of the bruising above the contact plane could be calculated from:

$$x=R-\sqrt{R^2-\frac{d^2}{4}} \qquad \text{........... 2.4}$$

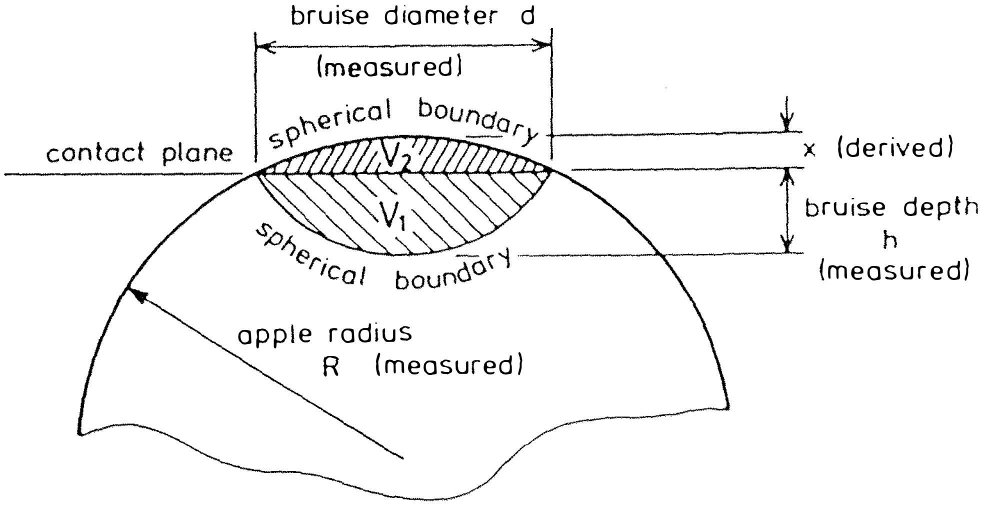


Fig. 2.3 Cross-section of an idealised bruise showing dimensions used in bruise volume calculations by Holt and Schoorl (1977).

Holt and Schoorl (1977) then used the following formulae to calculate bruise volumes both below (V_a) and above the contact plane (V_b):

$$V_a = \frac{\pi h}{24}(3d^2 + 4h^2) \qquad \text{.......... 2.5}$$

$$V_b = \frac{\pi x}{24}(3d^2 + 4x^2) \qquad \text{........... 2.6}$$

Total bruise volume was given by: $V = V_a + V_b$

$$V = \frac{\pi h}{24}(3d^2 + 4h^2) + \frac{\pi x}{24}(3d^2 + 4x^2) \qquad \text{.......... 2.7}$$

Diener *et al.* (1979) considered that the bruise was a partial sphere and used the following volume formula:

$$V = \frac{\pi}{6}h(0.75d^2 + h^2) \qquad \text{.......... 2.8}$$

Chen and Sun (1981) assumed that bruise shape was a semi-oblate spheroid and cut through the centre of the bruise region and measured maximum bruise width and depth with a scale.

$$V = \frac{1}{6}\pi h d^2 \qquad \text{.......... 2.9}$$

There are several problems with utilising volume as an indicator of bruise severity:

- ◆ Bruise shape varies depending on tissue type, impactor type, energy of impact and maturity of the apple and therefore care is needed in selection of the appropriate volume formula.

- Bruise diameter, depth and height are squared and/or multiplied in subsequent volume calculations. Any experimental errors associated with their measurement are compounded in the calculations thereby increasing statistical errors and reducing the accuracy of comparisons between treatment means.

It is clear that if a comparative statistical evaluation of the errors associated with each method of representing bruise severity was completed, then it may be possible to identify a suitable method of representation.

2.4.2 Influence of colour on bruise visibility

Visual cues, particularly colour, aid in the identification of colour-linked, perceived flavours (Christensen, 1983). As consumers primarily judge apples on their appearance (Opara *et al.* 1991), even a moderate amount of bruising on apples can reduce consumer acceptance. The degree of brown discolouration and the extent to which the brown colour is masked by apple skin colour are particularly important in this respect. For instance, 'Red Delicious' apples are more susceptible to bruising than 'Delicious' although industry perceives the latter to be more easily damaged (Zhang *et al.* 1992). Similarly, Johnson and Dover (1990) found 'Bramley's Seedling' less susceptible to bruising than other cultivars but, because of its lighter skin colour, it was perceived to be very bruise susceptible.

Manipulation of factors may reduce bruise size and make them less visible. There may be opportunities to manipulate bruise colour in an analogous way to reduce visibility further.

2.5 Factors influencing bruise size

Impact energy and bruise susceptibility are the most significant factors affecting bruise size. This section reviews current knowledge of the physical factors influencing impact energy and physiological factors which influence bruise susceptibility.

2.5.1 Impact energy

Many researchers have established significant relationships between bruise severity and impact energy (Holt and Schoorl, 1977; Diener *et al.* 1982; Klein, 1987; Brusewitz and Bartsch, 1989; Johnson and Dover, 1990; Chen and Yazdani, 1991). Impact energy (E ; J), is calculated from the equation:

$$E = M \cdot g \cdot (H - H_1) \qquad \text{.......... } \mathbf{2.10}$$

where

M = mass of impacting object (kg)
g = gravitational constant (9.81 m/s^2)
H = height object is dropped from (m)
H_1= rebound height (m)

Energy absorbed by the apple usually accounts for more than 90% of impact energy and rebound height is often ignored. It is clear from Equation 2.10 that a particular impact energy can be derived either by changing the mass of the impactor or altering drop height.

Development of a system of applying a standard impact to apples requires careful selection of the shape and mass of the indentor, impact energy and methodology by which the impact is applied to apples. A study by Banks *et al.* (1992) provides useful data if bruise susceptibility studies are to be linked to commercial situations. They observed that at particular points on grading equipment, apples (typical mass = 0.16 kg) can roll down drops of 0.3 m and generally land on other apples. From this study it was apparent that an impact energy E of approximately 0.38 J was common and that bruises often resulted from apple-apple collisions suggesting that spherical impact surfaces were common. The commercial relevance of some bruise susceptibility studies can be difficult to determine. For instance, Schoorl and Holt (1977) used a relatively large impact energy of about 1.25 J in their studies. At the other extreme

Rodriguez *et al.* (1990) were able to cause very small but measurable bruises using a 0.0012 J impact energy. Given that considerable extrapolation would be necessary to link their findings with typical commercial situations, this weakens confidence in the relevance of these latter studies to the damage that apples are likely to incur during postharvest handling. If the sizes of bruises generated in experimental bruise susceptibility evaluations were representative of the damage that apples incur during post harvest handling operations, then inferences regarding factors influencing commercial levels of bruising could be made with greater confidence

Banks *et al.* (1992) quantified the proportions of damage that were attributable to hand harvesting, bin filling, transport and grading. As most bruise damage occurs during grading and this process is easily repeatable when compared to the other phases of handling operations, this may be an appropriate location to determine a typical bruise size for bruise susceptibility studies. Using this approach Pang (1993) repeatedly graded a group of apples on a 'Treeways' grader in a standard manner. He concluded that any bruise over 150 mm^2 in area was unlikely to have occurred during grading. Unfortunately, Pang did not report the average apple mass used in his experiments and it is therefore not known if this bruise area was typical of bruises incurred by commercial sized apples. The area of bruises that apples typically incur during grading operations would be useful in determining a bruise size that could be generated by standard impacts.

2.5.2 Method of application

An early review of various methodologies to generate standard impacts to apples for use in bruising studies was given by Fluck and Ahmed (1973). However, Manor (1978) noted that as there was no standard method of measuring bruise damage, researchers often designed their own techniques.

Some researchers have dropped apples from a standard height onto a flat surface (Diener *et al.* 1982; Klein, 1987). Some or all dimensions of the resultant bruise were then used to assess bruise volume. However, there are a number of problems associated with this method:

◆ From Equation 2.10 it is clear that the impact energy of apples would be proportional to their mass. This method, therefore, provides a standard impact energy for fruit of uniform mass. Variation in bruise size caused by variable impact energies (apples of differing mass) can be compensated for in part, by expressing bruise volume as a percentage of total apple volume (Klein, 1987).

◆ Apples turn whilst falling and impacts are made at different sites on the apple. Bruise dimensions may vary because of the different sizes of cortical cells an apple has around its perimeter (Dedolph and Austin, 1962; Petrell *et al.* 1979; Pang, 1993). Furthermore, because of the variable radius of curvature of fruit, the surface area that is damaged during impact will vary thereby developing bruises of variable diameter and depth.

For these two reasons dropping apples of different mass onto flat surfaces is unlikely to provide an ideal comparative test.

Hyde and Ingle (1968) and Topping and Luton (1986) overcame these problems by swinging a pendulum with a flat impacting head against an apple which was held stationary at the bottom of the arc. Alternatively, Pang (1993) developed a pendulum that swung one apple against another stationary apple attached to a cord, similar in length to the pendulum. Unfortunately this type of apparatus is not easily used in the field and the procedure is time consuming.

A solution has been provided by Maness *et al.* (1992) who concluded that to overcome the effects of variable mass of individual peach fruit when dropped onto a surface, it may be better to drop a mass onto a fruit rather than drop a fruit onto a surface.

2.5.3 Modelling impacts

Utilisation of impact theory to calculate stresses and strains in fruit tissue during impact and to predict bruise damage has been hindered by the variability in, and dynamic nature of, responses of fruit tissue to impact. Hertz's (1881) theory of contact stresses for elastic bodies under static load requires material to be homogenous, have smooth surfaces and the radius of curvature of the impacting bodies must greatly exceed the radius of the contact surface (Sitkei, 1986). Despite fruit tissue being nonhomogenous, Hertzian theory can be utilised in a soft impact situation up to the point at which a significant bruise occurs (Horsfield *et al.* 1972). When two convex bodies collide the normal stress occurring at the contact surface is termed the contact stress. Sitkei (1986) outlined how contact stresses for fruit-fruit or fruit-flat plate impacts can be calculated. By utilising elastic impact theory, Pang (1993) showed that, depending on the type of impact, bruise surface area is similar to the contact area for sphere-sphere contacts. A range of parameters such as deformation, contact time and the distribution and variation of pressure as a function of time can be calculated. Contact area models demonstrate that the diameter or radius of curvature of the fruit has a significant effect on the bruise surface area.

An energy absorption model to describe bruising was advocated by Holt and Schoorl (1977) and has been shown to be useful at higher energy levels. This approach is dependent on bruise volume, the calculation of which poses several problems (Section 2.4.1.3).

Empirical models have been used (Siyami *et al.* 1988) to describe impacts to fruit. The acceleration, velocity and displacement of the impactor change rapidly within the duration of impact. Impacts can be described by impact energy and force history whilst the fruit absorbs energy and undergoes deformation, of which some is permanent. Chen *et al.* (1985) described a system whereby some of these parameters can be accurately measured allowing calculation of others. In application of this approach, Garcia *et al.* (1988) studied the relationship of these parameters to the ripeness of apples and pears. Impact duration and time to maximum force were strongly related to ripeness, maximum impact force rebound velocity and elastic rebound energy were of intermediate value and of least importance were maximum and permanent deformation, bruise size and impulse. Thus, final bruise dimensions were less affected by degree of ripeness than by parameters describing the dynamics of impact.

Whilst these models assist in explaining the nature of impacts, they have yet to be used as a basis for a general characterisation of the factors that influence bruise severity or tissue responses to impact. Whilst turgor effects were discussed by Pitt (1992), the effect on bruise susceptibility of small changes in cell number, cell wall thickness or strength, cell packing arrangement, skin strength, tissue temperature and maturity has yet to be attempted. The inclusion of some these variables into models is in part constrained by difficulties in measurement. Not-with-standing this, fruit tissue represents an integration of many attributes and the separation of the main effects at any point in time during ripening represents a challenge to those researchers who wish to develop either conceptual or quantitative models.

2.5.4 Bruise susceptibility

Bruise susceptibility has been defined as the measured bruise volume corresponding to the energy absorbed during either mechanically applied compression or resulting from free fall impacts ($mm^3 \cdot J^{-1}$; Holt and Schoorl, 1977; Garcia *et al.* 1988; Brusewitz and Bartsch, 1989). Potentially there are many factors that could either individually or in combination influence bruise susceptibility of apples.

2.5.4.1 Fruit variability

Agronomic and climatic factors influence the postharvest quality of fruit crops (Monselise and Goren, 1987; Sharples and Johnson, 1987) and it is likely that subtle changes in fruit contents or texture would influence susceptibility to bruising. Between-fruit variability has been documented by most researchers in bruising studies; generally groups of ten to 20 fruit have been used to assess between-treatment effects. Within-fruit variability has also been studied by Petrell *et al.* (1979) who noted that tissue strength varies around a fruit and that areas with greater cell numbers and reduced air spaces had greater strength. Brusewitz and Bartsch (1989) applied four bruises around the equator of apples and found that the blushed side sustained bruises that were 10.9% less in volume than those on the green side. They also found that there was less between-fruit variation in bruise volume on the blushed side. Within-fruit variation in bruise susceptibility has also been examined by Banks *et al.* (1989) who found that the blushed side of 'Royal Gala' was 30% more bruise susceptible than the opposite side. Tustin *et al.* (1988) related between-fruit variability in fresh fruit weight and soluble solids content to tree position and the degree that fruit are shaded. In consideration of the above it would seem prudent to attempt to reduce any potential experimental error by generating bruises on a standard position on the fruit surface (e.g. the equator of the blushed section of apples) and identifying within workable limits, the within-tree location of fruit.

2.5.4.2 Cultivar

It has been well established that different cultivars exhibit variable tissue damage responses to standard impact energies (Hyde and Ingle, 1968; Topping and Luton, 1986; Klein, 1987). Cultivar variation in specific gravity and intercellular air space in the outer parenchyma (Vincent, 1989) may account for the gross variation in bruise susceptiblity between cultivars. Different cultivars have characteristic skin strengths (Mohsenin, 1986) which may also be an important component in explaining variable cultivar bruise susceptibility. Pang *et al.* (1992) suggested that between and within-fruit variation in physical yield strength may account for the small differences in absolute bruise susceptiblity found between cultivars. A conclusion such as this could only be substantiated by a study where between and within-cultivar, and preferably within fruit variability, in susceptibility to bruising had been documented.

Considerable anecdotal evidence also suggests that a number of preharvest factors may be associated with bruise susceptibility. Packhouse operators observe that different orchard lots of the same cultivar vary in sensitivity to impact damage and this has been substantiated by Banks *et al.* (1989) in preliminary studies into causes of bruising. A comprehensive study of between-orchard variation in susceptibility to bruising as related to fruit contents and other fruit attributes could determine the potential to manipulate factors aimed at reducing bruising.

2.5.4.3 Maturity

Numerous researchers (Hyde and Ingle, 1968; Klein, 1987; Kampp and Nissen, 1992; Puchalski and Gorzelany, 1992) have observed that as apples mature, their susceptibility to bruise damage increases. In contrast, Diener *et al.* (1979) reported that more mature fruit were less easily bruised although in a later study (1982) the converse was found by the same research group. More recently, Johnson and Dover (1990) suggested that whilst bruising increases with maturity, the slope of this relationship varied with season.

Ruiz (1990) quantified the change in susceptibility associated with ripening: elastic rebound energy decreased from 40% to less than 10% as fruit ripened and Ruiz concluded that fruit changed from an elastic to a plastic state during ripening; as fruit matured they absorbed more energy, clearly providing a mechanism by which bruise susceptibility could develop with enhanced maturity.

Farhoomand *et al.* (1977) observed a linear trend in mean fruit ethylene production from the base to the apex of the tree. Thus, if apples from the same tree were harvested on the same date, they are likely to exhibit widely differing susceptibilities to bruising. A portion of this variability would result from maturity differences but it is also likely that fruit from different within-tree positions would also have different structural characteristics that contribute to tissue strength and thereby to bruise susceptiblity.

Holt and Schoorl (1984) reported that the longer fruit were stored the greater were the number of cell walls that ruptured rather than cleaved and bruise volume did not change which supports the concept of ripening causing reductions in cell wall strength.

2.5.4.4 Water status

Fruit water status has been recognised by researchers as a key factor that influences susceptibility to bruising. There are three ways by which reductions in fruit cell turgor could be utilised to reduce susceptibility to bruising:

- Whilst fruit are still on the tree, their water status may be influenced by irrigation, rainfall and leaf transpiration rates. Apples maturing under water deficits have lower water content and higher soluble solids than those grown under irrigation (Drake *et al.* 1981) and are less susceptible to bruising (Durand, 1990). During extended dry periods soluble solids accumulate within plant structures such as fruits. When the water supply increases suddenly, by irrigation or rainfall for example, water moves quickly into plant cells in response to the osmotic gradient. The rapid rise in hydrostatic pressure can rupture cell walls and possibly, cell membranes leading to splitting of fruits and other structures (Shewfelt and Prussia, 1993; Opara, 1996). According to the observations of Pitt and Chen (1983) highly turgid fruit may be very susceptible to impact damage. Orchardists often suggest bruise susceptibility increases after rainfall prior to harvest. An increase in water potential of the tree, and consequently the fruit, or water absorption directly through the cuticle, or a combination of both these mechanisms may explain this phenomenon. On the other hand, Garcia *et al.* (1995) reported that cessation of irrigation two weeks before harvest did not influence susceptibility to bruising of 'Golden Delicious' or 'Golden Supreme' apples. Longer periods of nil irrigation prior to harvest may be required to determine if fruit water status influences susceptibility of apples to bruising.

- The water potential of trees fluctuates diurnally and this is reflected in fruit water status which can be measured by changes in fruit diameter

(Berger and Selles, 1993; Lang, 1990). As leaves transpire in the heat of the day, transpirational losses may not be replaced by root supplies quickly enough to maintain leaf turgor and water may be drawn from the fruit to maintain leaf stomatal function. In the evening, when transpiration demands have reduced, root-supplied water moves to balance deficits and restore leaf and fruit water potential. Thus, apple turgor may reduce during periods of the day when transpiration demands are high and, under such conditions, apples might be expected to be less susceptible to bruise damage. Other possible daytime effects noted by Klepper (1968) were that pears from the west side of the tree had lower water potential than those from the east side. Thus, the time of day and the within-tree position from which fruit are harvested may influence their water status and thereby determine their susceptibility to bruising.

◆ As has been suggested by Johnson and Dover (1990), it may be possible to reduce turgor after harvesting as a strategy to reduce bruising. Bolin and Huxsoll (1987), using a scanning electron microscope, found that an apple moisture loss of 2% had a measurable effect on the ratio of cell perimeter to area which was termed a cell roundness index (*CRI*).

$$CRI=\frac{P^2}{4\pi A} \qquad \text{..........}\ \mathbf{2.11}$$

where: *P* was perimeter and *A* was area of a cell.

An increase in *CRI* (ie. increased roundness) would conceivably reduce the strength of cell-cell bonding and increase the area into which cells could re-orientate during compression. An induced 2% moisture loss after harvest, but prior to grading, may predispose fruit to shrivel later in storage life. It may be that even small reductions in moisture content of fruit reduce bruise susceptibility. Both Olsen and Bartram (1978) and Garcia *et al.* (1995) have found that weight losses of less than 1% were sufficient to cause a reduction in bruise volume. Freshly harvested apples may lose water quickly if they are placed in low humidity storage environments (Bartley and Knee, 1982). Zhang *et al.* (1992) stored apples at 50, 75 and 100% relative humidity and bruise susceptibility increased as relative humidity increased. In Europe, fruit are sometimes stored in reduced humidity controlled atmosphere (CA) stores to encourage weight loss to 3%, apparently to reduce bruise susceptibility (Waelti, 1991).

Unfortunately, fruit turgor potential is extremely difficult to measure (Zimmermann, 1978), but a simple method of cutting the fruit in half through the pedicel-calyx axis and measuring the resultant gap was developed by Skene (1980) and later used by Hatfield and Knee (1988). After this study had been completed, Jobling *et al.* (1997) developed a non-destructive method of measuring the water potential of fruit and vegetables whereby a number of small patches containing salt solutions are attached to the apple skin. The amount of water that a patch either donates or receives from the fruit is a linear function of the water potential of the fruit.

Lowering the water status of recently harvested fruit could be accomplished relatively easily by packhouse managers to reduce bruise damage. Pitt and Davis (1984) went further and suggested that it may be possible to reduce turgor to facilitate handling procedures and then store fruit in high humidity to maintain apparent freshness.

2.5.4.5 Temperature

Within the temperature range of 2 to 21°C, firmness of apple tissue has been shown to decrease as temperature increases (Bourne, 1982). Individual cells have been shown to be less brittle at warmer temperature than cold temperatures and undergo a greater deformation with a correspondingly greater force without rupturing (Nelson and Mohesenin, 1968). Studman and Boyd (1994a) have also documented that at low temperatures apple bruising increased, and suggested that cell walls are less flexible at cold than at warmer temperatures. Sekse and

Opedal (1993), Zhang *et al.* (1992) and Prange *et al.* (1994) found that warmer fruit (> 15°C) were less susceptible to bruise damage than cold fruit (0°C). In contrast, however, Saltveit (1984) reported that fruit coolstored for 26 weeks were more susceptible to bruising at warmer rather than colder temperatures. Schoorl and Holt (1977) used an impact energy of 1.25 *J* and found no differences in bruise susceptibility to apples in the temperature range 2 to 30°C. Klein (1987) also found that when apples were dropped 0.4 m onto a hard surface fruit, temperature had no effect on susceptibility to bruising.

If warm fruit were less susceptible to bruising than cold fruit then this information could be used in two ways to reduce bruise susceptiblity of apples. Whilst on the tree, fruit experience diurnal temperature fluctuations and could be harvested at or soon after mid-day when apple tissue temperature is presumably at its highest, and, after harvest, pre-cooled fruit could be rewarmed prior to grading.

Most of these studies on bruise susceptibility used fruit that had been coolstored for considerable periods. New Zealand's apple export programme generally requires fruit to be graded and packed soon after harvest although it is becoming increasingly common to bulk-store fruit prior to grading. Elucidation of the temperature effect on bruise susceptibility of apples at harvest, or soon after, should provide information which is less open to the undefined effects of long term coolstorage. This information could be also used by those involved with the fruit industry in its efforts to reduce bruise damage.

2.5.4.6 Mineral content

Apple composition has been shown to be influenced by many preharvest factors. Preharvest factors that exert an influence on apple composition or size and that can be controlled directly at least to some extent by orchardists include:

- rootstocks and planting density can influence fruit mineral content (Perring, 1984; Fallahi *et al.* 1985; Autio, 1991)
- fertilizer application (Tiller *et al.* 1959; Wills and Scott, 1976; Martin *et*

al. 1965; Letham, 1969; Sharples, 1985)

- foliar applications of minerals (Johnson and Yogaratnam, 1978; Yogaratnam and Sharples, 1982; Watkins *et al.* 1989)
- ground cover management (Perring, 1984)
- irrigation (Durand, 1990; Mills *et al.* 1996)
- pruning (Perring and Preston, 1974; Marini and Barden, 1982; Morgan *et al.* 1984)
- within-tree position (Heinicke, 1966; Jackson *et al.* 1971; Farhoomand *et al.* 1977; Krishnaprakash *et al.* 1983; Campbell and Marini, 1992)
- type, size, location or age of fruiting wood (Denne, 1963; Tustin *et al.* 1988; Volz, 1991)
- fruit thinning (Sharples, 1968; Quinlan, 1969)
- variable light reception by apples in different sectors of the canopy (Jackson *et al.* 1977; Barritt *et al.* 1987; Ferree, 1989).

Whilst not all of the above factors can be easily manipulated by orchardists, one production factor which could be, is the fertiliser and mineral spray regime. The calcium content of fruit tissue is known to influence cell wall strength and intercellular bonding (Poovaiah, 1986; Stow, 1989). By infiltrating minerals into apple tissue, Stow (1989) was able to show that calcium was in part responsible for the cohesion of cell walls. This confirmed the study of Bolin and Huxoll (1987) who found that dipping fruit in calcium solutions decreased the rate of reduction in the roundness index after fruit had 4% water loss when compared to untreated fruit. They also suggested changes in cell membrane permeability due to loss of calcium during ripening may change cell turgor and modify cell shape. Fuller (1976) observed that coolstored 'Cox's Orange Pippin' apples treated with calcium were less likely to show cell membrane and wall breakdown than apples with lower calcium content. Calcium content of apples can be increased by the application of foliar sprays during the growing season (Bramlage *et al.* 1985; Watkins *et al.* 1989; Siddiqui and Bangerth, 1995). High soil phosphate levels have also been associated with smaller apples of earlier maturity (Kotze *et al.* 1989). However, Sobolewska and Plich (1986) infused phosphorus into ripe apples through severed apple bearing branches. Later, these apples exhibited delayed production of ethylene, indicating that phosphorus may delay maturity. Whilst these results appear to be contradictory, the method, timing and rate of phosphorus applications may be important considerations as may be the phosphorus status of the recipient tissue. Phosphorus content of tissue has been negatively associated with cell volume (Letham, 1969). Despite the fact that increasing fruit size has been associated with greater bruise susceptiblity (Johnson and Dover, 1990) it is probable that orchardists would not perceive reduction of fruit size by manipulation of phosphorus fertilizer as a suitable means of reducing bruise susceptibility. A consistent negative relationship between storage breakdown and phosphorus levels in 'Jonathan' apples was reported by Martin *et al.* (1965). Phosphate sprays have increased fruit firmness and decreased breakdown during storage of 'Cox's Orange Pippin' (Johnson and Yogaratnam, 1978) and 'McIntosh' apples (Webster and Lidster, 1986). Given the above evidence it is probably safe to conclude that phosphorus content is likely to be involved in apple tissue strength. Phosphorus content of apples can be easily influenced by soil applied phosphate (Kotze *et al.* 1989) and phosphorus foliar sprays (Johnson and Yogaratnam, 1978; Webster and Lidster, 1986).

Letham (1961) applied nitrogen fertilizer to NZ grown 'Sturmer' apples and found that the number of cells per fruit decreased and their size increased, an effect which presumably would have a detrimental influence on tissue strength.

The strong influence of mineral contents on apple characteristics clearly offers an attractive approach to investigate possible methods to manipulate the susceptiblity of apples to bruising. Similar views have been expressed by Johnson and Dover (1990) although, in a long term orchard survey of UK 'Bramley's Seedling' apples, they found no consistent relationship between the endogenous mineral contents of fruit and bruise susceptibility. Orchards are likely to have different ratios of minerals that may have varied effects on the bruise susceptibility of apples and these effects may be obscured by management and/or climatic differences. Therefore, a within-orchard study specifically designed to elucidate the effect of two foliar applied minerals (calcium and phosphorus) on susceptibility to bruising may be an alternative to surveying a number of orchards.

2.5.4.7 Firmness

Contrary to the expectations that firmer fruit would be less susceptible to bruising, fruit firmness does not give an accurate indication of inherent bruise susceptibility (Hyde and Ingle, 1968; Robitaille *et al.* 1973; Topping and Luton, 1986; Klein, 1987; Pang, 1993) although Johnson and Dover (1990) found that a reasonably consistent relationship after 42 weeks of CA-storage. Penetrometer testing of fruit applies considerable pressure to a small, usually peeled, area of apple tissue. Not surprisingly, this action does not duplicate or characterise bruise susceptibility which is a whole apple response to an impact far shorter in duration, and generally involving a larger surface area, than a penetrometer test.

Firm apples were less bruise susceptible than softer apples after 42 weeks in coolstore (Johnson and Dover, 1990). However, this was presumably a difference in firmness relating to levels of ripening. Fruit firmness has been increased by foliar applications of calcium (Siddiqui and Bangerth, 1995) and Alar (N-dimethylamino-succinamic acid; Robitaille *et al.* 1973). Worthington and Yeatman (1967) and Heinicke (1966) found that fruit firmness was co-related to within-tree position. Fruit lower in the canopy and those from heavily shaded areas in the canopy were less firm than those from exposed positions.

Whilst selective harvesting from shaded and exposed tree sections does not present a viable option to orchardists, other management options aimed at increasing fruit firmness may also induce alterations to tissue structure that may influence bruise susceptibility.

2.5.4.8 Time in storage

Periods in coolstorage have been shown to decrease susceptibility of apples to bruising (Hyde and Ingle 1968; Schoorl and Holt, 1977; Brusewitz and Bartsch, 1989; Klein 1987; Prange, 1994). Reduced coolstore humidities decreased bruise susceptibility even further (Zhang *et al.* 1992) but also increased skin shrivel of 'McIntosh' (Prange, 1994). In contrast, Mohsenin *et al.* (1962) reported that after about 14 days in store 'Golden Delicious' and 'Delicious' susceptibility to bruising increased but their methodology required apples to be cut in half before impacting and it is not known to what extent this may have affected the result. Samim and Banks (1993b) found that periods in store did not reduce susceptibility to bruising of 'Granny Smith' apples. Lau (1983) and Prinja (1989) found that the rapid establishment (one day) of CA-storage was more effective than slow establishment (3 weeks) in reducing the susceptibility to bruising of apples after periods in store.

Despite some inconsistencies in the evidence it would seem that time in storage could be used as a strategy to reduce susceptibility of apples to impact damage provided that storage humidity, temperature and storage interval allowed only small weight losses and precluded rapid ripening.

2.6 Factors influencing bruise colour

Bruise colour is influenced by severity of impact (Klein, 1987); time elapsed after impact (Samim and Banks, 1993a), fruit temperature at the time of impact (Sekse and Opedal, 1993) and substrate concentration and enzyme activity (Amiot *et al.* 1992).

2.6.1 Time

After being bruised, brown discolouration of apple tissue is generally observed after 4 h and certainly by 14 h, with bruise colour fading over longer periods of time (Samim and Banks, 1993a). They explained this phenomenon by suggesting that the disrupted bruised tissue was initially saturated with sap but subsequently dehydrated as it lost water to the surrounding tissues and in doing so became progressively lighter in colour. Provided that bruise colour is measured soon after bruises have been generated, or at carefully replicated time intervals soon after bruising, the consequences of bruise fading should be managed in a consistent way in the experimental design.

2.6.2 Temperature

In an early study by Ingle and Hyde (1968), temperature did not seem to influence the rate of production of brown pigments up to 40 minutes after bruising. However, Sekse and Opedal (1993) observed that if apples were warmed for several days after bruising, less visible bruises developed than in fruit stored at lower temperatures. These observations perhaps could be explained by enhanced water loss at the warmer temperature which could contribute to dehydration effect suggested by Samim and Banks (1993a) as an explanation for 'bruise recovery'. Prange (1994) observed that warmer fruit temperatures reduced the size of visible bruising but this may have resulted from less tissue damage rather than reduced intensity of the bruise colour. Thomson *et al.* 1996 found that the temperature at which 'Golden Delicious' apples were bruised at did not influence bruise colour but 'Granny Smith' and 'Jonathon' apples developed darker bruises when stored at low temperatures.

From the above data it would seem that warmer temperatures somehow reduce the intensity of bruise colour. However, because warmer temperatures are associated with enhanced viscoelasticity and rate of biochemical reactions, as well as greater water loss a definitive explanation of temperature effects on bruise colour may be difficult to determine.

2.6.3 Substrate concentration and reactivity

As outlined in Section 2.3.2 phenolics are substrates for PPO activity, and have been shown to vary between apple cultivars (Walker, 1962; Ingle and Hyde, 1968; Klein, 1987; Amiot *et al.* 1992), during the season (Mosel and Herrmann, 1974; Zocca and Ryugo, 1975) and after periods in storage (Walker, 1962; Ingle and Hyde, 1968). Oszmianski and Lee (1990) found that a mixture of catechin and chlorogenic acid produced PPO oxidation products that were less brown than either catechin or chlorogenic acid alone. Thus, it appears phenolic content, or the ratios of these substances, are important in determining the susceptibility of a cultivar to discolouration (Ingle and Hyde, 1968; Mathies, 1983). Nadudvari-Markus and Vamos-Vigyazo (1984) suggested that two phenolic compounds (thought to be (+)-gallocatechin and (-)-epigallocatechin) were associated with the reddish brown colouration of bruises and may vary according to orchard location. Thus, if the variation between orchards could be attributable to identifiable management inputs or environmental conditions these data would indicate potential to manipulate bruise colour.

The level of phenols in plant tissue can be influenced by mineral nutrition. Boron has been implicated in this respect by Lee and Aronoff (1967) who suggested that its primary function was to form stable 6-P-gluconate-borate complexes and hence restrict and/or perhaps regulate (Birnbaum *et al.* 1977) the influx of substrate into the pentose-pathway and synthesis of phenols. This action would influence the rates of glycolysis and synthesis of hemicellulose and other related cell wall materials.

Boron could therefore be implicated in bruising in two ways. Firstly, a boron deficiency might lead to an accumulation of phenolics which may increase PPO activity and result in unstable reactive intermediates (caffeic quinones) being incorporated in cell membranes and cell walls, resulting in reduced integrity (Pilbeam and Kirby, 1983). Foliar applications of boron have decreased the phenolic content in potato tubers (Mondy and Munshi, 1993). Secondly, bruised tissue that contains higher concentrations of phenolics could result in a greater amount of brown discolouration than tissue with lower concentrations of phenolics.

Deficiencies of copper have been shown to reduce PPO contents and increase phenolic concentration (Marschner, 1986). Other minerals that may be involved are potassium, which in potato tuber has been associated with higher citric acid concentration and lower PPO activity resulting in less browning of pressed sap, less blackspot disorder and less discolouration after cooking (Marschner, 1986). Higher phenolic concentration in apple tissue also results from reduced nitrogen and potassium fertiliser (Lea and Beech, 1978). Smith and Cline (1984) found that apples sprayed with $CaCl_2$ during the growing season produced very pale apple juice after processing. To achieve an appropriately coloured juice, apples that had not been sprayed should be mixed with $CaCl_2$ sprayed fruit. Thus, it is clear that there is potential for mineral nutrition to play a significant role in determining the colour of bruised apple tissue.

Evidence relating storage time to phenol content in apples is conflicting. Harel *et al.* (1966) found in freshly harvested apples, that *o*-phenols decreased from 0.395 to 0.255 mg/g FW after 30 days in store. In contrast, Kolesnik *et al.* (1977) found that the total phenol content remained the same during storage, but the concentration of catechins and leucoanthocyanins decreased and those of anthogans and flavanols increased.

Potential anthocyanin content of apples is genetically determined, but incident light energy, temperature, pruning, water stress and mineral contents have been associated with variable levels in apples (Mazza and Miniati, 1993). Low nitrogen and high potassium favour anthocyanin production (Mazza and Miniati, 1993) and calcium ions have been shown to increase synthesis of anthocyanins in apple discs; in this tissue the magnitude of the effect depended on apple maturity and the type of calcium supplied (Vestrheim, 1970). Therefore, if the ratios of polyphenols are important in determining bruise colour, changes in these ratios by manipulation of mineral contents, the fruit position on the tree or periods in store might be expected to influence bruise colour.

AA reacts with *o*-quinones reducing the substrate for PPO and has been used to reduce browning in cut apple slices (Baurenfeind and Pinkert, 1970). AA can reduce melanin to lighter colours and is frequently used in processing of apple tissue for this reason. Intensity of browning in apple tissue was inversely related to AA content (Christensen, 1985). The action of AA to reduce browning seems to be enhanced if it is released slowly (Sapers *et al.* 1991). Poovaiah (1986) almost doubled the AA content of 'Golden Delicious' apples by increasing their calcium content to 4% and Mondy and Munshi (1993) increased the AA content of potatoes by foliar applications of boron. AA contents of apple have also been shown to decrease during storage but treatment with $CaCl_2$ slowed this reduction (Kovacs *et al.* 1994). Harel *et al.* (1966) also found that the rate of browning of apple slices decreased as the fruit ripens.

Thus, it appears that cultivar, stage of maturity, mineral nutrition and time in storage may influence factors that contribute to variation in bruise colour in a number of ways. Therefore, the possibility of reducing the bruise colour of apples by manipulation of some of these factors may be worthy of further investigation.

2.6.4 Bruise colour measurement

In early studies the measurement of cut apple tissue, apple bruise and tissue homogenate was carried out using reflectance techniques (Harel *et al.* 1966; Ingle and Hyde, 1968). Typically, reflectance from exposed tissue reduced (70% to 43%) as the browning reaction progressed. With the advent of tristimulus chromameters measurement of differences in tissue colour has been made considerably easier (Voss, 1992). Smith and Cline (1984) and Mastrocola and Lerici (1991) used such equipment in their studies and defined colour differences in terms of the lightness, a* and b* values. Reporting bruise colour in this way provides little information about chroma and hue angle which are essential in correctly defining colour (McGuire, 1992). Utilising this approach Aubert *et al.* (1992) found that chroma was more discriminant than lightness in measuring the colour differences between bruised tissue of 11 cultivars. Samim and Banks (1993a) reduced the size of the chromameter aperture to 8 mm and measured bruise colour development through the skin of 'Granny Smith' apples and found no differences in lightness, chroma and hue angle between bruised and unbruised tissue.

From the above it is apparent that further work would be required to measure the difference between light and dark coloured bruises.

2.7 Bruising and other aspects of apple quality

Bruising of fruit may affect the rate of ripening and other quality attributes. MacLeod *et al.* (1976) found bruised green tomatoes produced increased ethylene and CO_2, had higher AA content and reduced titratable acidity and ripened quicker than unbruised tomatoes. Robitaille and Janick (1973) found that severely bruised apples produced less ethylene than undamaged apples: they proposed that bruising destroyed tissue at the fruit surface that was responsible for its production. However, Lougheed and Franklin (1974) recorded increased respiration and ethylene from apple tissue that had been bruised.

Bruising has been associated with the incidence of blue mould infection in apples particularly after periods in coolstore (Burton, *et al.* 1987). Blue mould accounts for 80 to 95% of the postharvest decays in apples on the United States markets (Cappellini *et al.* 1987) but there appears to be no published information on the incidence of this disease in NZ export apples. This is probably because ENZA's quality grading standards ensure that most bruised and damaged apples are detected during grading (Robertson, pers comm. 1992); mould incidence on NZ export apples on arrival at overseas destinations is low. ENZA also requires a minimum calcium content for export apples which is known to improve resistance to mould infections (Conway *et al.* 1991). It therefore seems that the development of other postharvest storage problems caused by apple bruising are of little consequence to the NZ export apple industry.

2.8 Bruise susceptibility and handling damage

Although many methods have been developed to measure bruise susceptibility, none give results to which commercial relevance can be ascribed (McLeod, pers com. 1992). Pang (1993) reported in a study of bruise damage, caused during simulated apple grading operations, that the number of bruises per apple was a better predictor of bruise susceptiblity than bruise area. Whilst this study had an applied nature there is an essential question that appears to have been overlooked by researchers: 'Can bruise susceptibility, as determined by a standard impact, be validated in terms of damage that apples would be likely to incur during commercial handling operations ? ' To answer this question it would be essential to establish the bruise susceptibility of a group of apples and then relate these data to the damage that would occur to apples during handling operations. The results from such a study under NZ growing and harvesting conditions would then allow packhouse managers to gain a better insight into the commercial value of their efforts to reduce susceptibility.

The extent of between-season and between-orchard variability enabled Johnson and Dover (1990) to conclude that as bruise susceptibility varies more within seasons than between-seasons there may be scope for manipulation of factors thought to influence bruise susceptibility. Apart from a preliminary study by Banks *et al.* (1989) there appear to be few data on similar sources of variation in bruise susceptibility of NZ grown apples.

Based on the above literature review, the following proposition was developed: that various preharvest, harvest and postharvest factors could be manipulated within the bounds of current NZ apple growing and handling practices to reduce the susceptibility of apples to bruising or reduce bruise colour.

The study described in this thesis developed a simple method of generating commercially representative bruises for bruise susceptibility studies as well as identifying a method by which light and dark coloured bruises can be determined. The extent of variation of these two attributes that occurs between-orchard lines of fruit and their association with mineral content of fruit and other attributes is also examined. A more intensive investigation examines similar relationships within an orchard with two cultivars of apples. This is followed by an examination of the effects of various harvest and postharvest treatments on bruise susceptibility. In several of these studies bruise colour was measured to determine if there was potential to influence the visual consequences of bruising.

CHAPTER THREE
GENERAL MATERIALS AND METHODS

A series of experiments designed to elucidate the influence of preharvest, harvest and postharvest influences on the susceptibility of apples to bruising and bruise colour was carried out over three seasons (1990/92). This chapter describes materials and methods common to most of the work; specific details of individual experiments are included in later sections. Several of the materials and methods detailed in this chapter were developed through investigations designed specifically for that purpose; these investigations are explained in Chapter Four.

3.1 Fruit

Commercially grown 'Granny Smith', 'Royal Gala', 'Braeburn', 'Splendour' and 'Golden Delicious' apples were used in this series of experiments. Generally, fruit were harvested from trees which had scions grafted onto semi-dwarfing rootstocks (MM 106) and subsequently pruned to develop a central leader system about 5 m in height. Typically, plant spacings were 2.5 m within-rows and 5 m between-rows. Commercial, semi-intensive management practices of fertilizer applications, pruning, thinning and spraying aimed at maximising production of export quality fruit were utilised. Unless otherwise stated, commercially mature apples were harvested from:

- The Massey University Fruit Crops Unit (FCU), Palmerston North. Fruit were harvested from this orchard in 1991 and 1992. Both of these seasons were regarded as average years for fruit production. The soil was free draining, recent alluvium with interlayers of sand, silt and gravel (Manawatu fine sandy loam). A micro-jet irrigation system emitted 27 L of water/tree/h and maintained soil moisture tensiometer readings at 50 kPa.

- Eighteen commercial orchards in Hawkes Bay, the major apple producing area in New Zealand.

Export quality apples were harvested from trees and placed directly onto standard export trays. The trays were then placed in export cartons and transported to a laboratory or commercial packhouse for testing. Considerable effort was made to avoid bruising during harvesting, packaging and transportation. Before allocation to experiments, apples were weighed and closely examined for defects; fruit not of the required standard were rejected. Unless otherwise stated, twenty fruit were used in each of four blocks (n = 20 x 4).

3.2 Application of a standard impact

A standard impact test was used to facilitate comparisons of bruise severity of apples between controls and applied treatments as well as from apples from various orchards.

Apples were bruised in a standard manner by either one or a combination of three methods. A blushed (red skinned cultivars), lighter coloured (green skinned cultivars) smooth, blemish free area of the apple on the fruit equator was utilised for bruising. Assessment of individual bruise dimensions and total bruise area are described in Section 3.3.

3.2.1 Method 1

Apples were bruised by dropping a steel ball (diameter 25 mm; mass 0.110 kg) 0.130 or 0.200 m down a tube onto a firmly held apple (Fig. 3.1). The tube was mounted on a portable drill press which facilitated lowering of the tube onto the apple which was firmly held in a cupped device. The ball was loaded into the top of the tube and released by pulling out a rod inserted through the tube at the required height. Only one bruise was made on any given apple.

Fig. 3.1 Apparatus used to apply a standard bruise to individual apples using a 25 mm diameter steel ball.

3.2.2 Method 2

Apples were bruised by dropping a solid plastic-coated ball (70 mm diameter; mass 0.150 kg) 200 mm onto a firmly held apple (Fig. 3.2). A pvc pipe (200 mm long, 80 mm diameter) with air release holes at the bottom end and a thin elastic cord stretched across the diameter of the base of the tube was held vertically over the site on the apple to be bruised. Apples were firmly held in a cupped device. It was difficult to judge the correct height to hold the tube above the fruit because of the variable diameter of apples. This problem was overcome by resting the taut elastic cord on the apple skin and the ball was released from the top of the tube 200 mm onto the apple. Only one bruise was made on any apple.

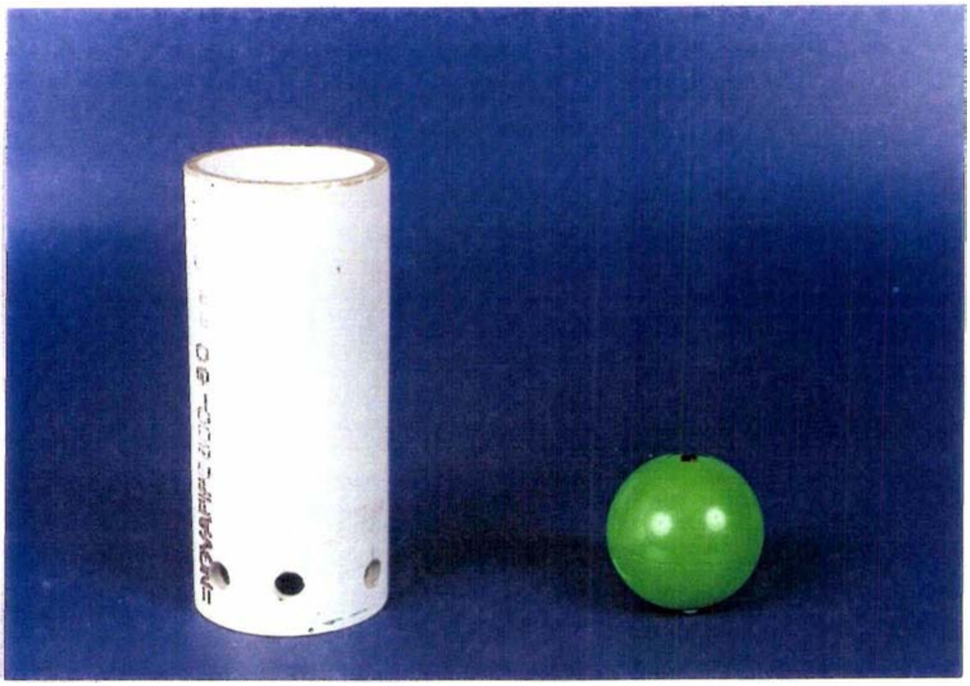


Fig. 3.2 Apparatus used to apply a standard bruise to individual apples using a 70 mm diameter plastic-coated ball.

3.2.3 Method 3

To simulate bruising that was likely to occur during commercial grading operations, fruit were graded in two ways:

- Groups of fruit were clearly identified and added to other apples immediately prior to grading on an electronic commercial grader. These experimental fruit were then separated and added to the flow of commercial fruit again so that the experimental fruit were graded four times. The addition of the experimental fruit to the commercial fruit increased the numbers of fruit being graded which may have increased the amount of damage that normally occurs.

◆ Fruit were graded on a 'Treeways' grader located at FCU (Fig. 3.3). Fruit were placed on the sorting table in a standard manner (six fruit per roller), which was operated at a speed of 250 rods/minute with all fruit dropping onto one packing table. Because the packing table was empty at the beginning of each repetition, fruit entering the packing table either first or last would probably have been subjected to different amounts of bruising from those in between. The probability that each apple in a sample of fruit to be tested would have incurred approximately the same number and type of bruises was enhanced by passing the fruit through the system four times. At each repetition, the position of each fruit on the grading table was randomly allocated, thereby attempting to ensure each apple at each pass was subjected to the bruises that are generated at different levels of packing table fill.

Fig. 3.3 Massey University, FCU 'Treeways' grader used to simulate bruise damage occurring during normal grading operations.

3.2.4 Harvesting and transportation damage

In 1990, variation in susceptibility to bruising between-orchards was assessed utilising randomly selected harvested fruit that had been delivered to the packhouse. An assessment of the damage that these apples had incurred during harvesting and transportation was carried out. Total bruise damage was assessed with no distinction being made between harvesting and handling damage.

3.3 Measurement of bruise dimensions

Each bruise generated by either method 1 or 2 (Sections 3.2.1 and 3.2.2) was cut directly through its centre on an equatorial plane and bruise dimensions: diameter (d), depth (h) were measured using micro-callipers with the height above the contact plane (x) being derived (see Fig. 2.3). Bruise diameter was chosen to represent bruise severity because of its practical convenience and lower variance than other methods of representing bruise susceptibility (Chapter 4).

Apples that had been graded in the standard manner (Method 3; Section 3.2.3) were closely inspected and each bruise was carefully outlined using a waterproof marker. Circles of different diameters (0.8 to 1.5 cm) had previously been drawn on a transparent A4 sheet and the appropriate circles were matched with the outlined bruises on the apples (Appendix 1). Bruise area was totalled for each apple and bruise area/apple and bruise number/apple were used in subsequent statistical analysis. Bruise areas per fruit were calculated for both harvesting and transportation damage (1990) and grader damage (1990 and 1991). The numbers of bruises/apple and bruise area/apple were averaged for each group of apples and then divided by four to give an indication of the amount of damage which would be incurred if the fruit had been passed just once over the grader.

3.4 Measurement of bruise colour

A Minolta chromameter (Model CR-100, Minolta Camera Ltd., Osaka, Japan.) was used to assess bruise colour. However, the diameter (8.54 mm) of the chromameter aperture exceeded that of the area of bruised tissue generated by standard impact methods 1 and 2 (colour was not assessed on bruises generated by method 3). Therefore, a hood or cover was designed and constructed that restricted incident light onto a smaller area of bruised tissue. The observation of Voss (1992) that a very small aperture (3 mm) may not only isolate a colour variant but produce a misleading evaluation of a larger mottled area was heeded. The chromameter aperture was reduced from 10.84 mm to 5 mm using a perforated disc, which if placed at the centre of the bruised tissue, avoided colour variations around the perimeter of the bruise. Before each series of bruise colour measurements were taken, the chromameter was calibrated to a white plate. Bruise colour measurements from several sections of experiments indicate that the chromameter should have been calibrated on a more regular basis.

The colour components characterised by the chromameter and used in this work were lightness and chroma and hue angle. These components describe colour closely to that which is perceived by the human eye and are generally understood by those involved in the marketing chain (McGuire, 1992).

Lightness - indicates the degree of lightness; high values are recorded from lighter tissue and lower values from darker tissue

Chroma - indicates the saturation of colour or colour intensity

Hue angle - indicates colour; hue angle values decrease as skin colour changes from red to green to yellow. Browner tissue has a lower hue angle than green tissue.

After measuring dimensions of the bisected bruise, the colour components on each exposed half of the bruise were determined and averaged to give values for each apple.

3.5 Fruit firmness and crush strength

A hand held Effigi penetrometer with an 11 mm diameter probe was used to determine the force (kgf) required to penetrate a peeled section of cortical tissue of each fruit half. These measurements were averaged to give one firmness value for each fruit. Force (kgf) was converted to force (N) by multiplying by the acceleration due to gravity (9.807 m/s^2).

A method developed by the Department of Agricultural Engineering, Massey University was used for measuring the crush strength of apples (Studman and Yuwana, 1992). The device consisted of a small blade (6 mm by 4 mm) attached 5 mm from the pointed end of a narrow shaft. The blade was pushed 10 mm into the apple which was manually rotated about the axis of the shaft until the tissue no longer offered any resistance. An offset arm measured the point at which the fruit tissue became crushed (Fig. 3.4). A prototype was used for the 1991 survey experiments and later electronic measurement of the crush point (kPa) and mechanical twisting replacing manual operation were made possible by additions to the device (Studman and Boyd, 1994b).

3.6 Starch Index

Starch index was assessed using the starch iodine test (Reid *et al.* 1982). Each apple was cut transversely at the equator and one half was placed, cut surface down, for 3 minutes in a solution (100 ml) of potassium-iodide (1 g) and iodine (0.25 g) in water. The resulting pattern on the cut surface, indicating relative amounts of starch and soluble sugar, was scored using a scale of 0-8, where 0 indicates the least and 8 the most starch to sugar conversion.

3.7 Soluble solids

Adjacent to the position of the standard bruise, a section of apple (10 x 10 mm; skin attached) was excised and hand squeezed. The refractive index of the resultant juice was measured using a hand-held Atago N-20 refractometer (Model N, McCormick Fruit Tech.) which had been calibrated to Brix range 0 - 20% at 20°C.

3.8 Fruit temperature

Fruit temperatures were taken using a digital temperature probe (Quartz Digi-

Thermo). Probes were inserted 200 mm into the apple flesh at the equator and temperatures were recorded after the reading had stabilised.

3.9 Water status

A method developed by Skene (1980) and used by Hatfield and Knee (1988) was adopted to measure the water status of apples. Apples were cut in half through the pedicel-calyx axis and the width of the gap which developed between the cut surfaces after 30 minutes was measured. The size of the gap that developed depended on the water status of the apple and was also an indication of growth stresses which are related to turgor.

3.10 Fruit mineral contents

A core borer was used to take a 10 mm long tissue plug from a peeled (1 mm) undamaged section above the fruit equator on each of 10 apples from each replicate. Ten samples from each replicate were bulked, homogenised and analysed for mineral content.

Total phosphorus and nitrogen were determined following Kjeldahl digestion. The digestion solution was prepared by heating 250 g of potassium sulphate, 2.5 g of selenium powder and 2.5 L of concentrated sulphuric acid until the solution cleared. Samples of homogenised tissue (0.5 g) were digested with 4 cm^3 of this solution at 350°C for 4-5 h (or until solution was clear), cooled and made up to 50 cm^3 with deionised water at 20°C. Nitrogen was determined colorimetrically at 630 nm following treatment of the digest with alkaline phenate and hypochlorite. Phosphorus was determined by colorimetry at 420 nm following treatment with vanado-molybdate.

Calcium, magnesium and potassium were determined using 0.5 g of homogenised tissue which were refluxed with concentrated nitric acid in digestion tubes occluded with small funnels at 150°C for 4-5 h or until the solution cleared, then boiled to dryness at 250°C. The warm residue was redissolved in 50 cm^3 of freshly prepared strontium and caesium (2.4% w/w for each element) in 8 mM HCl and stored at 4°C in a dark refrigerator until analysis of calcium and magnesium by atomic absorption spectrophotometry or analysis of potassium by atomic emission spectrophotometry.

3.11 Statistical evaluation

Statistical analyses was performed using SAS software (SAS Institute, Cary, NC, USA).

3.11.1 Experimental design

Unless otherwise stated twenty apples comprised one experimental unit (internally replicated) and were allocated to each combination of block and experimental treatment. Generally a randomised complete block design was used with 4 blocks and, where appropriate blocks were allocated to account for observable variation of physical or environmental factors.

3.11.2 Preliminary data analysis

Mean values were calculated for each variable from the original data set with the SAS procedure Tabulate. Normality of distribution of raw data and presence of outliers were checked in each data set using SAS Univariate procedure. Data from Method 3 were found to be highly skewed, transformation to square root resulted in a close to normal distribution which allowed standard analysis to be completed satisfactorily. These data were back-transformed for presentation.

3.11.3 Data analysis

Statistical models for each experiment are presented in the text. Analyses of variance were calculated using the SAS GLM procedure. Regression analyses were calculated using SAS REG procedure. Standardised regression was used to determine relative importance of variates. SAS CORR procedure was used to calculate correlations. Multivariate analyses (principal component or canonical correlations) were attempted but did not add substantively to the understanding of the data and results are therefore not presented. Means separations were determined by t-tests and Duncan's multiple range test.

3.11.4 Data Presentation

ANOVAS are presented of each experiment detailing statistical models with second order interactions. Means are presented either in graphic (SED, standard error of the difference) or tabulated form (means separation).

CHAPTER FOUR

DEVELOPMENT OF NEW MATERIALS AND METHODS

4.1 Development of bruise susceptibility tests

4.1.1 Introduction

This chapter describes investigations aimed at identifying new materials and methods to determine the commercial significance of susceptibility to bruising as well as measuring differences in bruise colour. These investigations were designed to:

i) identify the larger bruise sizes that contributed significantly to the bruise area incurred by apples during typical commercial handling operations

ii) develop a technique of applying a standard impact that would generate bruises of a size similar to the bruises identified in (i) above

iii) identify a statistically sound method of representing bruise severity using the technique identified in (i) above

iv) describe colour differences in colour components between light and dark coloured apple tissue damaged using the technique identified in (ii) above.

Each of these investigations was constrained by a requirement to employ uncomplicated, portable equipment that facilitated the generation of a standard impact (Methods 1 and 2), simulated grading damage (Method 3) and the subsequent ease of measuring bruise dimensions and colour components. There would also be a considerable saving of experimental time if the area of bruised apple tissue generated by the standard impact was large enough to measure bruise colour. Attention to these characteristics of the new materials and methods was appropriate because the desired experimental design of several studies, which are described later in this work, required large numbers of apples a standard manner and bruise dimensions and colour components to be measured and recorded in a limited time frame.

4.1.1.2 Simulation of damage that apples incur during commercial grading

To make investigations in following chapters relevant to situations encountered in the normal handling of apples it was desirable to select a method of generating standard impacts that caused bruises of similar dimensions to those that apples incurred during normal postharvest handling operations. Banks *et al.* (1992) identified that about 40% of apple damage occurred during harvesting with the remaining 60% occurring during grading and packaging. During both of these operations, apples can incur bruises up to 30 mm in diameter (Banks, pers comm. 1995). The incidence and severity of damage inflicted on apples depends to a large degree on the harvesting and grading system in use. Because of the difficulty in replicating harvesting operations, it was decided to focus on the bruise damage that occurs to apples during grading. Banks (1991) identified the key positions on a grader where bruising occurred (Fig. 4.1).

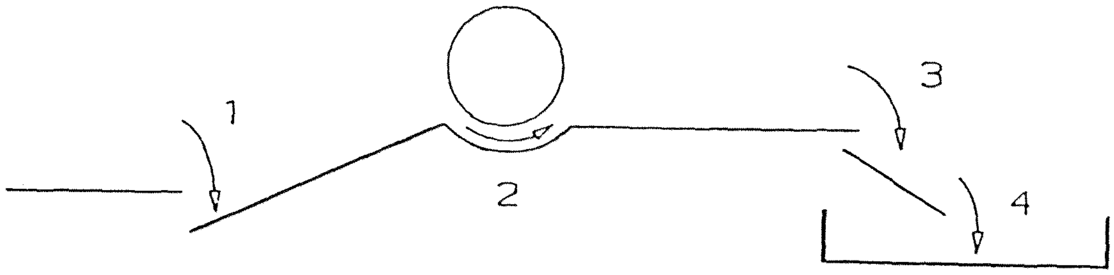


Fig. 4.1 Key positions on a fruit grader where apple bruising was consistently found to occur (Banks, 1991).

Point 1 was the fall of the fruit from the sorting table to the singulator; point 2 was the passage of fruit beneath the transfer wheel from the singulator to the cup race: point 3 was the drop from the cup race to the chute; point 4 comprised the passage of the fruit from the chute until it finally came to rest on the revolving final size bin or tray.

Whilst this study identified problem points on commonly used commercial graders, it also led to the notion that if groups of apples were graded in a standard manner on a commercial grader then bruise area/apple could be determined and comparisons made. If the susceptibility to bruising of that same group of apples was then determined by a standard impact test, a relationship between commercial handling damage and bruise susceptibility could be established.

Pang (1993) used the first part of this approach and repeatedly graded a group of fruit on a commercial grader (Fig. 3.3). One of his conclusions was that bruises greater than 150 mm^2 (d = 13.8 mm) in size were not likely to result from damage occurring during grading. However, the size of the bruises he reported in his study were less than those recorded in similar experiments done as part of this current work. This suggests that either the fruit size he was working with may have been small, or, for some other reason, perhaps related to storage conditions, did not bruise easily. It was not possible to confirm either cause from his report. Therefore, before adopting this technique, the effect of apple mass on bruise area/apple incurred during grading required verification. Such an experiment would describe the range of bruise sizes a group of apples would incur and their contribution to the total bruise area that apples incur during commercial grading operations.

4.1.1.2 Methods of applying standard impacts to apples

In an early study Manor (1978) recognised there was no established procedure for applying standard impacts to apples and it appeared that this was still the case; researchers studying bruise susceptibility have developed many techniques to apply standard impacts to apples. The relationship that some of these techniques have with the damage that apples incur during commercial handling operations is not known (McLeod, pers comm. 1992). Standard impacts to apples have been generated by:

◆ Pendulum techniques

i) by swinging an impactor against an apple (Hyde and Ingle, 1968)

ii) by swinging an apple against a solid wall (Holt and Schoorl, 1984)

iii) by swinging one apple against another apple (Pang, 1993).

The pendulum apparatus has disadvantages in that it is time consuming to set-up and if two apples are used then the time taken to measure bruise dimensions is increased and the distribution of bruise sizes between the pair of fruit is uneven. For these reasons the pendulum technique was not used.

◆ Dropping a fruit onto a flat solid surface (Diener *et al.* 1979, Klein, 1987). Whilst this is a quick and simple method, two problems became apparent in preliminary evaluations:

i) if individual apples of different mass are dropped from a similar height, apples of greater mass would develop greater impact energy, thereby reducing the validity of comparisons of bruise severity indices between groups of fruit

ii) apples may turn whilst falling and impact on different regions of the outer surface. Because of the variable radius of curvature and cell size around a fruit's periphery (Ruiz, 1990), bruise damage on these different regions of an apple may not be consistent, thereby precluding a basis for valid comparisons between bruise severity indices. For these reasons this method was also rejected.

◆ Dropping a weight on to a stationary apple (Garcia *et al.* 1988; Sekse and Opedal, 1993). This method of generating standard impacts has also been used by Massey University (Department of Plant Science) and the

University of California (Kader, pers comm. 1992). A steel ball (0.11 kg mass; 25 mm diameter) was dropped from a set height (0.20 m) down a vertically held tube onto a firmly held apple. This method overcomes the two problems previously detailed, is rapid and the apparatus is portable, however it has a number of characteristics that warrant discussion:

> i) the radius of curvature of the impacting ball is small and may create bruises that are deep for their width compared to bruises inflicted by objects with larger radii of curvature. Studman (pers comm. 1993) noticed that after impact with a small steel ball, apple tissue 7 mm below the skin was violently disrupted. The depth and colour intensity of such bruises greatly exceeds the tissue damage that generally occurs during handling operations. Typical handling damage results from fruit-fruit impacts. Fruit have larger radii of curvature than the steel ball and the elastic properties of the skin and the cell packing arrangement, especially in the hypodermal layer which are important in the transfer of impact energy to apples (Klein, 1987), may not be adequately taken into account when a small ball is used. The skin area and the number of hypodermal cells that directly absorb energy increase exponentially as contact area increases at the moment of impact. The skin and several layers of cells directly beneath are not normally damaged during impact (Ruiz *et al.* 1993) but must contribute to energy absorption. Topping and Luton (1986) proposed that the size of the 22 mm flat head used on their pendulum impactor should be increased if sensitive fruit were to be tested. Their comment supports the suggestion that differences in bruise dimensions may be easier to detect if impact energy was spread over a greater area of the apple surface.
>
> ii) the difference between the maximum and minimum bruise dimensions from a sample of apples bruised using the steel ball

may be small. Therefore, differences in bruise dimensions between experimental treatments may be difficult to detect.

An improvement to this approach may be to drop a ball of similar diameter and weight to an average sized apple from a height that apples were observed to fall during commercial handling operations. A plastic-coated ball (0.16 kg mass; 70 mm diameter) was chosen because its size and mass were similar to apples in the 113 count range which was a common NZ packing grade size. The ball was dropped from a standard height of 0.20 m (a typical height apples were observed to drop during commercial handling operations; Banks *et al.* 1992). It was considered appropriate to determine if any loss or gain in accuracy could be achieved in characterising the bruisability of a group of apples by generating standard impacts with the large plastic-coated ball rather than the smaller steel ball. It would then be possible to determine if the bruise dimensions were in any way similar to those that were incurred during simulated commercial grading operations.

Tests for bruise susceptibility should be sufficiently sensitive to quantify differences between groups of fruit which are treated to influence apple tissue response to standard impacts. For instance temperature or humidity manipulations for short periods (< 24 h) are not likely to induce gross changes in cell structure but rather influence cell visco-elastic properties in a subtle manner. The treatment effects on susceptibility to bruising are determinedy measuring the area or volume of apple tissue that is visible after generation of a standard impact. Should any impact test not accurately characterise the bruise susceptibility of a group of apples then the possibility of identifying differences between applied treatments (causing slight modifications to visco-elastic properties) may be difficult.

4.1.1.3 Methods of representing bruise severity and the relationships between impact energy, bruise diameter and bruise volume

Researchers have used numerous methods to represent bruise severity (Section

2.4), some of which have been used in calculations of bruise susceptibility. Examination of the homogeneity of variance (using Chi squared; χ^2) of several methods of representing bruise susceptibility at various impact energies may identify statistical characteristics at particular impact energies that may assist in identifying the most robust method of representing bruise severity.

The final task was to validate the relationship between the chosen method of representing bruise severity and impact energy. It has been well established that there is a linear relationship between impact energy and bruise volume (Schoorl and Holt, 1977). Using a small steel ball dropped from 0.2 m, Banks (1990) found the coefficient of variation (CV; the ratio of the standard deviation to the mean,) for bruise diameter (*d*) in 'Granny Smith' apples to be 10%. This was much less than that for bruise volume (CV = 36%) and is similar to the volume CV of 28% documented by Brusewitz and Bartsch (1989). In Banks's study the relationship between d and impact energy (E) was curvilinear, that between d and $E^{1/3}$ was nearly linear and the CV was strongly dependent upon the impact energy used in the test. Thus, as bruise dimensions increase with increasing impact energy, this technique may not give a reliable estimate of variability for comparisons at each of the eight impact energies. A more rigorous investigation of the statistical variation associated with various impact energies utilising the large ball may provide further information that could assist in identifying the most appropriate impact energy to utilise for the method of generating standard impacts.

4.1.2 Materials and methods

4.1.2.1 Simulation of apple damage that occurs during commercial grading

Two groups each of eighty 'Granny Smith' apples, one comprising medium sized fruit (average mass, 0.18 kg) the other of small fruit (average mass, 0.13 kg) were graded in a standard manner (Method 3: Section 3.2.3). Twenty-four h after grading, the sizes and numbers of bruises incurred were manually assessed (Section 3.3).

4.1.2.2 Methods of applying standard impacts to apples

Twenty 'Granny Smith' apples were subjected to two standard impacts (Method 1 and Method 2: Sections 3.2.1 and 3.2.2 respectively) on similar even sections on each apple at least 60 mm apart midway between the stem and calyx. Apples were left for 24 h to allow full bruise colour development before bruise dimensions were measured. Average bruise diameter (d), depth (h), and volume (V; Eqn. 2.7) were calculated and compared.

4.1.2.3 Methods of representing bruise severity and the relationship between impact energy, bruise diameter and bruise volume

An impact generating device (Fig. 4.2) based on that developed by Michigan State University (Marshall, pers. comm. 1993) was constructed by the Department of Agricultural Engineering, Massey University.

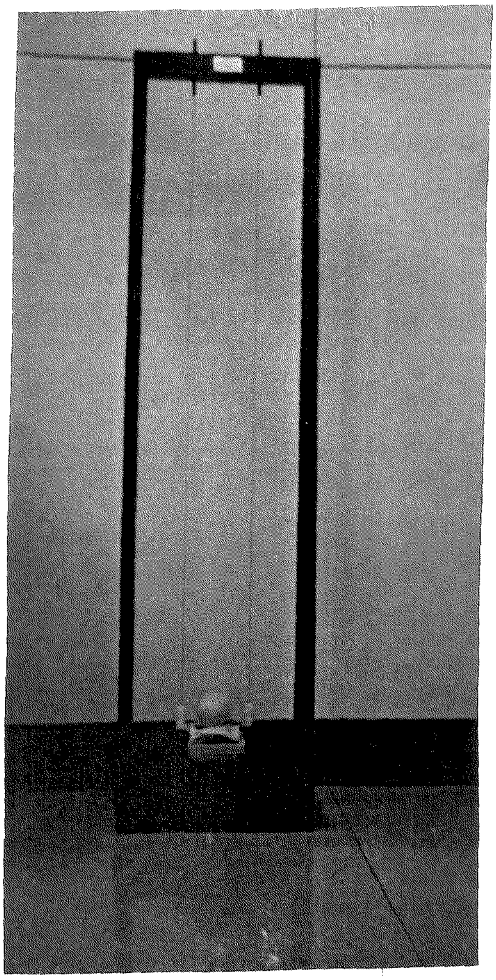


Fig. 4.2 Impact generating device developed by Michigan State University.

This comprised a 1.6 m high frame constructed using 0.02 m steel pipe welded to the corners of a 0.4 x 0.2 m heavy steel base. Piano wires were secured running parallel from the base to the top, 0.14 m apart. Two 'frictionless' plastic holders were drilled and threaded onto each wire before tensioning. These were then joined by a circular aluminum ring fashioned to hold the 70 mm radius ball with slightly less than half of the ball protruding through the bottom of the aluminium ring. The impacting ball could then be dropped easily from various set heights guided by the wires onto an apple firmly held at the base. 'Splendour' apples that had been coolstored for 24 weeks were then bruised by dropping a plastic-coated ball (0.160 kg mass; 0.07 m diameter) from 0.05, 0.10, 0.15, 0.2, 0.25, 0.3, 0.35, and 0.4 m onto firmly held apples. Ten apples were bruised at each of the 8 impact energies. Means, variance and CV were calculated at each of the drop heights for:

A) bruise diameter (d)
B) bruise depth (h)
C) bruise area (A)

$$A = (\pi r^2) \qquad \text{..........} \ \mathbf{4.1}$$

D) surface area S of the inner bruise boundary (Zhang *et al.* 1992; Section 2.4.1.2, Equation 2.2)
E) bruise volume V_1 (Chen and Sun, 1981; Section 2.4.1.3, Equation 2.9).
F) bruise volume V_2 (Holt and Schoorl, 1977; Section 2.4.1.3, Equation 2.7).

Homogeneity of variance was assessed using software (Gordon, pers comm. 1994) based on the method for χ^2 tests (Steel and Torrie, 1981) for each method of representing bruise severity for the eight impact energies. This investigation characterised the statistical characteristics of methods of representing bruise severity at the various impact energies and provided indications of:

i) the most appropriate impact energies to utilise for the standard impact
ii) the most appropriate method of representing bruise severity.

Linear and non-linear regressions were used to determine the lines of best fit for each data set and coefficients of determination were compared.

4.1.3 Results and discussion

4.1.3.1 Simulation of apple damage that occurs during commercial grading

After simulation of grading (Method 3) examination of damaged tissue on each apple indicated that bruises with diameters of 12 mm or larger accounted for about 78% and 24% of the bruise area incurred by the individual apples of medium mass (Table 4.1) and smaller mass (Table 4.2) respectively. Bruises of 14 mm diameter accounted for approximately 30% and 24% of the total bruise area on medium and small apples respectively.

Table 4.1 Bruise diameter (mm), number of bruises, total bruise area/apple (mm^2) and percent of total bruise area/apple attributable to each bruise diameter size incurred by medium sized 'Granny Smith' apples (mass = 0.18 kg; n = 80) during simulation of commercial grading.

Bruise diameter (mm)	6-8	10	12	14	16	18	20	22
Total number of bruises/80 apples	17	13	20	15	3	1	1	1
Bruise area/apple (mm^2)	8	12.76	28.3	28.9	7.5	3.18	3.92	4.75
Percent of total bruise area/apple	8.2	13.1	29	29.6	7.7	3.2	4	4.8

The observations of Pang (1993) that bruises greater than 150 mm^2 (d = 13.8 mm) were not likely to be incurred during commercial grading operations was not substantiated by this study. For apples of medium mass, 49% of the total bruise area was attributable to bruises 14 mm or more in diameter. However, apples of smaller mass did not incur any bruises that were greater than 14 mm in diameter. These data suggest that Pang's observations were made using either apples of small mass, lower bruise susceptibility or that he selected a different grader speed. The latter explanation may be appropriate because he recorded fewer large bruises but considerably more smaller bruises.

It is clear that during 'commercial' grading apples on the FCU grader the majority of bruises were 12 - 14 mm in diameter. Thus, if a method of generating standard impacts developed bruises that were about 14 mm in diameter these would represent bruises that were incurred by apples during normal handling operations.

Table 4.2 Bruise diameter (mm), number of bruises, total bruise area/apple (mm^2) and percent of total bruise area/apple attributable to each bruise diameter size incurred by small apples (0.13 kg mass; n = 80) during simulation of commercial grading.

Bruise diameter (mm)	6-8	10	12	14	16	18	20	22
Total number of bruises/80 apples	13	4	6	3				
Bruise area/apple (mm^2)	6.25	3.92	8.48	5.77				
Percent of total bruise area/apple	25	16	35	24				

4.1.3.2 Method of applying standard impacts to apples

Bruise diameter was more consistently characterised in this line of 'Granny Smith' apples by impacting with the larger ball rather the small ball (Table 4.3). The standard errors of bruise diameter indicated that approximately 50% more apples would be required to characterise susceptibility to bruising of this line of apples with the same accuracy by using the small ball rather than the large ball. There was no significant difference in the permanent indentation caused by either the large or small ball. Impacting with the small ball resulted in a 30% smaller range in bruise depth than when the large plastic-coated ball was used.

The small ball inflicted bruises that were 0.52 mm deeper and 1.47 mm smaller in diameter than when the large ball was used ie. the smaller steel ball generated bruises that were relatively deep for their width. In contrast, bruises incurred by apples during commercial handling tend to be shallow for their width (Studman, pers. comm. 1993). Similarly, Dedolph and Austin (1962) found that apple bruises generated on grading equipment had depths that were about 30% of their diameter.

Table 4.3 Bruise diameter, depth, and volume of standard bruises on medium sized 'Granny Smith' apples generated by impacting with a small steel ball (0.21 *J*; n = 20) and a large plastic-coated ball (0.32 *J*; n = 20)

Variable	Small ball	Large ball
Bruise diameter (mm)	13.23	14.7
Range	2.07	1.84
Standard error	1.4	1.1
Coefficient of variation	4.6	3.4
Bruise depth (mm)	6.85	6.33
Range	1.27	1.94
Standard error	0.8	1.2
Coefficient of variation	5.5	8.6
Bruise volume (mm^3)	630	738
Range	275	346
Standard error	190	200
Coefficient of variation	12.4	13.5

Similar ratios for the bruises generated by the small ball were 51% and those with the larger ball were 40%. Thus, the large ball generated bruises that were on average 14.7 mm in diameter; this was slightly larger but within the size range of bruises that contribute significantly to the total bruise area that an apple sustains during grading. Furthermore, the diameter to depth ratio of bruises generated by the larger ball was closer to the ratio determined by Dedolph and Austin (1962) than those bruises generated by the smaller ball.

The standard errors associated with bruise volume generated by impacting with both large and small balls were considerably greater than those calculated for both bruise diameter and depth. Generation of the standard impact using the larger ball more efficiently characterised the susceptibility to bruising of this line of apples if bruise diameter was to be used to represent bruise severity. This bruise measurement had one of the lowest coefficients of variation and standard error of the six data sets (Table 4.3). The smaller ball did however generate bruises that were consistent in depth.

When a small diameter impactor collides at high impact energy with a fruit, cells in the impact zone are likely to be violently disrupted; the surrounding undamaged tissue and the elasticity of the skin would probably limit further entry of the impactor into the fruit. Bruises generated in this manner would not closely mimic fruit-fruit impacts that occur during grading. When a larger diameter impactor with an increased radius of curvature was used bruise depth was smaller, perhaps because the number of cells involved in energy dissipation increased. In this case, cell wall and cell-cell damage was not as extensive and therefore more closely represented damage resulting from fruit-fruit impacts that occur during handling.

4.1.3.3 Methods of representing bruise severity and the relationship between impact energy, bruise diameter and bruise volume

Bruise diameter provided a suitable means of representing bruise severity based on both its practicality and statistical evaluation. Bruise diameter was easy to measure and had the lowest coefficient of variance and low variance when compared to other methods of representing bruise severity. All six methods of representing bruise severity had variances that were heterogenous for the range of impact energies (0.07 to 0.6 *J*) used. However, the variances of bruise depth and diameter were homogenous for the impact range 0.225 to 0.45 *J*; at impact energies below and above this range, variances increased by at least a factor of three. The variances of bruise area A_1 (Eqn 4.1), surface area of the inner bruise boundary S (Eqn. 2.2), bruise volume V_1 (Eqn. 2.9) and bruise volume V_2 (Eqn. 2.7) showed considerable inconsistency and were much higher than the variances of bruise depth and diameter over the range of impact energies. This was expected because derivation of other variables from data on bruise diameter and depth compounds any errors associated with the original measurements.

Coefficients of variation were plotted (Figs. 4.3 and 4.4) to illustrate the inadequate information they provide for discrimination between methods of representing bruise severity.

These data revealed that within a group of apples there was considerable variation in the sizes of bruises that developed in response to either low or high impact energies. This variation in sensitivity of apples may be of value where very small changes in bruise severity require study; eg. the difference in bruise susceptibility of apples on the same spur. The magnitude of the standard errors of bruise diameter indicate that the number of apples/group would need to be increased from 20 to at least 60 to achieve the same statistical precision provided by medium energy impacts if either low or high impact energies were used (assuming that the variances shown here relate to other groups of apples). There must be a balance between the statistical accuracy of results and the number of apples within a group that can be physically handled. Zhang *et al.* (1992), using the inner bruise boundary as an indicator of bruise severity, concluded that there should be 2 bruises on each of 14 fruit to accurately characterise the bruise susceptibility of a group of apples. Unfortunately the justification for this conclusion was not documented. The coefficients of determination of each measure of bruise severity were similar with a range of 1.64% and therefore, did not provide a basis for discrimination (Table 4.4). The findings of Zhang (1992) that inner bruise boundary area had 30% less variation than bruise volume were not confirmed by this study.

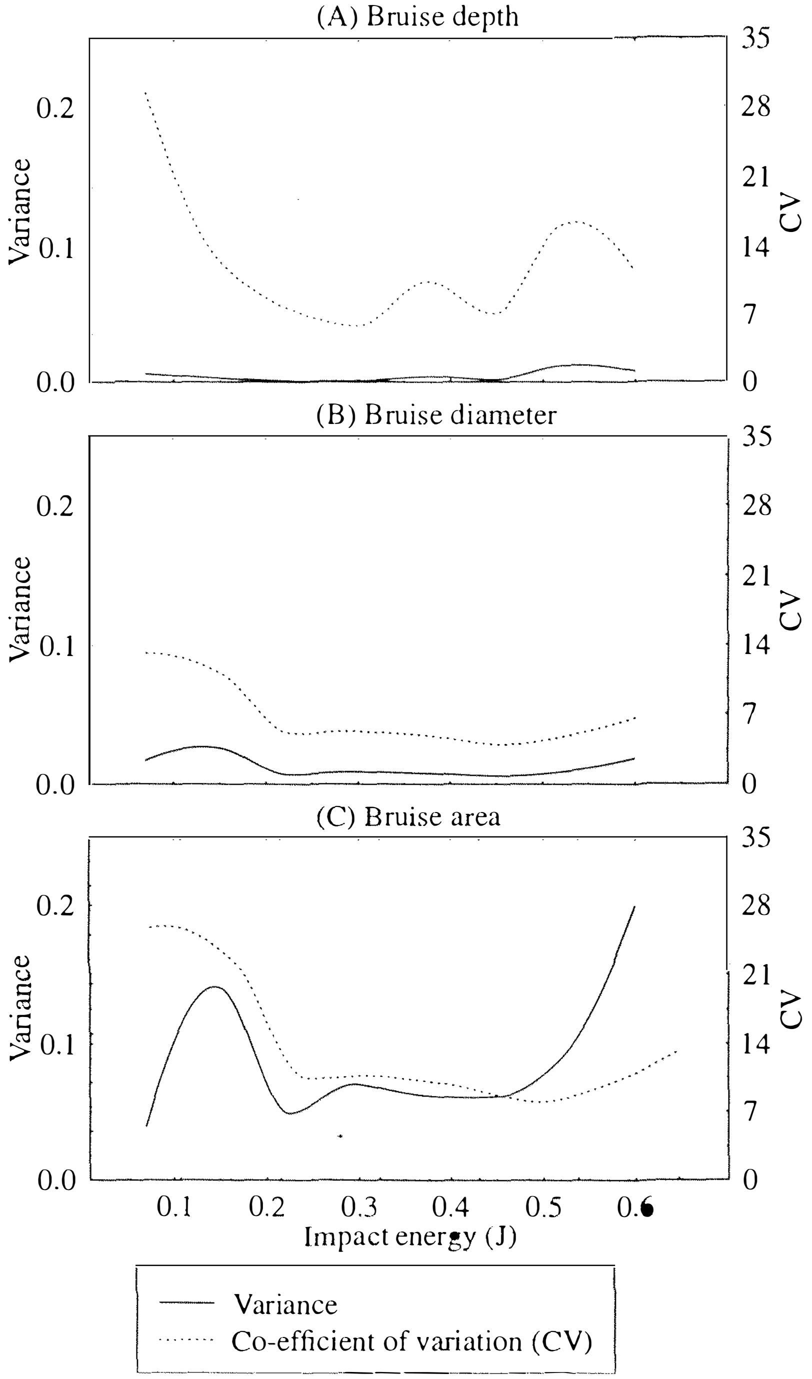


Fig. 4.3 Coefficient of variation and variance at eight impact energies from 0.07 to 0.6 J for (A) bruise depth, (B) bruise diameter and (C) bruise area.

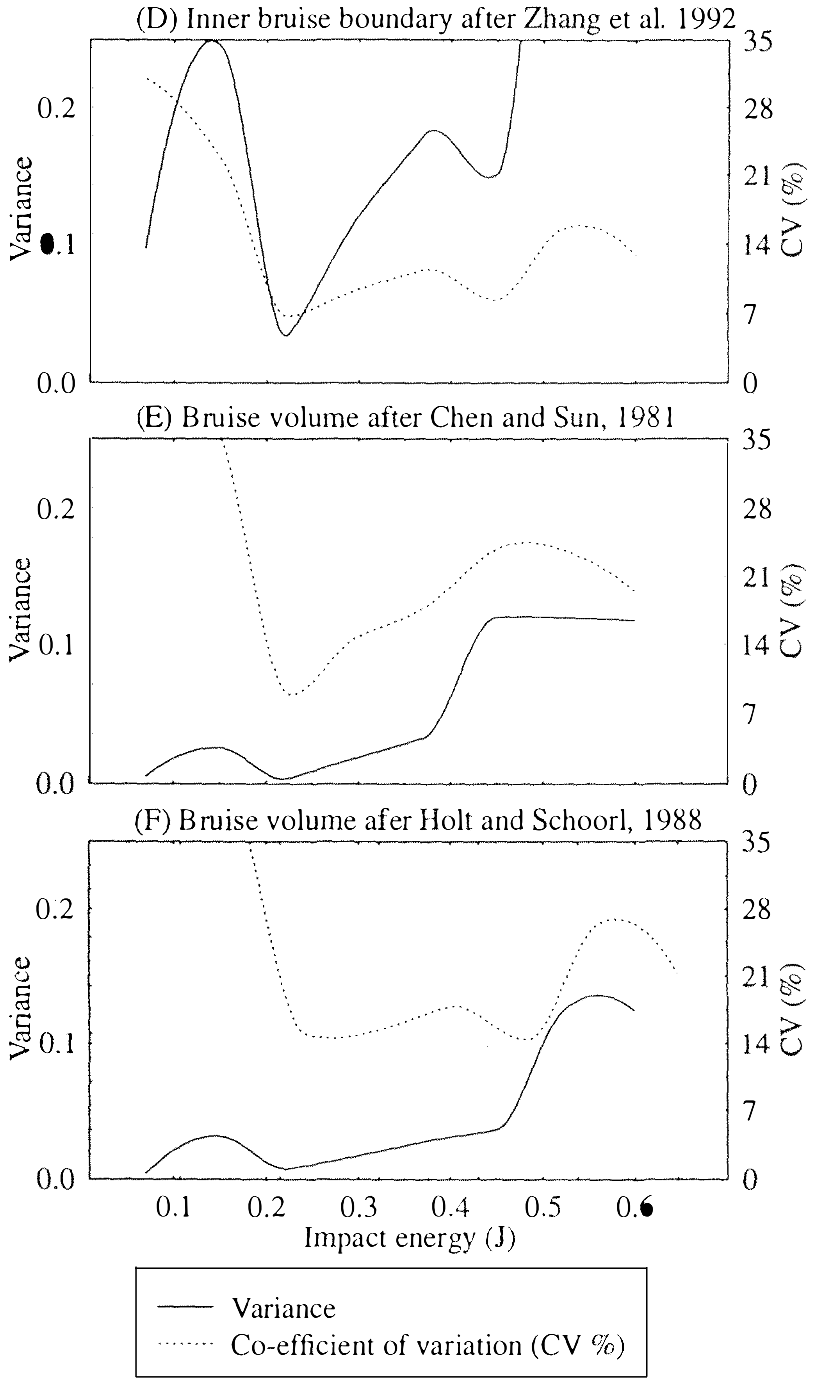


Fig. 4.4 Coefficient of variation and variance at eight impact energies from 0.07 to 0.6 *J* for (D) surface area of inner bruise boundary, (E) V_1 and (F) V_2

Table 4.4 Regression equations and coefficients of determination of six parameters used to represent bruise severity (E = energy; J).

Parameter	Regression equation	Coefficient of determination (%)
Depth	$-02.86 + 12.2E^{0.307}$	98.76
Diameter	$-12.50 + 36.59E^{0.174}$	97.38
Area	$-536 + 950E^{0.165}$	99.02
Inner bruise boundary area	$-227.46 + 910E^{0.39}$	98.95
Bruise volume V_1	$-17.99 + 2959E$	98.47
Bruise volume V_2	$-34.81 + 2775E$	98.21

Bruise volume was linearly related to impact energy ($E(J)$; Fig. 4.5A; $V = -0.253 + 12.64E$; $R^2 = 0.98$), whilst the relationship between d and E was curvilinear ($d = 2.49E^{0.3137}$; $R^2 = 0.96$). The transformation of impact energy to $E^{0.3137}$ resulted in a relationship with bruise diameter that was close to being linear (Fig. 4.5B). Coefficients of variation were consistently lower (5%) for d than for V (10 - 18%) for impact energies between 0.2 and 0.5 J (Fig. 4.5C). At the medium impact energies of 0.2 to 0.4 J the standard deviations of bruise diameter and depth decreased by at least a third to be approximately 3% of the mean for each impact energy. Thus, for this particular group of apples, an impact energy of 0.32 J gave the lowest combination of standard deviations for both bruise diameter and depth.

Therefore, when apples were bruised by impacting with a sphere of similar radius to themselves, d provided a more repeatable means of quantifying fruit susceptibility to bruising than did V.

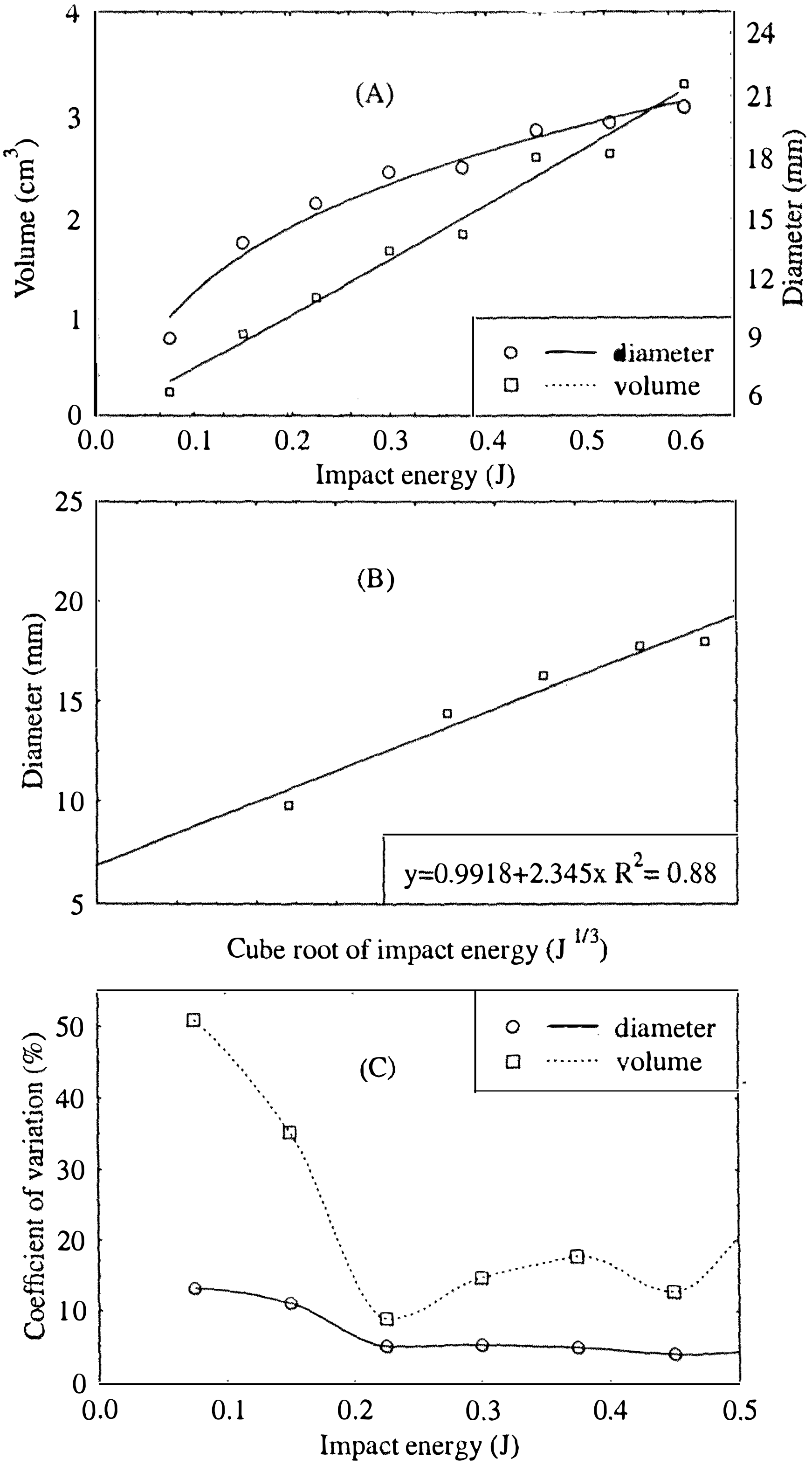


Fig. 4.5 Plots of (A) Bruise diameter and volume versus E, (B) bruise diameter versus $E^{0.3137}$; and (C) coefficient of variation of bruise diameter and volume for 'Splendour' impacted at different energy levels.

Marshall and Burgess (1991) impacted a suspended apple with an instrumented sphere and also found the highest coefficient of determination was between bruise diameter and E absorbed using a third order polynomial fit. At given impact energies, V may give larger proportional differences between treatments than d. However, the variation associated with measuring bruise depth also would be included in the calculation of V. Therefore, any advantages in determining differences in bruise susceptibility between groups of fruit may be negated by the multiplication of errors associated with measuring bruise depth. As commercial relevance of bruise area is greater than bruise volume, and as d is the key variable involved in bruise severity calculations, d is likely to be the most suitable means of representing bruise severity. The close relationship between d and bruise severity suggests that if other fruit characteristics were associated with susceptibility to bruising, then their correlation with d could be usefully examined.

From these tests it was concluded:

- d was the most suitable means of determining differences in susceptibility to bruising between groups of apples

- the variances of bruise diameter and depth were minimal at impact energies between 0.22 to 0.5 J and impacting fruit with a large ball at 0.32 J gave the lowest combination of standard errors for bruise diameter and depth.

4.2 Bruise colour measurement on whole apples and the difference in colour components between light and dark bruises.

4.2.1 Introduction

Experimental work in following chapters of this study focuses on preharvest,

harvest or postharvest treatments to apples to reduce both bruise severity and bruise colour. It was therefore essential to quantify measurable colour differences between light and dark coloured bruises that had been generated by Method 2. Bruise colour, relative to that of the surrounding skin, is important in determining perceptions of bruise severity, which in turn determines whether or not apples are suitable for export and will be accepted by consumers.

Bruise colour can be measured quantitatively by either spectrophotometry or by using a tristimulus colorimeter. Using a spectrophotometer, Ingle and Hyde (1968) found considerable differences between cultivars in development of bruise colour intensity at a reflectance of 600 nm. Sample preparation for spectrophotometry is time consuming but its use may give the most accurate absolute colour co-ordinates. Portable tristimulus colourimeters are probably the most suitable equipment for measuring colour differences in studies of this kind (Voss, 1992). They are quick, simple to use and integrate reflection curves in 3D co-ordinates which are associated with response curves of the human eye to colour (Francis, 1980). Bruise colour could be measured in two ways: either through the skin or on exposed sections of damaged tissue.

Samim and Banks (1993a) were unsuccessful in characterising changes in bruise colour of 'Granny Smith' apples by measuring colour of a bruised and an adjacent non-impacted area through the skin. Elimination of the positional variation involved in their approach may be achieved by measuring the difference in colour components of the same section of apple skin before and after bruising. Therefore, if it were possible to determine the variation in skin colour measurements immediately before and at periods after a standard impact was applied to 'Granny Smith' apples of differing initial skin colour, an indication of the suitability of this method for measuring bruise colour differences could be obtained.

To characterise the difference between light and dark coloured bruises it was desirable to first explore the differences in colour between bruised and unbruised apple tissue. These differences would hopefully give an indication of the degree of change in colour components caused by bruising and thereby identify the colour attribute(s) of most importance in this change. To achieve this it was necessary to group bruises visually according to the severity of bruise colour and then measure the colour components of each group and determine the difference between the two groups.

4.2.2 Materials and methods

4.2.2.1 Bruise colour measurement on whole apples

A Minolta chromameter was used to measure colour components on an identified equatorial section on two 'Granny Smith' apples of differing skin colour: green and pale yellow. A standard impact (Method 2) was applied to the same area of fruit surface. A colour photograph was taken and lightness, chroma and hue angle were measured on bruised tissue immediately after this and at 30 minute intervals for 4 h and then every h for 3 subsequent h. As reported by Samim and Banks (1993a) a mask was used to reduce the width of the aperture of the chromameter to avoid sampling of non-bruised tissue at the periphery of the bruise. Colour data presented are therefore relative rather than absolute. Means and standard errors of the three colour attributes were calculated and plotted for each observation time.

4.2.2.2 The difference in colour components between light and dark coloured bruises

A standard impact (Method 2; Section 3.2.2) was applied to 48 freshly harvested 'Granny Smith' apples. Each bruise was bisected at right angles to the skin and the colour of bruised and nearby unbruised tissue was measured by chronometer.

'Granny Smith' apples were harvested from the FCU orchard early, mid and late season (2 reps/harvest, 56 fruit/rep) and all data were grouped for statistical analysis. A standard impact (Method 2; Section 3.2.2) was applied to all apples immediately after harvest and 24 h later the apples were bisected at right angle to the skin. A chromameter was used to measure lightness, chroma and hue angle on each half of the sectioned bruise. The bruised tissue of each fruit was also visually assessed in an attempt to group the fruit by bruise colour. However, there was considerable variation in the shades of brown present on the bruised tissue between apples within each replicate. To overcome this, fruit with distinctly light brown bruised tissue were separated from those fruit with darker bruises. The bruise colour components of these two groups of fruit were then compared.

4.2.3 Results and discussion

4.2.3.1 Bruise colour measurement on whole apples

There was an immediate decrease in values for all colour attributes after bruising (Figs. 4.6 and 4.7). These values subsequently recovered to higher than initial values and then underwent a slow decline to reach steady levels after about 240 minutes. These changes might be explained in the following way. Actual lightness and hue angle of the bruised tissue declined continuously after impact, an effect associated with the browning of the tissue, but changes in surface contour of the bruised fruit which initially became concave (depressing lightness and hue angle) and then flattened (increasing lightness and hue angle). However, overall these changes in lightness and hue angle were small in relation to the initial differences between the fruit. Measurement of bruise colour through the skin is unlikely to provide satisfactory characterisation of the changes in colour associated with bruising as suggested by Samim and Banks (1993a).

4.2.3.2 The difference in colour components between light and dark coloured bruises

There were significant differences between the three colour components of bruised and unbruised apple tissue (Table 4.5). Bruised apple tissue had a significantly higher lightness component than unbruised tissue and this change

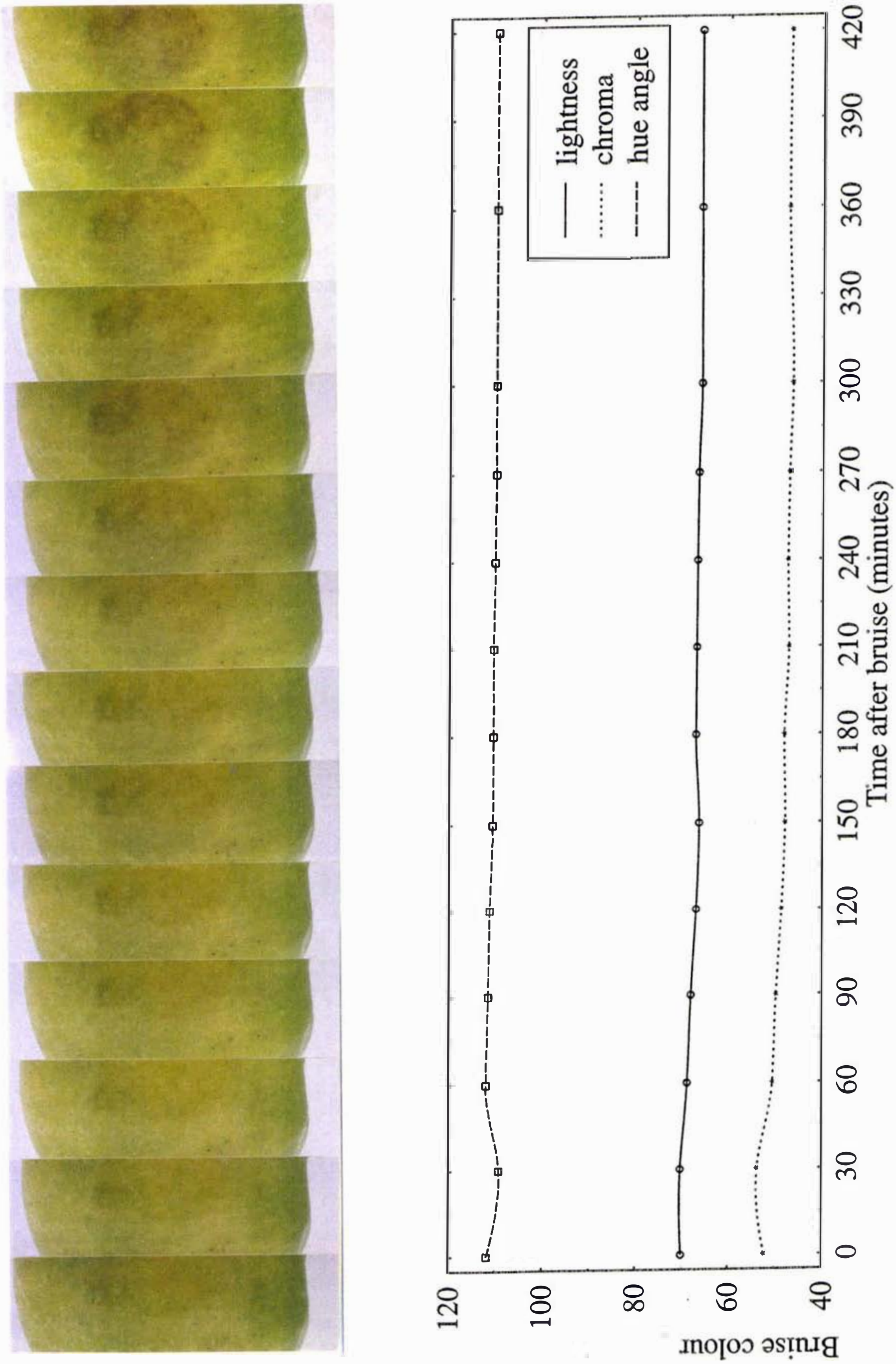


Fig. 4.6 Bruise colour development after a standard bruise was applied to a yellow skinned 'Granny Smith' apple.

Fig. 4.7 Bruise colour development after a standard bruise was applied to a green skinned 'Granny Smith' apple.

was associated with a large increase in colour intensity (chroma). Bruised tissue also had a lower hue angle than unbruised tissue, indicating a deeper brown colour. These data identify the change in colour components before and 24 h after bruising and provided an indication of the values that could be expected.

Table 4.5 Colour components of bruised and unbruised apple tissue of 'Granny Smith' apples (n = 48) measured with a Minolta chromameter.

	Minolta chromameter colour components		
	Lightness	Chroma	Hue angle
Unbruised apple tissue	58 b	46 b	112 b
Bruised apple tissue	75 a	9 a	80 a

Values within columns followed by different letters are significantly different at 0.01

Table 4.6 Colour of bruised tissue of 'Granny Smith' assessed visually and as measured with a Minolta chromameter.

Visual assessment of bruise colour	Minolta chromameter colour components		
	Lightness	Chroma	Hue angle
Light colour	74.9 a	4.5 a	78.6 a
Dark colour	74.2 b	4.6 a	73.5 a

Values within columns followed by different letters are significantly different at 0.05.

When apples were grouped according to visual differences in brown colour, apples which were distinctly darker in colour had a 5° lower hue angle and a 0.7 unit higher bruise lightness than apples with light brown bruises (Table 4.6). There was no difference in the chroma of the two groups of fruit. Differences in bruise lightness although statistically significant, were small. Hue angle was therefore probably the most accurate indicator of visual appearance of bruise colour.

4.3 Conclusions

This section on the development of new materials and methods has identified that:

- Dropping a ball (of similar size and mass to an apple) 0.2 m onto an apple generated bruises with diameters (14 mm) that were reasonably similar to those bruises incurred during normal grading operations

- Bruise diameter was a suitable means by which to represent bruise severity

- Differences between light and dark coloured bruises are best identified by differences in hue angle.

CHAPTER FIVE
PREHARVEST SOURCES OF VARIATION IN BRUISE SUSCEPTIBILITY AND BRUISE COLOUR

5.1 Introduction

Preharvest growing conditions have been linked to postharvest behaviour of fruit. Monselise and Goren (1987) reviewed data that detailed variable postharvest performance of fruit from areas with distinctly different climates and soils. In a more localised study, Sharples and Johnson (1987) documented variable responses to CA treatments in storage life of apples from different orchards in Kent, a predominant apple growing area in the England. Johnson and Dover (1990) linked preharvest conditions to between-season and between-orchard variation in bruise susceptibility and suggested that it may be possible to consider manipulating preharvest conditions to manage bruise damage. Many investigations have determined relationships between bruise severity and impact energy and the effect of different graders on bruising of NZ grown fruit has also been examined (Bollen and Dela Rue, 1990; Banks, 1991). Whilst several measures of bruise susceptibility have been documented, these indices have not been related to actual bruise damage that fruit incur during postharvest handling (Pang, 1993). Quantification of between-orchard, between-tree and within-tree variability of susceptibility to bruising and bruise colour, and the links between bruise severity tests and commercial damage, do not appear to have been studied.

Any factor that influences cell number, size, contents and strength would be likely to affect an apple's ability to absorb impact energy without damage. Between-season variation in apple characteristics are attributable to the interaction of numerous factors, such as climatic conditions, maturity of plantings and management changes by orchardists. Susceptibility to bruising is therefore the result of many combinations of environmental influences and management options. Within an orchard, a number of soil types, or at least variation in the predominant soil type, may be present. Depending on the height, density and placement of shelter trees, the degree of protection from prevailing wind and consistency of incident light across a block may vary. There are a number of management options available to orchardists that influence fruit size, mineral contents or storage life (Section 2.5.3.6). Within-tree variability in fruit characteristics may result from incident photon flux which varies both vertically and horizontally within the tree canopy (Tustin *et al.* 1988) and with other physiological factors such as the type of fruiting wood on which fruit mature (Volz, 1991) are also important. Some of these factors have been shown to influence susceptibility of apples to bruising or the intensity of enzymatic browning of damaged tissue. For instance Durand (1990) has shown that regulated deficit irrigation can reduce susceptibility of apples to bruising. Smith and Cline (1984) found that apples sprayed with $CaCl_2$ produced juice that showed less brown discolouration than juice from unsprayed apples.

It is therefore clear that, depending on the season, orchard location, within-orchard tree location and within-tree fruit position, individual fruit would be expected to have variable characteristics such as mass, maturity, tissue structure and composition and consequently have tissue that develops bruises of variable size and colour. Quantification of variability in susceptibility to bruising and bruise colour is fundamental to identifying the potential to reduce bruise severity through manipulation of at least some of these factors.

In this study, between-season and between-orchard variation in susceptibility to bruising and bruise colour was investigated in 1991 and 1992 by surveying orchards producing 'Granny Smith' apples. Attempts were made to explain such variation in terms of various fruit attributes and also to relate susceptiblity to bruising derived from a standard impact test to bruise damage that fruit incur during postharvest handling. Between-tree and within-tree variation in bruise susceptibility and bruise colour was investigated more intensively in 1992. The association of such factors with fruit attributes and the effect of foliar applications of calcium and phosphorus sprays and variable irrigation regimes on susceptibility to bruising and bruise colour were also examined.

5.2 Between-orchard variation

5.2.1 Materials and methods

In 1990, approximately 250 'Granny Smith' apples (average mass = 0.180 kg) were taken from each of nine orchards and, in 1991, 176 fruit count size 88 (average mass = 0.204 kg) and 250 fruit of count size 125 (average mass = 0.144 kg) of the same cultivar were taken from each of twelve Hawkes Bay orchards. In both years, fruit were commercially harvested. In 1990 fruit were randomly selected from the water dump prior to grading and the following year cartons of export packed fruit were randomly selected. In 1990 all fruit were scored for bruises caused by field handling prior to grading.

In both years, a standard impact (Method 1; Section 3.2.1) was applied to all apples and, according to the diameters of the generated bruise, grouped into three categories: most, intermediate or least susceptible to bruising with the intermediate group being discarded. In 1990, there were 22 fruit for each of the most and least susceptible groups (44 fruit selected from 250) from each of nine orchards. The following year there were 20 of the most and least susceptible fruit from each of two sizes (large fruit: 40 selected from 176; small fruit: 40 selected from 250) from each of 12 orchards.

In 1990, fruit were assessed for field and transportation damage, then carefully packed onto export trays and then transported to a packing shed located in Hawkes Bay and graded (Method 3; Section 3.2.3) using a 'Treeways' electronic grader. Experimental fruit were marked according to susceptibility ranking and orchard and then loaded into a flow of other non-experimental fruit on the belt immediately before the singulator, providing a total fruit loading of approximately 8 fruit per rod. All fruit were delivered down a single chute to a rotary bin which was pre-loaded to give an initial cover of about 60% of the bin base. Fruit from the least and most susceptible groups from each grower were passed over the grader together to permit direct comparison of these groups by grower. Fruit were then returned to Massey University where a second standard impact (Method 1; Section 3.2.1) was applied the next day. In the 1991 study, the two groups of fruit from each grower were graded (Method 3; Section 3.2.1) on the FCU 'Treeways' grader.

In each year, fruit firmness, soluble solids and starch were assessed. A 12 mm diameter core borer was used to take a 10 mm long tissue plug from an undamaged section of the top half of 10 apples from each group. The skin was removed, the 10 samples from each group were bulked, homogenised and tested for minerals. Bruise diameter was chosen to represent susceptibility to bruising (Section 4.1.3.3).

In 1991, a Minolta chromameter was used to determine colour components (lightness, chroma and hue angle) on two areas of skin adjacent to the area that had been subjected to a standard impact. After two measurements of skin colour, the bruise was bisected at right angles and colour components were measured on each half. These data were then averaged to give colour components for both apple skin and bruise colour.

Regression analysis was used to determine functional relationships between standard impact bruise area with grader damage, mineral contents and fruit attributes. Correlation coefficients were used to determine associations between attributes.

5.2.2 Results and discussion

The average within-year difference between the individual minimum and maximum standard impact bruise diameters was 40% (Table 5.1; mean of 1990, 17% and 1991, 63%) which compares with an 86% difference in minimum and maximum bruise volumes documented by Johnson and Dover (1990) in their six year survey. This two year study identified a 2.8% difference in between-season mean bruise diameter whilst Johnson and Dover's study identified a 23% difference in between-season mean bruise susceptibility for the six years of their study. Using maximum and minimum standard impact bruise diameters, within-season variability in susceptibility to bruising was considerably greater than between-season variability (Table 5.1).

Table 5.1 Between and within-season comparisons of standard impact bruise dimensions of 'Granny Smith' apples. Standard errors are in parenthesis.

	1990	1991	Between-season difference
Pooled data			
Mean bruise diameter (mm)	12.87 (0.15)	13.24 (0.06)	2.8%
Range (mm)	11.8 - 13.79	10.92 - 17.90	
Difference in range (percent)	17%	63%	
Mean bruise depth (mm)	6.33 (0.06)	6.32 (0.03)	
Least susceptible fruit			
Bruise diameter (mm)	12.30 (0.11)	12.88 (0.07)	4.4%
Bruise depth (mm)	6.26 (0.08)	6.03 (0.06)	
Most susceptible fruit			
Bruise diameter (mm)	13.44 (0.08)	13.59 (0.08)	1%
Bruise depth (mm)	6.40 (0.10)	6.15 (0.04)	
Within-season difference between bruise diameter of least and most bruise susceptible fruit (mm)	11.7%	5.5%	

In 1990 the difference between maximum and minimum impact bruise diameters was 17% (average fruit mass, 0.180 kg; range, 0.157-0.207 kg) and the following year on the difference was 63% (average fruit mass, 0.178 kg; range, 0.098-0.278 kg). When grouped according to susceptibility, apples classified as most susceptible to bruising had an 11.7% (1990) and a 5.5% (1991) larger bruise diameter than least bruise susceptible fruit respectively (Table 5.1). Like the 'Bramley's Seedling' apples studied by Johnson and Dover (1990) susceptibility to bruising of 'Granny Smith' apples in the study varied more within a season than between seasons. However, these data indicate that NZ grown 'Granny Smith' apples may exhibit less seasonal variation in susceptibility to bruising than UK grown 'Bramley's Seedling' apples.

Variation in susceptibility to bruising between years was presumably the result of a number of factors including differing seasonal environmental conditions; however variable maturity and firmness or some other more complex association of management inputs may have also contributed to the differences.

Both this and Johnson and Dover's studies focused on cultivars that are perceived to be very susceptible to bruising, primarily because of the visibility of bruised tissue. However, this perception is not supported by measures of bruise susceptiblity *per se.*, which indicate that 'Granny Smith' (Klein, 1987) and 'Bramley's Seedling' (Johnson and Dover, 1990) are only moderately prone to bruising when compared with other cultivars. It is possible that other more bruise susceptible cultivars ('Golden Delicious') would show a greater variation if subjected to similar studies. This suggests that there is potential to identify and possibly manipulate factors that may influence susceptibility to bruising as well as determining if such variability can be used to advantage by orchardists to reduce fruit damage losses.

The difference in standard impact bruise diameter between orchards producing the most and least susceptible fruit was 6.1% and 7% in 1990 and 1991 respectively (Table 5.2). Preliminary investigations of dependence of susceptibility to bruising upon soil type and tree age failed to identify any relationships (data not shown).

In 1990, the most bruise susceptible group of apples incurred more than three times the field damage than least susceptible fruit (Table 5.3). The reductions in grader bruise area/fruit between the most and least bruise susceptible groups of fruit were 42% (1990) and 39% (1991) respectively. In that year standard impact bruise diameter was related to field damage (harvesting and transportation; r =

0.57; $P < 0.025$) and grader damage ($r = 0.45$; $P < 0.05$).

Table 5.2 Standard impact mean bruise diameter of orchards in the 1990 and 1991 survey. Within each year orchards are ranked from largest to smallest average bruise diameter, different orchards were used in each year. Standard errors are in parentheses.

Orchard	1990 Bruise diameter (mm)	1991 Bruise diameter (mm)
1	13.18 (0.24) a	13.66 (1.1) a
2	13.11 (0.58) a	13.63 (0.26) a
3	13.06 (0.51) a	13.46 (0.14) a
4	13.02 (0.76) a	13.45 (0.25) a
5	12.84 (0.75) ab	13.43 (0.12) ab
6	12.82 (0.56) ab	13.36 (0.23) ab
7	12.74 (0.51) ab	13.26 (0.22) ab
8	12.67 (0.55) ab	13.05 (0.19) abc
9	12.42 (0.62) b	12.95 (0.14) bcd
10		12.81 (0.15) cd
11		12.79 (0.19) cd
12		12.76 (0.24) d

Values within columns followed by different letters are significantly different at 0.05.

Percent difference in bruise diameters of fruit from orchards producing the most and least bruise susceptible fruit.

	1990	1991
	6.1%	7%

Table 5.3 Field and grader damage (mm^2) of the most and least susceptible groups of 'Granny Smith' apples from each of the 1990 and 1991 orchard surveys.

	1990		1991
Apple group	Field damage (mm^2)	Grader damage (mm^2)	Grader damage (mm^2)
Most susceptible	38	132	320
Least susceptible	11.2	77	195
Percent reduction	70%	42%	39%

In 1990, field damage was more strongly associated with susceptibly to bruising as determined by standard impact bruise diameter than grader damage. This suggests that the type of bruises incurred by apples whilst being harvested may be better related to the standard impact test than grader inflicted bruises. The slope of the regression line for the relationship between the standard impact bruise diameter and area of bruising (R^2 = 0.21) incurred with a single pass of fruit across the grader, indicated that for every 1 mm increase in standard impact bruise diameter grader damage area increased by 33 mm^2 (Fig. 5.1). In 1991, standard impact bruise diameter was also related with grader bruise area/fruit (R^2 = 0.49) and bruise number/fruit (R^2 = 0.28). A 1 mm (8%) increase in bruise diameter (12.6 to 13.6 mm) equated to an 87% increase in grader damage (from 16 to 30 mm^2; Fig. 5.2) and a 42% increase in the number of grader bruises incurred (from 0.26 to 0.37 bruises/fruit; Fig. 5.3).

In both years, small differences in absolute magnitude of the bruise diameter resulting from the standard impact corresponded to quite substantial differences in the tendency to become bruised during post harvest handling. These findings confirm that testing for susceptibility to bruising with a standard impact test provides valuable data that relates bruise diameter at harvest to its tendency to incur bruises during grading.

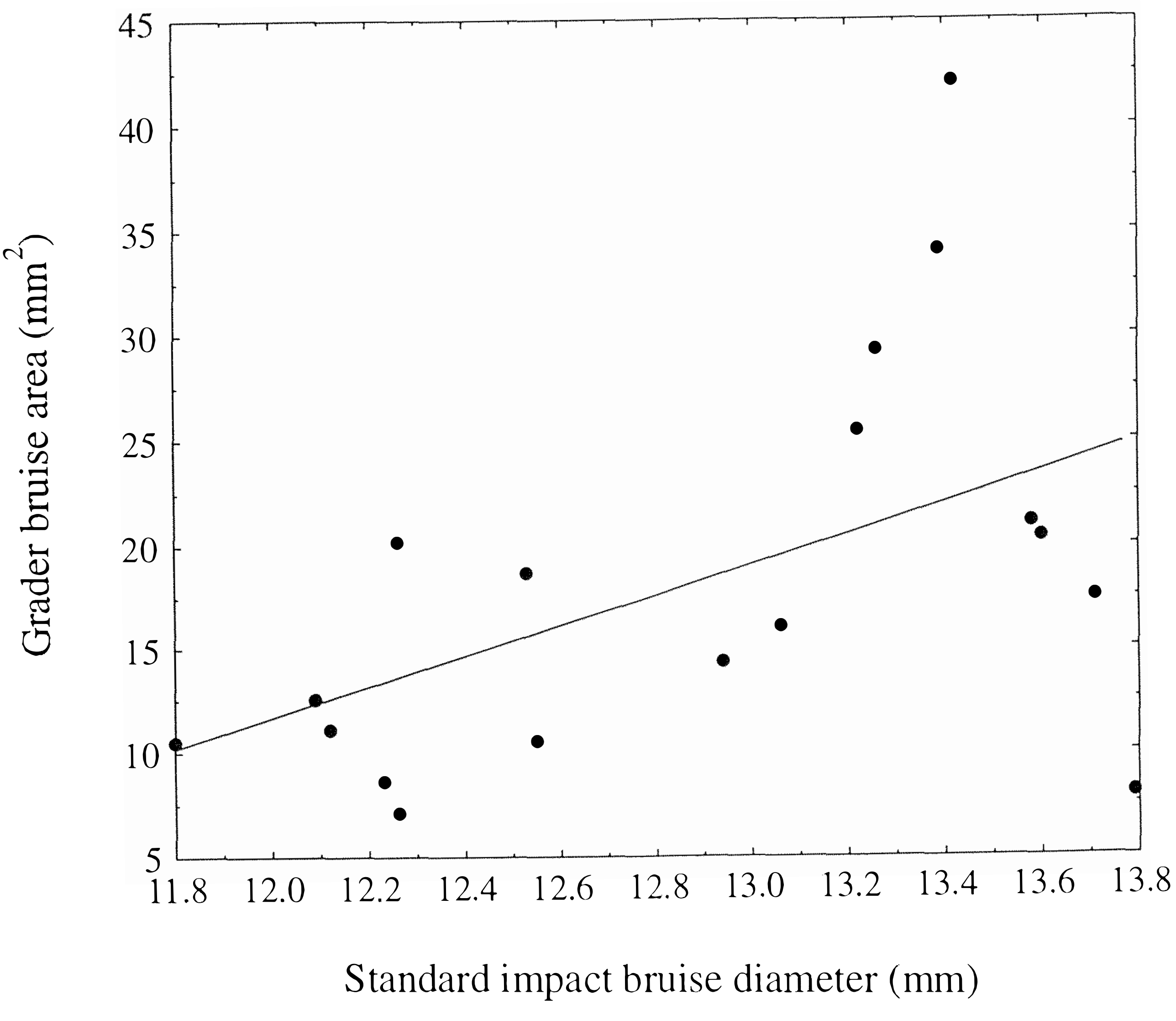


Fig. 5.1 Relationship between standard impact bruise diameter and bruise area/fruit for high and low susceptibility groups of fruit from each orchard incurred whilst grading in 1990 ($R^2 = 0.21$).

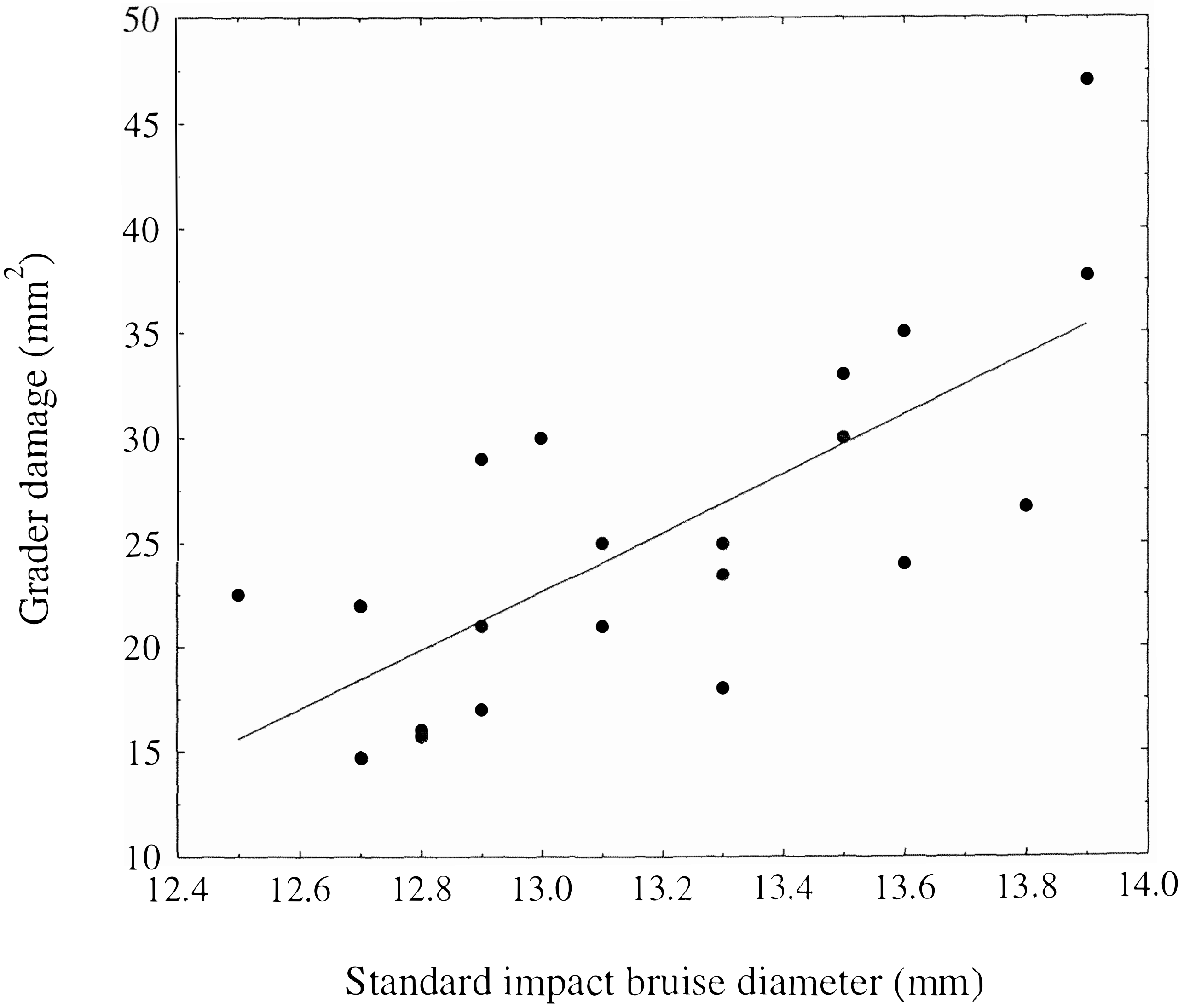


Fig. 5.2 Relationship between standard impact bruise diameter and bruise area/fruit for high and low susceptibility groups of fruit from each orchard incurred whilst grading in 1991 (R^2 = 0.49).

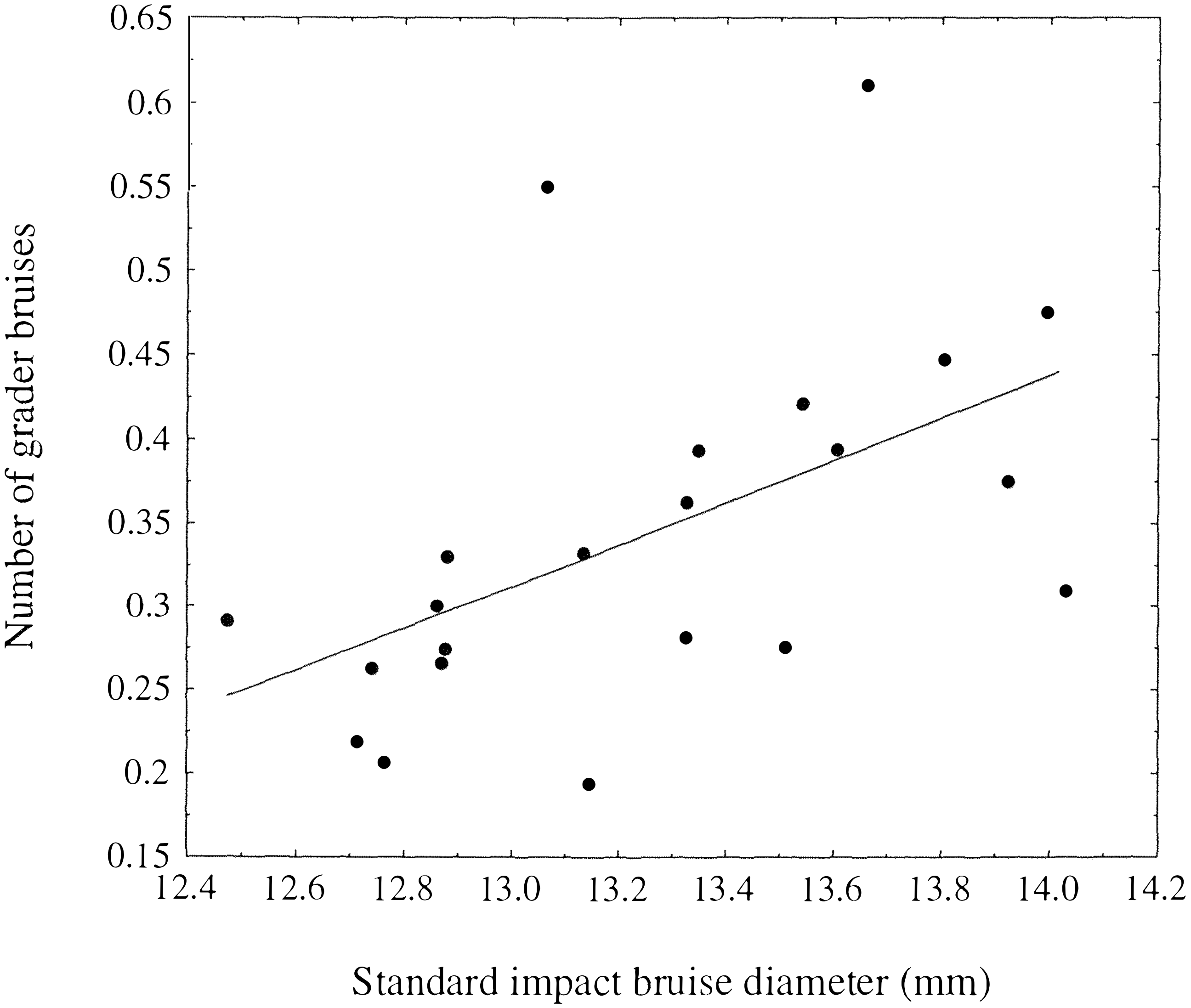


Fig. 5.3 Relationship between standard impact bruise diameter and bruise number/fruit for high and low susceptibility groups of fruit from each orchard incurred whilst grading in 1991 ($R^2 = 0.28$).

It is recognised that a single standard impact test does not readily mimic the range of bruises that apples are likely to incur during postharvest handling. In both years the relationship between standard impact bruise diameter and grader damage was influenced by a number of factors:

- ♦ grader damage is largely a result of apple-apple collisions, the impact characteristics of which differ considerably from those resulting from the standard impact test. Two colliding apples (both considered to have elastic properties) each have some ability to absorb the resultant impact energy and may also be able to move at the moment of impact. Therefore, the dimensions of bruises incurred during grading are likely to be different to those produced by standard impacts with similar impact energies

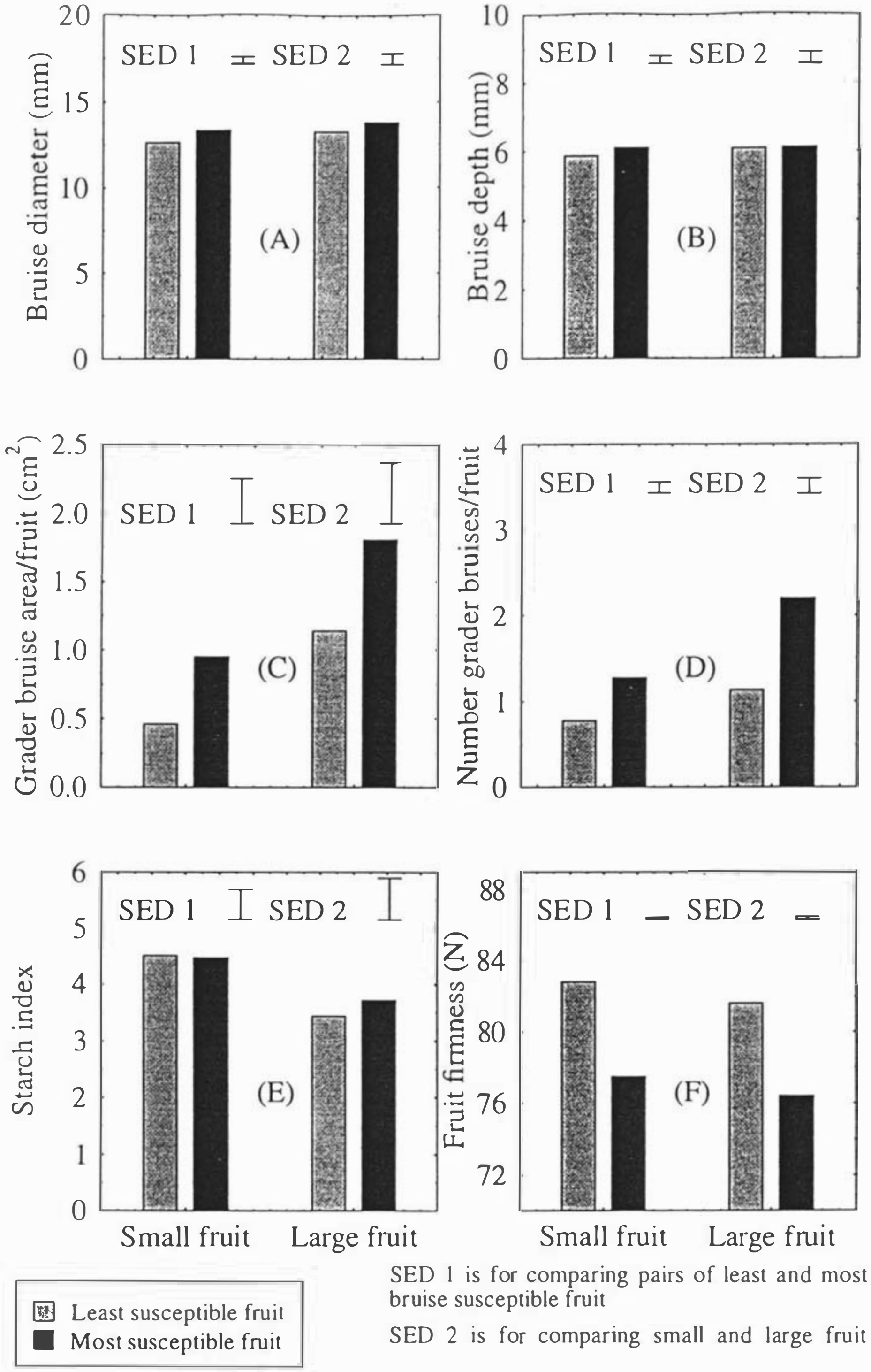
- ♦ the standard impact was applied to the equator of each apple. Grader (and handling) bruises occur over the whole apple surface where differing responses to impact may result from variation in cortex cell size (Petrell *et al.* 1980; Pang, 1993). In addition, the magnitude of impact energies experienced by apples during grading would vary considerably.

The disparity in grader damage between years relates to the use of different graders and techniques to simulate the grading operation, as well as seasonal differences in susceptibility of fruit to bruising. In the 1990 study, grader damage would have been higher than that normally expected to be incurred during commercial operations because of the large numbers of fruit dropping coincidentally from the cups down to the chute; this would have elevated the number of fruit-fruit collisions above those which normally would have been encountered. The following year a different grader was used and the fruit were graded in small groups and as a consequence the apple-apple damage may have been less than expected in a normal commercial operation. Counter to this was the fact that the grader design used in 1991 may have imparted more kinetic energy to the fruit than did the grader in 1990. Different absolute levels of bruising were expected because different graders are known to cause widely differing amounts of damage to apples (Banks 1991).

In 1990, fruit were randomly selected from the water dump and as a consequence fruit mass was variable; there was clear distinction between the bruise susceptibilities of large and small fruit. In that year, small fruit tended to have smaller standard impact bruise diameters ($r = 0.71$; $P < 0.001$) and to incur less damage during harvesting and grading operations ($r = 0.55$ and 0.41; $P < 0.025$ and 0.05, respectively) than larger fruit. However, the magnitude of the difference in average mass of fruit in these two groups was only 10% and was not large enough to explain the considerable difference in bruise area resulting from postharvest handling for the two groups of fruit. In an effort to further clarify the effect of fruit size on susceptibility to bruising the design of the 1991 experiment was changed to include groups of both large and small fruit from each orchard.

In the second year, fruit of greater mass sustained larger standard impact bruise diameters than did smaller apples (Fig. 5.4A). Smaller, less bruise susceptible fruit had significantly lower standard impact bruise diameters than the other three groups; this group of fruit also had the shallowest bruises (Fig. 5.4B). There is a well known proportionality between bruise size and impact energy and therefore between bruise size and fruit mass for a given drop height (Schoorl and Holt, 1980). The difference in fruit mass would have led to a greater impact energy for fruit dropped from a given height within the postharvest handling system. Given that these fruit were also more susceptible to bruising there was a predictably greater area and number of bruises on large fruit (Figs 5.4; C and D). Whilst there would be little commercial potential for limiting bruise severity through reducing the average size of harvested fruit this study identified that extra care and more impact absorbing material is required when large apples are being handled.

Both area and number of bruises resulting from the grader damage test were significantly higher on the most susceptible compared to the least susceptible fruit of both sizes (Figs. 5.4C and D). Similarly, both the area and number of



SED 1 is for comparing pairs of least and most bruise susceptible fruit

SED 2 is for comparing small and large fruit

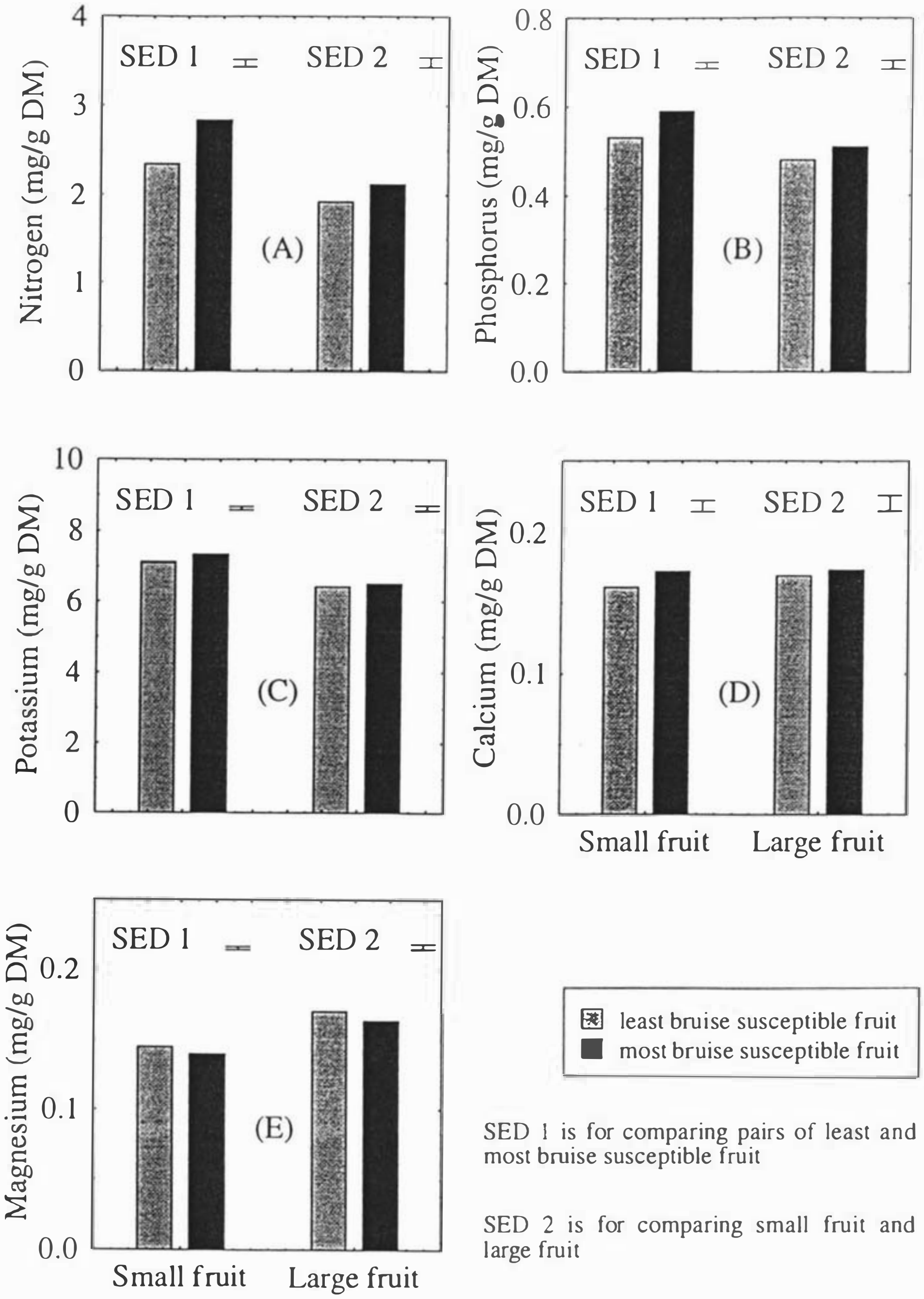
Fig. 5.4 Standard impact bruise diameter (mm), bruise depth (mm), grader bruise area/fruit (mm^2), number of bruise/fruit, starch index and fruit firmness (N) of the most and least susceptible groups of large and small fruit from the 1991 survey.

grader damage bruises were greater on the large apples than on the small apples (Fig. 5.4D). Both of these findings confirmed the expectation that large, bruise susceptible fruit would suffer much more bruising than small less bruise susceptible fruit.

In 1990, bruise diameter was approximately the same at the beginning and end of the experiment (2 days later), with diameters of initial and final standard impact bruise diameter being correlated ($r = 0.85$; $P < 0.001$). However, susceptibility to bruising (Method 2) measured after the fruit were returned to Massey University was less strongly associated with both types of handling damage. A possible reason for this surprising result may have been identified by Samim and Banks (1993b). Bruised apple tissue releases sap which is absorbed by the surrounding fruit tissue which would reduce fruit turgor and would therefore probably depress bruise susceptibility if the fruit were bruised again.

Fruit mineral contents differed consistently between the two bruise susceptible groups (Fig. 5.5). In both years the most susceptible fruit had more phosphorus, nitrogen, calcium and magnesium than the least susceptible fruit. If these differences were causative, they presumably affect susceptibility to bruising through effects on fruit texture or tendency of membranes to rupture upon impact.

Large fruit had less nitrogen, phosphorus and potassium, similar amounts of calcium but more magnesium than small fruit (Fig. 5.5A to E). The most bruise susceptible smaller fruit had more nitrogen, phosphorus, potassium and calcium than the least susceptible fruit of similar size. Although similar trends were evident in the large fruit there were no significant differences in mineral contents between the most and least susceptible fruit apart from magnesium which was higher in the least susceptible fruit.



SED 1 is for comparing pairs of least and most bruise susceptible fruit

SED 2 is for comparing small fruit and large fruit

Fig. 5.5 Nitrogen, phosphorus, potassium, calcium and magnesium content (mg/g DM) of the least and most susceptible groups of large and small fruit from the 1991 survey.

Standardised multiple regression analyses of means from most and least susceptible groups of each orchard lot of fruit (Table 5.4) determined that in 1990 fruit calcium concentration and fruit mass were functionally related to standard impact bruise diameter ($R^2 = 0.68$). By standardising data (each variable has zero mean and unit variance) fruit mass (standardised variate = 0.74) was of more importance than fruit calcium contents (standardised variate = 0.24) in this relationship.

Table 5.4 Regression ANOVA of standard impact bruise diameter on fruit calcium content and fruit mass (raw data) - 1990 survey data.

Source	df	SS	MS	F	Probability
Model	2	4.859	2.429	15.95	0.0002
Error	15	2.28	0.152		

The regression equation of standard impact bruise diameter on fruit calcium concentration and fruit mass (absolute data) was given by:

$$\textit{Standard impact bruise diameter} = 6.37(\pm 1.26) + 34(\pm 0.69)\textit{fruit mass} + 4.13(\pm 1.45)\textit{fruit calcium}$$

Where:

fruit calcium = calcium concentration of apple tissue (% dry matter)
fruit mass = fruit fresh mass (kg)

Handling damage at harvest was weakly related to fruit mass ($P < 0.025$) which indicates that factors other than the momentum that fruit generate during handling were associated with this type of damage. Regression analysis (Table 5.5) determined that grader damage was more closely related to tissue phosphorus concentration (% dry matter) than to any other variable (including fruit mass).

Table 5.5 Regression ANOVA of grader damage on fruit phosphorus concentration (raw data) - 1990 survey data.

Source	df	SS	MS	F	Probability
Model	1	1.76	1.76	8.85	0.008
Error	16	3.18	0.20		

The regression equation of grader damage on fruit phosphorus concentration ($R^2 = 0.33$) was given by:

$$\textit{Grader damage} = -0.85\ (\pm 0.066) + 1.52\ (\pm 0.512)\textit{fruit phosphorus}$$

Where:

fruit phosphorus = phosphorus concentration of apple tissue (% dry matter)

In one of the two years, these preliminary findings provided correlative evidence on the association of fruit mass and mineral composition with susceptibility to bruising and handling damage; further work would be required to substantiate causal relationships. If further studies demonstrated that these attributes were causal then some compromises would be required on other aspects of fruit quality if this approach to reducing bruise susceptibility was to be adopted.

Both phosphorus and calcium have been shown to have beneficial effects on apple quality and reducing levels of these minerals in fruit to reduce susceptibility to bruising may have undesirable consequences. Johnson and Yogaratnam (1978) and Letham (1969) found that increasing phosphorus enhanced postharvest storage life of apples. Similarly higher calcium content of apples has been associated with improved storage life of fruit (Poovaiah, 1986) and increased resistance to postharvest disorders (Conway, *et al.* 1994). Optimisation of fruit phosphorus and calcium levels to reduce susceptibility to bruising, whilst minimising other possible adverse effects on quality, would therefore be an important exercise in development of this strategy. Johnson and Dover (1990) found no consistent relationship between fruit mineral contents and bruise susceptibility. However, their survey programme was primarily designed to investigate variation in bruise susceptibility between seasons and between orchards. This study measured differences in susceptibility to bruising and fruit attributes within a number of orchards in a particular season. This made it possible to examine more closely differences between the most and least susceptible fruit within-orchards.

In 1991 multiple regression analysis did not relate any fruit attribute with either standard impact bruise diameter or handling damage. Fruit firmness was negatively related to grader damage ($r = -0.47$; $P < 0.05$), indicating the potential to reduce bruising damage by harvesting firmer, less mature fruit within the recognised commercial harvesting period. Fruit firmness was itself negatively linked to phosphorus levels and fruit mass ($r = -0.67$ and -0.66; $P < 0.01$ respectively).

In that year fruit firmness was less negatively correlated with standard impact bruise diameter ($r = -0.18$; $P < 0.0001$). These data substantiate those of Johnson and Dover (1990) and Garcia *et al.* (1995) who found a significant negative relationship between bruise volume and firmness ($r = - 0.47$ for CA-stored fruit and $r = - 0.24$ for fresh fruit, average of three cultivars; respectively). These data contrast with that of Klein (1987) who found no relationship between bruise susceptibility and firmness.

There was no consistent relationship between maturity, as assessed by starch index and standard impact bruise diameter on an orchard basis. In fact two of the orchards with lines of apples had fruit with small standard impact bruise diameters. However, there was a trend suggesting that bruise susceptible fruit were more mature (higher starch index and lower firmness) than less susceptible fruit within an orchard.

There was little difference in starch index between the two susceptibility groups but using this index small fruit were more mature than large fruit (Fig. 5.5E).

Despite this the smaller fruit had lower susceptibility to bruising probably because they were firmer. The least susceptible fruit were significantly firmer than the most susceptible fruit with smaller fruit firmer than larger fruit (Fig. 5.5F).

Bruise colour was not associated with susceptibility to bruising. Bruise hue angle was functionally related to fruit nitrogen content ($R^2 = 0.55$) indicating that apples with higher nitrogen had bruises that were less brown than those that developed on apples of lower nitrogen content. Of the skin colour attributes only hue angle was associated with nitrogen ($r = 0.28$, $P<0.0001$) indicating apples with higher nitrogen were more green. Thus, one may conclude that 'Granny Smith' apples with higher nitrogen contents may have had bruised tissue that was less brown than that which develops on apples of lower nitrogen content and that these bruises may also be less visible because of the enhanced greenness of the skin.

Between orchard variation in bruise lightness and chroma were low, but there were considerable differences in bruise hue angle. It was noted previously (Section 4.2.3.2) that when bruised tissue from different apples was classed visually, either as light or dark brown and then measured, a 5° hue angle quantified those visual differences.

Bruise colour data of each orchard were ranked according to increasing hue angle (decreasing brownness). Between-orchard differences in bruise hue angle indicate potential to manipulate bruise colour (Table 5.6). Whilst these differences in bruise hue angle may have been partially due to nitrogen content, other factors such as AA or calcium content may have contributed to the differences.

Table 5.6 Bruise lightness, chroma and hue angle of bruised apple tissue from 12 Hawkes Bay orchards ranked according to bruise hue angle - 1991 data.

Orchard	Bruise lightness	Bruise chroma	Bruise hue angle
1	75.20 a	9.50 abc	70.67 b
2	75.24 a	9.39 abc	75.51 ab
3	75.96 a	9.43 abc	76.31 ab
4	75.17 a	9.50 abc	78.37 ab
5	76.46 a	9.96 ab	78.37 ab
6	74.67 a	8.32 c	79.62 ab
7	76.71 a	8.69 bc	81.90 ab
8	75.06 a	9.78 ab	83.47 ab
9	75.37 a	9.84 ab	84.00 a
10	75.79 a	10.11 a	85.67 a
11	77.54 a	9.06 bc	85.73 a
12	76.46 a	10.06 a	86.56 a

Values within columns followed by different letters are significantly different at 0.05.

Overall, this study identified that there was considerable within-season variation in susceptibility to bruising of ‘Granny Smith’ apples and links between susceptibility to bruising and fruit size, maturity firmness and mineral contents were identified. The potential to manipulate the susceptibility of apples to reduce bruise damage incurred during postharvest handling was also established. Small reductions in measured susceptibility to bruising of harvested fruit corresponded to large reductions in actual damage that apples incurred. Some reductions in damage could be achieved by harvesting fruit slightly less mature (without compromising fruit quality) than current commercial practices and paying particular care to the gentle handling of the larger, more mature fruit in the population. Further gains might be made by manipulating fruit mineral contents if these could be shown to have causal influences on susceptibility to bruising with-out detracting from other fruit quality attributes. Before this potential could be realised the influence of local environment, orchard factors and management factors that may also be involved would have to be identified.

This study also identified that degree of brownness of bruised apple tissue varies considerably between orchards. Whilst apple tissue with higher nitrogen content was associated with reduced brown colour of bruised tissue, other, as yet unknown factors may also be associated.

It is clear that even if manipulation of production factors could only achieve small reductions in susceptibility to bruising (as determined by the standard impact bruise diameter), then considerable reductions in the quantity of fruit that are rejected because of bruising could be achieved. By using 'Granny Smith' apples from an important NZ apple production area, a worthwhile commercial interpretation of the standard impact test has been accomplished.

5.3 Within-orchard variation

5.3.1 Materials and methods

Fifty-six 'Granny Smith' trees (MM 106 rootstocks, 2.5 x 5 m spacings) and 85 'Royal Gala' (56 treatment and 29 buffer) trees (MM 106 rootstocks, 2 x 5 m spacings) at Massey FCU orchard were used in this experiment. These trees had been planted in 1985 in a north/south orientation in adjacent blocks on an alluvial soil type. Trees were semi-intensively managed with a central leader training system.

In 'Granny Smith', the randomised complete block experimental design took into account a number of factors. Two rows of trees were planted on a soil type that changed from shallow alluvial soil with rocks (Blocks 1 and 3) to a deeper alluvium with few rocks (Blocks 2 and 4). Block 3 was also sheltered by 12 m willows on the eastern side. 'Granny Smith' trees in blocks 1 and 3 were less vigorous than those in blocks 2 and 4. The 'Royal Gala' blocking took into account the shorter rows of trees. Blocks 1, 2 and 3 were on each of three rows whilst block 4 comprised trees from the southern end of rows not included in blocks 1 and 2. The northern end of blocks 1 and 2 were sheltered by 12 m willows. In this planting there was little variation in soil type and tree vigour. The closer spacing of the 'Royal Gala' planting made it essential to have an untreated buffer or guard tree between each pair of treatment trees.

For each cultivar there were 4 experimental blocks each comprising 7 pairs of trees (experimental units). Seven spray treatments were randomly allocated to these pairs of trees within each block:

1 Unsprayed (control)
2 Phosphorus 0.2% as H_3PO_4 - sprayed 4 times at about 1 week intervals after fruit set
3 Phosphorus 0.2% as H_3PO_4 - sprayed 4 times at about 1 week intervals prior to harvest
4 Phosphorus 0.2% as H_3PO_4 - sprayed a combination of treatments 2 and 3
5 Calcium 0.6% as $CaCl_2$ - sprayed 4 times at about 1 week intervals after fruit set
6 Calcium 0.6% as $CaCl_2$ - 4 times at about 1 week intervals prior to harvest
7 Calcium 0.6% as $CaCl_2$ - a combination of treatments 5 and 6

Sprays were applied using a motorised Solo knapsack sprayer at rates which were similar to commercial spray applications (2,000 L/ha). All trees were subjected to normal commercial management practices and other orchard sprays which included a standard spray regime of $CaCl_2$ ((360 g/100 L) and $CaNO_3$ (600 g/100

L). 'Granny Smith' trees received six applications of $CaCl_2$ whilst 'Royal Gala' trees received two applications of $CaNO_3$ and four $CaCl_2$ sprays.

At the beginning, midway and end of the commercial harvesting period (Table 5.7) eight fruit were harvested from the upper north and lower south position of each experimental unit. The total number of fruit harvested from each varietal trial was as follows:

3 harvests x 2 within-tree positions x 7 spray treatments x 8 fruit x 4 blocks
= 1344 fruit.

At each harvest, the order in which blocks were harvested was randomly selected. Generally, there was a 24 h interval between the harvesting of each block with harvesting beginning about mid-morning. Immediately after harvest, fruit were weighed and assessed for susceptibility to bruising (Method 2), bruised tissue colour components, firmness and crush strength, starch index, soluble solids were measured (Section 3.4 to 3.7). Because of the lower tissue strength of 'Royal Gala', a smaller Effigi penetrometer was used (8 mm) and a larger blade was used on the crush strength measuring apparatus for the third harvest only. Twenty fruit from each spray treatment of each block at each harvest were analysed for nitrogen, phosphorus, potassium, magnesium and calcium contents (Section 3.10).

Table 5.7 Early, mid and late season harvest dates for 'Granny Smith' and 'Royal Gala'.

	'Granny Smith'	'Royal Gala'
Early-season	April 15	February 25
Mid-season	April 26	March 13
Late-season	May 15	March 31

Experimental design was randomised and blocked, with a split block (fruit position and spray treatment) with a split-plot in time (harvests).

Irrigation trial

The effect of different irrigation regimes on susceptibility to bruising was investigated using an existing trial comprising two blocks each of twelve five-year-old 'Braeburn' trees at the FCU orchard. A 1 m deep trench was dug down both sides of the rows of experimental trees approximately 1 m from the trunk (Mills *et al.* 1996). Black polythene sheeting (2 m wide and 250 μm thick) was laid over the root zone of the trees and buried in the trench to a depth of 0.75 m. Each block either received no irrigation at all or sufficient irrigation to maintain soil moisture similar to that in an adjacent untreated block. The induced water stress was not sufficient to reduce shoot growth. Twenty fruit from each treatment were harvested at commercial maturity and soluble solids, firmness, crush strength, dry matter content, mineral contents and susceptibility to bruising (Method 2; Section 3.2.2) were determined (Sections 3.3, 3.5 to 3.7 and 3.10). Experimental design was randomised with internal replicates.

In each of the three experiments, analysis of variance was used to determine main effects and interactions. Differences between means were determined by least significant differences. Correlation coefficients were used to determine relationships between fruit attributes. Multiple linear regression was utilised to determine functional relationships between bruise dimensions and fruit attributes. Exploratory use of multi-variate techniques (principal components and canonical correlations) did not aid in understanding relationships in pooled data sets and are not reported.

5.3.2 Results and discussion

5.3.2.1 Between-tree variation

To avoid confounding by possible block*spray treatment interactions and to reduce the number of trees to be compared, between-tree variation was assessed only on data from each of the two control trees in each of the four blocks of the

'Granny Smith' and 'Royal Gala' trials.

'Granny Smith'

Between-tree differences in standard impact bruise diameter were small and were outweighed by the very significant harvest date differences (Table 5.8).

Table 5.8 Analysis of variance for standard impact bruise diameter for 'Granny Smith' control trees.

Source	DF	SS	MS	F value	Pr > F
Tree	7	10.179	1.45	1.84	0.0828
Harvest date	2	24.99	12.498	15.83	0.0001
Fruit position	1	0.313	0.313	0.40	0.529
Tree*harvest date	14	21.342	1.52	1.93	0.0267
Tree*fruit position	7	2.11	0.302	0.38	0.911
CV = 5.19%					

The significance of the tree*harvest date interaction was attributable to the significance of the main harvest date effect; standard impact bruise diameter was not related to the within-tree position of fruit nor was there a significant tree*fruit position interaction.

Means separation identified significant between-tree differences in susceptibility to bruising and all other fruit attributes (Table 5.9). The expectation that the least bruise susceptible fruit would be firm and relatively immature was substantiated by fruit on tree 56. These fruit were most resistant to bruising using standard impact bruise diameter and depth; they were very firm, of average crush strength and had a low starch index but had average soluble solids content. In contrast fruit from tree 2 had the largest standard impact bruise diameter, the bruise being of reasonable depth, were the least firm, of average crush strength

Table 5.9 Between-tree variation in standard impact bruise diameter (mm), depth (mm), mass (kg), firmness (N), crush strength (kPa), starch index and soluble solids (°Brix) for 'Granny Smith' apples.

Tree number	Block number	Bruise diameter (mm)	Bruise depth (mm)	Mass (kg)	Firmness (N)	Crush strength (kPa)	Starch index	Soluble solids (° Brix)
1	1	17.23 ab	7.10 ab	0.157 ab	80.73 c	61.75 ab	3.25 c	10.1 cb
2	1	17.37 a	7.19 ab	0.150 b	77.54 c	59.83 ab	3.58 bc	9.6 c
19	2	17.10 bc	7.36 a	0.162 ab	85.06 b	53.31 d	3.58 bc	11.2 a
20	2	17.09 bc	7.22 ab	0.163 ab	86.49 ab	54.70 cd	3.67 abc	10.45 b
33	3	16.81 bc	7.10 ab	0.158 ab	89.15 ab	62.94 a	3.87 ab	9.87 bc
34	3	17.25 ab	7.18 ab	0.173 a	86.16 ab	61.40 ab	4.17 a	10.03 bc
55	4	17.26 ab	7.08 b	0.151 b	89.01 ab	54.29 d	3.38 bc	10.38 b
56	4	16.65 c	6.96 c	0.149 b	89.06 a	58.18 bc	3.25 c	10.39 b

Numbers within columns followed by different letters are significantly different at 0.05.

and had the lowest soluble solids content. Bruise susceptible fruit would be expected to be less firm and relatively mature; however, these fruit with a soluble solids content of 9.6 and starch content of 3.58 were relatively immature. Thus, attributes of fruit from tree 56 confirm the expectation that firm, immature fruit should be relatively resistant to bruising. However to conform with expectations, the most bruise susceptible fruit from tree 2 should have been mature but this was not the case. The most significant by-tree multiple regression ($R^2 = 0.39$) was on tree 56 which related standard impact bruise diameter to fruit firmness ($p = 0.01$) and starch ($p = 0.04$). Tree 2 produced fruit that were the most susceptible to bruising, but standard impact bruise diameter was not associated with any of the measured fruit attributes (Table 5.10). In contrast, attributes of fruit from tree 56 which produced the least bruise susceptible fruit were

Table 5.10 Correlation coefficients for within-tree and pooled data between standard impact bruise diameter and fruit attributes for ‘Granny Smith’ apples harvested from control trees.

Tree & block number		Fruit mass	Firmness	Crush strength	Starch index	Soluble solids
1	1	ns	ns	$-0.59^{0.002}$	ns	ns
2	1	ns	ns	ns	ns	ns
19	2	ns	ns	ns	$0.69^{0.0002}$	$0.49^{0.01}$
20	2	$0.44^{0.03}$	ns	ns	ns	ns
33	3	ns	ns	$-0.41^{0.04}$	$0.59^{0.002}$	$0.45^{0.02}$
34	3	ns	$-0.54^{0.006}$	ns	ns	ns
55	4	ns	ns	$-0.48^{0.02}$	$0.46^{0.02}$	$0.44^{0.03}$
56	4	ns	$-0.58^{0.003}$	$-0.54^{0.005}$	$0.64^{0.0008}$	ns
Pooled data		$0.21^{0.002}$	$-0.37^{0.0001}$	$-0.33^{0.0001}$	$0.38^{0.0001}$	$0.18^{0.009}$

Superscript values denote level of significance associated with standard impact bruise diameter.

Pooling data produced significant but small correlations of fruit attributes with standard impact bruise diameter. Attributes other than those measured such as mineral contents, cell size and/or volume, internal air-space may have been responsible for a proportion of the variation and may have explained more specifically relationships with standard impact bruise diameter.

Multiple regression analysis of the pooled data set determined standard impact bruise diameter was functionally related ($R^2 = 0.30$) to fruit attributes.

$$\begin{aligned}\textit{Standard impact bruise diameter} &= 19.43(\pm 0.89) + 5.4(\pm 2.19)\textit{mass} \\ &- 0.02(\pm 0.008)\textit{crush strength} - 0.02(\pm 0.007)\textit{firmness} + 0.16(\pm 0.035)\textit{starch index}\end{aligned}$$

Standardised variates were as follows: mass, 0.14; crush strength, - 0.16; firmness, -0.25; starch index, 0.30. The fact that the most significant ($R^2 = 0.58$) by-tree multiple regression of susceptiblity to bruising and fruit attributes was on tree 56, which produced the least bruise susceptible fruit, is of interest. Standardised variates were mass, -0.31; crush strength, 0.04; firmness, - 0.55 and starch 0.48. Both regressions rated firmness and starch of most importance in predicting standard impact bruise diameter. Tree 56 was visually assessed to be very high yielding compared to tree 2 which produced the most bruise susceptible fruit. According to Westwood *et al.* (1967) and Martin *et al.* (1964); light blooming trees produce larger fruit with more cells and in some cases larger cells than heavy blooming trees. Thus an explanation for the difference in bruise dimensions of fruit from these two trees may have been because fruit on tree 56 had more cells than fruit on tree 2. Because of their similar mass, bruise dimension comparisons of fruit from these two trees is of further interest. A positive association of fruit mass with susceptibility to bruising has been established (Section 5.2.2). However, in this closer examination at orchard level, fruit from trees 2 and 56 represented extremes of bruise susceptibility but were of similar mass. These observations and data suggest that the significance of fruit mass on susceptibility to bruising may be overridden by between-tree differences in crop load.

Of note were the fruit from tree 19 which had the highest soluble solids and the deepest bruises. A positive association between dense, juicy tissue with low air-space and bruise depth was established by Garcia *et al.* (1988), who determined that fruit with juicy texture tend to have deeper cone shaped bruises. The greater depth of bruises on fruit from tree 19 tend to substantiate this observation.

Bruise lightness and chroma showed only slight between-tree variation (Table 5.11). Whilst there was greater between-tree variation in bruise hue angle, the

Table 5.11 Between-tree variation in colour components of bruised 'Granny Smith' apple tissue.

Tree number	Block number	Bruise lightness	Bruise chroma	Bruise hue angle
1	1	73.87 a	4.39 bc	72.85 ab
2	1	73.84 a	4.32 c	74.12 ab
19	2	74.35 a	4.89 a	72.30 b
20	2	74.32 a	4.75 ab	74.05 ab
33	3	74.13 a	4.61 abc	71.86 b
34	3	74.21 a	4.61 abc	73.34 ab
55	4	73.89 a	4.31 c	76.22 a
56	4	73.87 a	4.62 abc	72.74 b

Numbers within columns followed by different letters are significantly different at 0.05.

only visual difference was that fruit from tree 33 developed bruise tissue that was browner in colour than bruised apple tissue from tree 55; this may be somehow linked to the visually assessed levels of crop load (tree 33 < tree 55).

Between-tree variation in susceptibility to bruising and the intensity of brown discolouration of damaged apple tissue, although small, was statistically significant in this orchard planting of 'Granny Smith'. One tree produced fruit that were 4% more susceptible than those from several other trees; such variation was slightly less than that recorded between-orchards (Table 5.2; 6%) but more than that recorded between-seasons (Table 5.1; 2.8%). A 4% (13.5 to 13 mm) reduction in susceptibility to bruising as measured by the standard impact bruise diameter would be expected to translate into approximately a 24% (29 to 22 mm^2) reduction in grader damage when fruit are graded (Fig. 5.2).

The scope for reducing bruise colour by selection of fruit from individual trees was limited; clear visual differences could only be determined between bruised tissue on apples from tree 55 and 33.

'Royal Gala'

Between-tree differences in standard impact bruise diameter were small compared to the very significant harvest date differences (Table 5.12). Standard impact bruise diameter was not related to the position on the tree from which fruit were harvested and the significance of the tree*harvest date interaction was largely attributable to the main harvest date effect.

Despite this planting having a more uniform soil type and less variation in tree vigour than the 'Granny Smith' planting, a closer examination of between-tree data (Table 5.13) indicated that 'Royal Gala' displayed greater variation in susceptibility to bruising.

Table 5.12 Analysis of variance for standard impact bruise diameter for 'Royal Gala' control trees.

Source	DF	SS	MS	F value	Pr > F
Tree	7	56.71	8.10	5.61	0.0001
Harvest date	2	205.22	102.61	71.09	0.0001
Fruit position	1	3.94	3.94	2.73	0.102
Tree*harvest date	11	30.47	2.77	1.92	0.04
Tree*fruit position	7	2.31	0.33	0.23	0.977
CV = 12.47%					

The most bruise susceptible fruit were harvested from tree 22 which developed bruises that were 11% larger in diameter than bruises on fruit from tree 2 (Table 5.13). The most bruise resistant fruit were harvested from tree 2; they had relatively shallow bruise depth but were less firm than fruit from other trees. The twist test indicated that apple tissue from this tree had reasonable resistance to crushing and the fruit were of average maturity as measured by starch index and soluble solids. The most bruise susceptible fruit were from tree 22 and had average bruise depth, were firm, of good crush strength, had average starch content but had low soluble solids.

The expectation that the most bruise resistant fruit would be firm and relatively immature with the converse applying to the most bruise susceptible fruit does not seem to have been applicable to fruit from this 'Royal Gala' planting. Multiple regressions, using individual tree data of standard impact bruise diameter on fruit attributes, did not identify significant relationships. The reasons may be complex and are addressed later in this section.

Within-tree correlations of fruit attributes with standard impact bruise diameter did not identify consistent relationships (Table 5.14). Three of the eight trees

Table 5.13 Within-orchard variation in standard impact bruise diameter (mm) and depth (mm), mass (kg), firmness (N), crush strength (kPa), starch index and soluble solids (°Brix) for 'Royal Gala' apples

Tree number	Block number	Bruise diameter (mm)	Bruise depth (mm)	Mass (kg)	Firmness (N)	Crush strength (kPa)	Starch index	Soluble solids (°Brix)
1	1	15.53 cd	6.38 b	0.127 a	90.7 b	45.5 a	4.00 ab	10.1 a
2	1	15.24 d	6.32 b	0.118 a	87.2 b	47.07 a	3.78 b	9.7 ab
21	2	16.13 bc	6.60 ab	0.123 a	99.8 a	45.83 a	4.43 ab	10.1 a
22	2	17.12 a	6.52 b	0.131 a	99.7 a	45.81 a	4.45 ab	9.2 ab
29	3	16.08 bc	6.39 b	0.124 a	97.7 a	38.89 b	5.06 a	8.82 b
30	3	15.96 bcd	6.47 b	0.126 a	97.3 a	40.54 b	4.5 ab	9.18 ab
49	4	16.72 ab	6.72 ab	0.129 a	98.6 a	45.77 a	4.37 ab	9.49 ab
50	4	16.55 ab	6.97 a	0.126 a	98.0 a	46.37 a	4.64 ab	9.15 ab

Values in columns followed by different letters are significantly different at 0.05.

failed to show any relationship between standard impact bruise diameter and fruit attributes. It is worthwhile to note, that as with the 'Granny Smith', the 'Royal Gala' tree that produced the least bruise susceptible fruit, the most positive relationship between attributes and standard impact bruise diameter was from the that produced the least bruise susceptible fruit. Pooling data provided correlations between standard impact bruise diameter and fruit mass, firmness crush strength and starch content (Table 5.14).

Table 5.14 Within-tree and pooled data correlation coefficient between standard impact bruise diameter and attributes for fruit from 'Royal Gala' control trees.

Tree & block number		Fruit mass	Firmness	Crush strength	Starch index	Soluble solids
1	1	ns	ns	ns	$0.64^{0.009}$	ns
2	1	ns	ns	ns	ns	ns
21	2	ns	$-0.43^{0.09}$	ns	$0.47^{0.08}$	$-0.69^{0.05}$
22	2	$0.44^{0.03}$	$-0.67^{0.004}$	ns	ns	$0.61^{0.06}$
29	3	ns	ns	$0.63^{0.04}$	$0.65^{0.08}$	ns
30	3	ns	ns	$0.77^{0.0005}$	ns	ns
49	4	ns	ns	ns	ns	ns
50	4	ns	ns	ns	ns	ns
Pooled data		$0.23^{0.004}$	$-0.20^{0.05}$	$0.17^{0.03}$	$0.49^{0.0001}$	ns

Superscript values denote level of significance

Multiple regression analysis of the 'Royal Gala' control trees pooled data set related crush strength to standard impact bruise diameter (R^2 = 0.10).

Bruise lightness and bruise chroma showed statistically significant variation between trees (Table 5.15) but these components are not as important as bruise hue angle in determining the perceived brownness of bruised tissue (Section 4.2.3.2). The considerable between-tree differences in bruise hue angle was such that a visual distinction of degree of brownness could be made relatively easily between bruised tissue from most trees. Differences were generally between pairs of trees from different blocks despite the absence of the broad physical differences between blocks noted in the 'Granny Smith' planting. The only obvious visual physical difference between blocks was that trees 1 and 2 were shaded early in the morning by 6 m shelter willows at the northern end of the block. Should photosynthetic photon flux have been substantially reduced for these two trees, then this might be expected to have reduced mass and soluble solids (Tustin *et al.* 1988), although there was no evidence for this. The putative reduced photosynthetic photon flux may explain why fruit from both trees in this block were also less firm than fruit harvested from those in other blocks.

Table 5.15 Between-tree variation in colour components of bruised 'Royal Gala' apple tissue.

Tree number	Block number	Bruise lightness	Bruise chroma	Bruise hue angle
1	1	75.56 a	6.15 abc	84.89 a
2	1	75.65 a	6.19 abc	84.84 a
21	2	74.54 b	5.49 dc	79.89 ab
22	2	74.48 b	5.26 d	77.65 b
29	3	72.92 c	5.28 d	80.98 ab
30	3	73.17 c	5.58 bcd	75.73 b
49	4	73.25 c	6.31 ab	69.04 c
50	4	73.44 c	6.48 a	69.23 c

Values within columns followed by different letters are significantly different at 0.05.

Overall, comparing data from both cultivars it can be seen that fruit from individual 'Royal Gala' trees showed more variation in bruise diameter (15.24 to 17.12 mm) than 'Granny Smith' (16.65 to 17.39 mm) despite there apparently being less within-planting soil type diversity than in the 'Granny Smith' planting. The reasons for this probably relate to varietal differences in cell wall strength/thickness or cell volume. In contrast, the other measured fruit attributes showed more variation in the 'Granny Smith' planting. 'Royal Gala' is sometimes perceived to be a crisper, more juicy apple than the more dense 'Granny Smith'. There was a significant relationship between crush strength and firmness with 'Granny Smith' but not with 'Royal Gala' which further indicates that textural differences exist between the two apple cultivars.

This study identified a difference of 11.4 and 12.6 N between the firmest and least firm fruit within the populations of 'Granny Smith and 'Royal Gala' apples, respectively. Worthington and Yeatman (1967) found a 35 N difference in firmness between fruit from the extreme two of four 'Red Delicious' trees and, on a similar basis, a 14.7 N difference between 'Golden Delicious'. Between-tree differences may be greater in other orchards where greater variation in soil type and growing conditions exist. Support for this suggestion comes from previous work (Section 5.2.2) where the extreme difference in firmness from the data set pooled for 9 orchards in 1990 was 13 N and the following year with 12 orchards was 29 N.

This within-orchard, between-tree study has identified that despite variable block effects, individual 'Granny Smith' trees produced apples that showed less variation in susceptibility to bruising and bruise colour than did 'Royal Gala' trees. Susceptibility to bruising was related to fruit mass and crush strength in 'Granny Smith' and starch index in 'Royal Gala'. The magnitude of differences between trees suggests that, if factors that influence susceptibility to bruising and bruise colour could be identified, and then manipulated to advantage, considerable reductions in bruise damage and colour could be potentially achieved. 'Royal Gala' trees within-blocks produced fruit that had considerable variation in bruised tissue colour.

5.3.2.2 Time of harvest

'Granny Smith'

All data were pooled and analysed for main effects and interactions (Table 5.16). There was a significant time of harvest effect which also contributed to the significance of the fruit position*time of harvest effect. It was also clear from the significance of block effect that allocating variations of soil type and tree vigour to individual blocks contributed to improved precision of data analysis.

As harvests progressed through the season, susceptibility to bruising, as measured by standard impact bruise diameter, increased by nearly 5% (Table 5.17). Despite the shorter interval between the early and mid season harvest, susceptibility to bruising increased more in this period than between the mid and late harvest.

Table 5.16 Analysis of variance for standard impact bruise diameter for all main effects and interactions used in the 'Granny Smith' trial.

Source	DF	SS	MS	F	Pr>F
Block	3	29.35	9.78	12.58	0.0001
Time of harvest	2	154.58	77.28	99.32	0.0001
Fruit position	1	0.51	0.51	0.65	0.420
Fruit position*time of harvest	2	31.31	15.65	20.12	0.0001
Spray treatment	6	2.47	0.41	0.53	0.787
Error	1330	1037	0.77		
CV = 5.15%.					

This was in contrast with standard impact bruise depth which increased only between the mid and late harvest. A relationship between greater fruit mass and increased susceptibility to bruising was established earlier (Section 5.2) However, as fruit mass did not vary between harvests, in the current experiment the increase in susceptibility to bruising associated with time of harvest effect cannot be attributed to an effect of fruit size.

Despite the association between firmness and susceptibility to bruising observed in the between-orchard survey (Section 5.2), this orchard study indicated that although firmness did not change between the early and mid harvest, susceptibility to bruising increased most over this period. Starch index and soluble solids increased, and crush strength decreased, as harvests progressed through the season.

Table 5.17 Time of harvest effects on 'Granny Smith' fruit attributes.

Attribute	Time of harvest		
	early season	mid season	late season
Bruise diameter (mm)	16.70 a	17.20 b	17.53 c
Bruise depth (mm)	7.10 a	7.12 a	7.26 b
Mass (kg)	0.162 a	0.163 a	0.163 a
Firmness (N)	86.5 a	85.5 a	83.2 b
Starch index	1.6 a	3.8 b	5.6 c
Soluble solids (° Brix)	8.7 a	10.9 b	11.3 c
Crush strength (kPa)	58.7 a	59.8 a	55.8 b
Bruise lightness	74.15 A	74.29 A	74.14 A
Bruise chroma	4.49 A	4.39 A	4.94 B
Bruise hue angle	73.39 A	71.83 B	76.77 C

Values within rows followed by different letters (a and A) are significantly different at 0.0001 and 0.05 respectively.

Lightness of bruised tissue of 'Granny Smith' apples did not change with increasing maturity. However, bruise chroma and hue angle were highest at the last harvest (Table 5.17). The magnitude of the differences in the bruise hue was slightly less than that required for a distinct visual difference (Section 4.2.3.2) but it does indicate that apple tissue bruised early in the season was slightly browner than tissue bruised later in the season.

'Royal Gala'

All data were pooled and analysed for main effects and interactions (Table 5.18). There was a significant time of harvest effect which contributed to the significance of the fruit position*time of harvest effect. There was considerable variation between blocks in standard impact bruise diameter even though soil type and tree vigour were reasonably constant.

Table 5.18 Analysis of variance for standard impact bruise diameter for all main effects and interactions used in the 'Royal Gala' trial.

Source	DF	SS	MS	F	Pr>F
Block	3	34.15	11.37	8.64	0.0001
Time of harvest	2	1992	960	729.4	0.0001
Fruit position	1	2.60	2.60	1.98	0.16
Fruit position*time of harvest	2	10.65	5.32	4.05	0.02
Spray treatment	6	5.04	0.84	0.64	0.679
Error	1140	1500.5	1.31		
CV = 7.11%					

As harvests progressed through the season, susceptibility to bruising increased by 21% as measured by both standard impact bruise diameter and depth (Table 5.19). Even though time intervals between the three harvests were similar, susceptibility to bruising increased more in the later period (10.5%) than early in the season (2.5%). This is in contrast with standard impact bruise depth which increased more (11%) between the early and mid-harvest than the mid and late harvest (8.7%). In contrast, bruise diameter for 'Granny Smith' increased slightly more between the early and mid-season harvest (3%) than in the later period (2%). These data indicate that there would be advantages in harvesting 'Royal Gala' at early or mid-season. Both cultivars showed reasonable consistency of mass across harvests which supports the proposition that the observed increase in susceptibility to bruising with advanced harvest date cannot be attributed to a fruit size effect.

Of the skin colour components, skin hue angle showed the greatest change. This occurred between the mid and late season harvests and indicated that later harvested apples had significantly redder skin than those harvested earlier.

Mid-season harvested fruit developed bruises with the highest lightness values (Table 5.19). Bruise chroma decreased as the season progressed, indicating that the intensity of discolouration declined throughout the harvest period. The brownness of bruised tissue decreased at mid harvest and then increased at the last harvest indicating that mid-season harvested fruit developed bruise tissue that was less brown in colour than bruised tissue on fruit from the other two harvests.

The greatest reduction in firmness was between the mid and late harvest, which coincided with the largest increase in standard impact bruise diameter. This was consistent with the association between firmness and susceptibility to bruising observed in the between-orchard survey. Starch index and soluble solids increased, and crush strength decreased as harvests progressed through the season consistent with increased maturity and enhanced susceptibility to bruising.

Comparisons between the two cultivars indicate that there were considerable differences in susceptibility to bruising between 'Granny Smith' and 'Royal Gala' as measured by standard impact bruise diameter. 'Royal Gala' was considerably less susceptible to bruising than 'Granny Smith' at the early harvest, but both cultivars were similarly susceptible by final harvest. Klein (1987) pooled two years of 'Granny Smith and 'Royal Gala' data and showed that over a one month harvest period the ratio of bruise mass to apple mass increased by 11.4%.

Table 5.19 Time of harvest effects on 'Royal Gala' fruit attributes.

Attribute	Time of harvest		
	early season	mid season	late season
Bruise diameter (mm)	14.66 a	16.03 b	17.74 c
Bruise depth (mm)	5.92 a	6.60 b	7.18 c
Mass (kg)	0.124 a	0.126 b	0.128 b
Firmness (N)	109.8 a	106.6 a	99.70 b
Starch index	1.70 a	3.18 b	5.4 c
Soluble solids (°Brix)	-	9.42 a	9.71 b
Crush strength (kPa)	43.17 a	36.00 b	53.7*
Bruise lightness	73.35 A	75.20 B	73.52 A
Bruise chroma	7.05 A	5.93 B	4.91 C
Bruise hue angle	75.88 A	92.73 B	67.21 A
Skin lightness	70.20 A	71.73 B	70.8 A
Skin chroma	8.35 A	7.73 B	8.34 A
Skin hue angle	30.47 B	34.61 A	15.77 C

Values within rows followed by different letters (a and A) are significantly different at 0.001 and 0.05 respectively. Crush strength value denoted * should not be compared because of different experimental procedure (Section 5.3.1).

Pooled data from this study revealed an increase in standard impact bruise diameter of 13% due to maturation over a similar period. Other researchers (Hyde and Ingle, 1968; Klein, 1987; Johnson and Dover, 1990; Kampp and

Nissen, 1990) have also found an increase in susceptibility to bruising with increased maturity. In direct contrast to these studies, Diener *et al.* (1982), who accounted for increasing apple mass by using specific bruise volume (ratio of bruise volume to apple volume) found no increase in susceptibility to bruising by delaying harvests. Hyde and Ingle (1968) found that over two years, each of six cultivars harvested over 10 days showed an average increase in bruise diameter of 3.35%. They also found that with three harvests the timing of the maximum increase in susceptibility to bruising was not consistent. In the first year of the study the greatest increase in susceptibility to bruising was between the first and second harvest, and in the next year it was between the second and third harvest.

The reasons for this may be explained by differences in cell number and volume of maturing 'McIntosh' apples (Blanpied and Wilde, 1968). These researchers found, that prior to commercial harvest, a ratio of cell dimensions (circumference^2/area) described cell shape as hexagons and at late harvest this ratio indicated cells were shaped like pentagons. It may be that the variable rate of change of cell shape influences susceptibility to bruising and may explain the variable change in standard impact bruise diameter between 'Royal Gala' harvests.

Differential susceptibility to bruising between the two cultivars should include recognition of the differences in apple mass and shape; 'Granny Smith' and 'Royal Gala' weighed 0.163 and 0.126 kg respectively but 'Granny Smith' were longer than the shorter, squat 'Royal Gala'. For these reasons diameters of both cultivars were similar and therefore had similar contact area at the point of impact (Method 2; Section 3.2.2). Standard impact bruise diameter differed by 2 mm at the early harvest and were reasonably similar for both cultivars by the late season harvest despite 'Royal Gala' being 30% less mass.

Firmness reduced 2 and 7 N between the mid and last harvest for 'Granny Smith' and 'Royal Gala' respectively, similar to the observations of Marmo *et al.* (1985) who found that firmness reduced 7 N during the last seven days of harvest.

However, Hyde and Ingle (1986) found no difference in pulp firmness when harvests were made only 5 days apart. With the fruit numbers employed in this study at least a 20-day interval would be required to produce a statistically significant between-harvest difference in firmness. In each cultivar the greatest reduction in firmness occurred between the second and third harvests, coinciding with the greatest increase in standard impact bruise diameter of 'Royal Gala' but not 'Granny Smith'. Firmness and crush strength data suggest substantial tissue strength differences between 'Granny Smith' and 'Royal Gala', but because a smaller Effigi penetrometer probe and larger crush strength blade were used for 'Royal Gala', these values cannot be directly compared. There were no major differences in starch index between cultivars but the late harvest 'Granny Smith' had higher soluble solids content than 'Royal Gala' although starch index was similar.

Bruise lightness was similar for both cultivars, but 'Granny Smith' had considerably lower bruise chroma indicating a lower degree of colour saturation. Bruise hue angle was similar for both cultivars at early harvest but reduced for 'Granny Smith' and increased for 'Royal Gala' at mid season harvest, indicating that bruised tissue from the latter was considerably less brown. The reasons for the rapid decline in bruise hue angle, and therefore increase in brown colour for 'Royal Gala' at the late harvest are difficult to explain, but may be related to the deepening of the red skin colour. Red skinned cultivars have higher anthocyanin content than lighter skinned cultivars and it is known that these compounds contribute to enzymatic browning (Mazza and Miniati, 1993). At the last harvest, skin hue angle indicated a very deep red skin which corresponded to a substantial increase in brownness of bruised tissue. It is not known why bruise lightness decreased at mid-harvest; the magnitude of this inconsistency indicates a calibration problem (Section 3.4).

It could be reasonably argued that because harvesting procedures utilised commercial practices of selecting fruit that were ready for harvest, later harvested fruit may have developed on late blooms, thereby reducing the potential maturity difference between early and late harvested fruit. None-the-less, these data reflect the commercial implication of bruising following sequential harvests rather than the potential difference in susceptibility to bruising that could have resulted had it been possible to harvest fruit at predetermined maturity intervals.

As harvests progressed for each cultivar, correlations (Table 5.20) showed that fruit mass was not consistently associated with standard impact bruise diameter. However, apart from the missing data for the 'Royal Gala' early harvest firmness was consistently negatively associated with standard impact bruise diameter. Although crush strength measures a different aspect of cell strength, this was also correlated with standard impact bruise diameter. Neither starch index nor soluble solids content was consistently related to standard impact bruise diameter in either cultivar as harvests progressed.

Table 5.20 Correlations and significance of standard impact bruise diameter with other fruit attributes for 'Granny Smith' and 'Royal Gala.'

Cultivar	Fruit mass (kg)	Firmness (N)	Crush strength (kPa)	Starch index	Soluble solids
'Granny Smith'					
early harvest	ns	$-0.32^{0.0001}$	$-0.26^{0.0001}$	$0.12^{0.009}$	$-0.33^{0.0001}$
mid-harvest	$0.32^{0.0001}$	$-0.34^{0.0001}$	$-0.16^{0.0007}$	ns	ns
late harvest	$0.28^{0.0001}$	$-0.24^{0.0001}$	ns	ns	ns
'Royal Gala'					
early harvest	ns	md	$-0.33^{0.001}$	ns	md
mid harvest	$0.22^{0.0001}$	$-0.14^{0.04}$	$-0.15^{0.005}$	ns	ns
late harvest	ns	$-0.14^{0.007}$	$-0.20^{0.0001}$	ns	$-0.13^{0.009}$

Superscript denotes level of significance; md = missing data.

Multiple regression analysis for each cultivar at each harvest produced equations that explained little of the variation associated with standard impact bruise diameter. The 'Granny Smith' early season harvest data produced the strongest regression equation ($R^2 = 0.24$):

$$\begin{gathered}\textit{Standard impact bruise diameter} = 18.78(\pm 0.36) + 5(\pm 0.9)\textit{mass} \\ - 0.008(\pm 0.003)\textit{crush strength} - 0.0227(\pm 0.003)\textit{firmness} + 0.017(\pm 0.015)\textit{starch} \\ - 0.04(\pm 0.016)\textit{soluble solids}\end{gathered}$$

Standardised variates for fruit attributes were: apple mass, 0.18; crush strength, 0.12; firmness, -0.18; starch index, 0.14 and soluble solids -0.53.

Multiple regressions on 'Royal Gala' harvest data did not generate equations that accounted for more than 10% of variation in the data set. It was clear that other factors not measured or not yet measurable are required to explain the variation associated with susceptibility to bruising. Some of these factors may be simple, measurable attributes such as intercellular space, fruit density and mineral contents. Other more complex influences may relate to the energy absorbing capacity of the fruit which could be described by variable cell wall strength, area of cell-cell bonds and their strength, changes in turgor pressure or some factor that describes the energy absorbing characteristics of the whole apple.

In summary, it can be seen that susceptibility to bruising of both cultivars, was directly related to time of harvest: later harvested fruit develop wider and deeper bruises than those harvested earlier in the season (Tables 5.17 and 5.19). When fruit of similar mass were used, firmness was negatively related to bruise size. Despite susceptibility to bruising increasing with enhanced maturity, starch index and soluble solids content explained very little of the variation in the data set. If bruising is to be reduced it is clear that early harvesting of fruit, particularly for 'Royal Gala', would be advantageous. Furthermore, any practical technique that orchardists could use to increase fruit firmness should be employed.

Bruise hue angle, a key component in describing the brownness of bruised tissue, showed sufficient increase with later harvested 'Granny Smith' to suggest that these fruit may develop lighter coloured bruises. However, later harvesting would subject more bruise susceptible fruit to postharvest handling systems. Bruise hue angle for 'Royal Gala' showed that earlier harvested fruit developed bruise tissue that was considerably lighter in colour than late harvested fruit. Therefore, early harvesting of this cultivar might be expected to reduce bruising potential twofold and to reduce brownness of any bruises that were incurred.

5.3.2.3 Within-tree location

'Granny Smith'

Although the standard impact bruise diameter for apples harvested from the upper north and lower south tree position did not differ, the interaction between fruit position and time of harvest was statistically significant (Table 5.16). Apples harvested early from the lower south tree position were more susceptible to bruising as determined by standard impact bruise diameter and depth than those harvested from the upper north tree position (Table 5.21). By mid season fruit bruises on apples from the upper north position were of greater diameter and of less depth than bruises on apples harvested from the lower south tree position. By late season there were no significant differences in standard impact bruise diameter or depth on bruised apples harvested from the two tree positions.

Apples harvested from the upper north tree position were of greater mass than those harvested from the lower south tree position; mass of apples harvested from the two tree positions did not increase uniformly as harvests progressed.

There was no significant difference in firmness of fruit harvested from the two tree positions although there was a trend for lower south fruit to be firmer than upper north fruit (Table 5.21). There were no consistent within-tree differences between firmness and crush strength, probably because both measure different aspects of fruit texture.

Apple maturity as measured by the starch index did not differ according to tree position but upper north apples had higher soluble solids than lower south apples.

Table 5.21 Within-tree variation of 'Granny Smith' fruit attributes.

Attribute		Time of harvest		
		early season	mid season	late season
Bruise diameter (mm)	LS	16.94	17.05	17.42
	UN	16.46 ***	17.17 ***	17.63
Bruise depth (mm)	LS	7.27	7.21	7.28
	UN	6.95 ***	7.02 *	7.23
Mass (kg)	LS	0.150	0.140	0.148
	UN	0.173 ***	0.178 ***	0.177 ***
Firmness (N)	LS	86.43	86.65	84.15
	UN	86.52	84.45	82.24
Crush strength (kPa)	LS	57	61.02	55.61
	UN	60.24 *	58.38	55.90
Starch index	LS	1.69	3.84	5.64
	UN	1.57	3.77	5.53
Soluble solids (° Brix)	LS	8.00	10.53	10.86
	UN	9.41 ***	11.31 ***	11.75 ***
Bruise lightness	LS	73.67	73.81	73.78
	UN	74.61 ***	74.78 ***	74.49 ***
Bruise chroma	LS	4.05	4.16	4.89
	UN	5.11 ***	4.62 **	4.97
Bruise hue angle	LS	69.72	71.64	75.28
	UN	76.98 ***	71.99	78.27 ***

LS = apples from the lower south position of the tree. UN = apples from the upper north position of the tree. Pairs of means within-columns followed by ***, ** or * are significantly different at 0.0001, 0.001 or 0.01.

Bruised tissue of apples harvested from the upper north tree position had higher lightness, chroma and hue angle than those from the lower south position of the tree. The magnitude of the bruise hue angle differences at the early harvest indicated that a visual distinction could be made between the colour of bruised apple tissue from the two tree positions (Section 4.2.3.2) with fruit from the upper north tree position developing lighter brown bruises.

'Royal Gala'

Standard impact bruise diameter for apples harvested from the upper north and lower south tree position did not differ (Table 5.18) but the interaction between fruit position and time of harvest was statistically significant. Apples harvested mid season from the upper north tree position were more susceptible to bruising (as determined by standard impact bruise diameter) than those from the lower south position (Table 5.22). Early in the season, standard impact bruise depth was shallower on fruit harvested from the upper north position. However, by the end of the season there was no significant difference in standard impact bruise diameter and depth of apples harvested from the two tree positions.

Apples harvested from the upper north tree position were heavier than those harvested from the lower south tree position. Apple weight increased in fruit harvested from the lower south tree position as harvests progressed, but this did not occur for apples harvested from the upper north tree position.

There was a significant difference in firmness of fruit harvested from the two tree positions, with upper north fruit being the firmer. Crush strength reduced as season progressed to the extent that by late harvest apple tissue did not provide sufficient resistance for the small twist blade that was used. For this reason a larger twist blade was used for the last harvest and therefore late season values are not directly comparable with the other harvest values.

Apple maturity, as measured by the starch index, did not differ consistently according to tree position but there were significant differences in soluble solid

Table 5.22 Within-tree variation of 'Royal Gala' fruit attributes.

Attribute		Time of harvest		
		early season	mid season	late season
Bruise diameter (mm)	LS	14.70	15.96	17.68
	UN	14.62	16.37*	17.73
Bruise depth (mm)	LS	6.05	6.63	7.10
	UN	5.79 ***	6.70	7.20
Mass (kg)	LS	0.107	0.111	0.119
	UN	0.140***	0.141***	0.136***
Firmness (N)	LS	-	103.59	97.12
	UN	-	108.89***	101.44***
Crush strength (kPa)	LS	42.9	35.94	54.48
	UN	43.36	36.82	53.05
Starch index	LS	-	3.0	5.5
	UN	1.93	3.5 **	5.3
Soluble solids (° Brix)	LS	-	8.91	9.51
	UN	-	9.79**	9.90**
Bruise lightness	LS	73.90	73.90	74.90
	UN	72.80 *	72.80*	75.51*
Bruise chroma	LS	7.25	6.04	4.73
	UN	6.84***	5.83*	5.08**
Bruise hue angle	LS	73.04	89.91	65.16
	UN	78.98***	95.89***	69.51**
Skin lightness	LS	72.12	72.69	71.34
	UN	68.3***	70.75 **	70.41**
Skin chroma	LS	7.63	8.01	8.59
	UN	9.06***	7.44 **	8.10 **
Skin hue angle	LS	39.85	40.09	18.73
	UN	21.1***	29.1***	12.80 ***

LS = apples from the lower south position of the tree. UN = apples from the upper north position of the tree. Pairs of means within-columns followed by ***, ** or * are significantly different at 0.0001, 0.001 or 0.01. Crush strength values should not be compared between harvests; see text.

content, with upper north apples recording the higher values.
There were inconsistent trends in bruise lightness, chroma and hue angle between the two tree positions. Bruise hue angle values indicated that bruised tissue of apples harvested from the upper north tree position were less brown than bruised tissue from the lower south position of the tree. The magnitude of these differences indicate that a visual distinction (Section 4.2.3.2) could be made between the colour of bruised apple tissue from the two tree sectors at all harvests.

As expected, 'Royal Gala' apples harvested from the upper north tree position were much redder (lower skin hue angle) than those from the lower south. The higher levels of anthocyanins which are precursors for enzymatic browning, that would be present in the redder skin of these fruit may in part account for the substantial decrease in bruise hue angle in late harvested fruit. As noted earlier (Section 3.4) it seems likely that the large differences between mid season and the earlier and later harvests may be related to calibration; trends with time therefore need to be examined with due caution.

Differences in susceptibility to bruising of fruit and development of bruise colour from the two tree positions may be a result of the considerable differences in micro-climate. Differences in light reception and diurnal temperature fluctuations of fruit in the two tree positions are considerable; Campbell and Marini (1992) found that 40% of the within-tree variation of fruit characteristics could be accounted for by cumulative seasonal light measurements. In a pruning and fruit quality experiment in Hawkes Bay, Morgan *et al.* (1984) found that upper north fruit received a photosynthetic photon flux (PPF, % of open sky measurement; μmol/s/m^2) of 49.3 whilst lower south fruit received a PPF of only 6.3. This nearly eightfold increase in PPF reception by the upper north tree position produced fruit that had 14% more blush, were 24 g heavier and were 1.5% higher in soluble solids than fruit from the lower tree position. A similar association between tree position and PPF was documented by Tustin *et al.* (1988). On average, upper tier fruit received 32% PPF whilst basel tier fruit received a PPF of 16.2%. Had north and south orientation also been studied by Tustin's group, then similar differences to that noted by Morgan would probably have resulted. Variable incident light reception by apples from different tree positions may also influence their susceptibility to bruising.

Klepper (1968) found that leaf water potential on the eastern tree side was lowest in the morning with the west side being lower in afternoon, the difference being as much as 7 to 8 bars around a tree. If fruit showed similar variation, then consequential changes in fruit turgor may be reflected in susceptibility to bruising.

Links between extent of shading, apple characteristics and storage quality have been investigated (Jackson *et al.* 1971; Jackson *et al.* 1977). Shading reduced incidence of bitter pit and increased incidence of core flush. Shade also reduced fruit size through reductions in cell size and number of cells/fruit. These fruit also had less dry matter and less starch per unit fresh mass. The implications of these data for variation in susceptibility to bruising are particularly important. Early season harvests of 'Granny Smith' and 'Royal Gala' from the lower south tree position were more susceptible to bruising than those fruit harvested from the upper north tree position. 'Granny Smith' fruit from the two positions were of similar firmness and starch index which does not assist in explaining the differences in susceptibility. On the other hand shaded fruit would be expected to have lower dry matter which would reduce the fruit's ability to absorb energy without rupture.

The reasons for the mid-season change in upper north fruit of both cultivars to become more susceptible to bruising (as reflected in both standard impact bruise diameter and depth) than the lower south fruit may relate to differential rates of maturation. The firmness of upper north 'Granny Smith' fruit declined more rapidly as harvests progressed than the firmness of lower south fruit. Thus, the advanced maturity of the upper north fruit may have over-ridden any dry matter or cell size characteristics that caused the early harvested lower south fruit to be most susceptible to bruising.

Differences in fruit mass between the two tree positions could have indirectly influenced susceptibility to bruising: Westwood *et al.* (1967) found that as fruit mass increased from 0.130 to 0.214 kg, intercellular airspace increased from 21% to 24%. The differences in fruit mass in this study were not as large as those used by Westwood's group; but increasing proportions of intercellular spaces are associated with increasing mass would be expected to enhance susceptibility to bruising.

Generally, shaded fruit are less firm than exposed fruit (Seeley *et al.* 1980; Ferree 1989) and this was the case with 'Royal Gala'. There were no significant positional differences with 'Granny Smith' firmness although there was a trend for lower south fruit to be firmer. The increase in firmness of exposed apples probably relates to the increases in dry matter and cell number. It has been shown that in leaves grown under high light intensities, a greater proportion of calcium pectate forms than in those grown under low light intensities (Cassells and Barlass, 1976). If this also incurred in fruit, cell wall strength would presumably increase and may explain the increased firmness of exposed fruit.

Susceptibility to bruising of fruit from the two tree positions is an expression of many attributes and variables (Table 5.23). The integration of these influences at a particular maturity determines susceptibility to bruising.

An indication of the effect of measured fruit attributes on susceptibility was given by multiple regression. Between the positional effects of the two cultivars the strongest multiple regression ($R^2 = 0.30$) of the variation in the data set was with 'Granny Smith' harvested from the lower south tree position. This regression related fruit mass, firmness and starch to standard impact bruise diameter. Regressions on 'Royal Gala' did not consistently relate any fruit attributes to standard impact bruise diameter.

Table 5.23 Fruit attributes and factors influencing susceptibility to bruising of fruit harvested from the upper north and lower south tree position. (- = reducing effect and + = increasing effect on susceptibility to bruising)

Lower south fruit		Upper north fruit	
Factor influencing susceptibility to bruising	Bruising effect	Factor influencing susceptibility to bruising	Bruising effect
Less mass	_	Greater mass	+
Less firm	+	Firmer	_
Lower starch index	_	Higher starch index	+
Less soluble solids	_	Higher soluble solids	+
Less dry matter	+	More dry matter	_
Less cells	+	More cells	-
Smaller cells	_	Larger cells	+

It seems likely that other attributes not measured in this work, such as intercellular space, skin strength, cell wall strength and cell-cell bond strength probably play important roles in determining susceptiblity to bruising.

5.3.2.4 Mineral content

Analysis of variance did not identify any significant differences in susceptibility to bruising that related to the mineral spray treatments applied to either ‘Granny Smith’ (Table 5.16) or ‘Royal Gala’ (Table 5.18). Little can be inferred as to the effect foliar sprays have on susceptibility to bruising in either of the cultivars because there were no significant differences between the calcium or phosphorus contents of apples in relation to the spray regimes used (Tables 5.24 and 5.25) The nitrogen, potassium and magnesium tissue content were not influenced by the spray treatments.

Table 5.24 The calcium and phosphorus content of 'Granny Smith' apples subjected to foliar sprays (Section 5.3.1).

Timing of spray applications	'Granny Smith' Calcium foliar spray	 Phosphorus foliar spray
	Calcium (μg/g FW)	Phosphorus (μg/g FW)
No spray (control)	67.11	53.68
Early season sprays	72.37	50.36
Late season sprays	66.31	51.62
Early and late sprays	82.36	46.62
SED	8.08	11.5

Table 5.25 The calcium and phosphorus content of 'Royal Gala' apples subjected to foliar sprays (Section 5.3.1).

Timing of spray application	'Royal Gala' Calcium foliar spray	 Phosphorus foliar spray
	Calcium (μg/g FW)	Phosphorus (μg/g FW)
No sprays (control)	31.48	89.51
Early season sprays	37.15	89.15
Late season sprays	37.42	93.05
Early and late season sprays	37.92	95.16
SED	8.2	7.2

Statistical analysis determined that each of the minerals had particulary high coefficients of variation and therefore analysis of variance was unable to detect differences between treatment means. The reasons that calcium and phosphorus sprays did not enhance fruit mineral content are difficult to explain given that other researchers applying similar sprays have enhanced fruit content of these two minerals. More recent analyses of fruit from the trees used in this study have indicated that it has been similarly difficult to increase calcium levels by using $CaCl_2$ foliar sprays, the reasons for which are unknown (Max, pers comm. 1996).

5.3.2.5 Irrigation

'Braeburn' apples from non-irrigated trees had standard impact bruise diameters and depth that were 6% less than bruises on fruit from irrigated trees (Table 5.26). These observations confirm those of Durand (1990) who found that susceptibility to bruising of NZ grown 'Royal Gala' apples was reduced if trees were subjected to water stress. Because the mass of fruit from both treatments was similar it is possible to conclude that the difference in standard impact bruise diameters was attributable to the treatments and not due to the relationship of greater fruit mass with enhanced susceptibility to bruising (Sections 5.2.2 and 5.3.2.3). The expectation that more mature fruit with higher soluble solids content would be more susceptible to bruising than less mature fruit was not substantiated here. Non-irrigated fruit had higher soluble solids than irrigated fruit but they also tended to have higher dry matter content, crush strength and less calcium which would be expected to offset increased levels of bruise susceptibility with high turgor. The higher soluble solids content of the non-irrigated fruit suggests that either these fruit were of advanced maturity or that the stress induced a reaction to maintain turgor or a combination of both these mechanisms had occurred. Apple fruit maturing under water deficits have been shown to have higher soluble solids and increased ethylene and be more mature (Ebel *et al.* 1993) and have higher dry matter (Drake *et al.* 1981). Higher soluble solids would be expected to reduce tissue resilience but this effect may have been compensated for by other components of the higher dry matter content. Higher dry matter levels would presumably increase the amount of tissue that would be present to absorb impact energy and may explain the enhanced crush strength of non-irrigated fruit. Lower tissue calcium levels were associated with improved resistance to impact damage presumably by reducing the strength of cell-cell bonds. The bruise resistant fruit in this study had 40% less calcium content than those fruit from irrigated trees (Table 5.26).

Table 5.26 Effect of water stress on 'Braeburn' attributes.

Attribute	Irrigated	Non-irrigated
Bruise diameter (mm)	16.54 a	15.54 b
Bruise depth (mm)	7.60 a	7.20 b
Mass (kg)	0.257	0.248
Dry matter (mg/g FW)	148	155
Firmness (N)	50.22	50.55
Soluble solids (^{0}Brix)	11.8 b	12.5 a
Crush strength (kPa)	1021 b	1095 a
Nitrogen (mg/g FW)	2.2	1.93
Phosphorus (mg/g FW)	0.658	0.619
Potassium (mg/g FW)	9.63	8.69
Calcium (mg/g FW)	0.324 a	0.196 b
Magnesium (mg/g FW)	0.349	0.289

Values within rows followed by different letters are significantly different at 0.05.

Of NZ apple cultivars grown for export 'Braeburn' is considered to be relatively bruise resistant and to achieve a reduction in susceptibility to bruising is particularly significant. Reduced irrigation of other more susceptible cultivars would presumably be well worth investigating.

Crush strength was significantly higher for fruit from non-irrigated trees, indicating a higher level of resistance to shear than fruit from irrigated trees. Durand (1990) found that fruit that had developed on trees subjected to water stress were firmer than fruit from irrigated trees. Garcia *et al.* (1995) found that nil irrigation of 'Golden Delicious' apples 2 weeks before harvest did not reduce bruise susceptibility. Shorter periods of reduced irrigation closer to harvest may not result in structural changes to apple tissue although under dry conditions it would be reasonable to expect turgor to reduce and therefore susceptibility to bruising also to decrease.

There was a trend for non-irrigated fruit to have less nitrogen, phosphorus, potassium and magnesium. Similarly, Guelfat'Reich *et al.* (1974) found a general decrease in fruit mineral contents when trees were subjected to water stress though this contrasts with the later work of Irving and Drost (1987) who recorded no difference in mineral contents. In this study, fruit from the non-irrigated trees had less calcium and were less susceptible to bruising than those from irrigated trees.

Another explanation for the reduced susceptibility of non-irrigated apples may be derived from the work of Davies and Lakso (1979). As water is lost from plants by transpiration and not replaced, many plants are unable to maintain turgor. This reduction in turgor results in stomatal closure and eventually growth ceases. Apple trees however, have a good ability to withstand drought stress (Powell, 1976) through a combination of osmotic adjustment, dehydration and the influence of stored water. Davies and Lakso (1979) suggested that cell elasticity may act to reduce cell volume and thereby maintain cell turgor. Drought induced increases in elasticity have been observed in beans (Elston *et al.* 1976) although water stress decreased elasticity in sorghum (Jones and Turner, 1978). If apple fruit cells react to stress in a similar manner to that proposed for apple leaves, water stress could induce them to increase their cell wall elasticity. Such apples would be ideally prepared to resist impact damage. Their cells may be of reduced size and have flexible intercellular connections (to facilitate non-damaging movement), increasing the potential for movement without damage and therefore increasing their capacity for absorbing energy when impacted.

Reduced irrigation of 'Braeburn' trees produced apples that were less susceptible to bruising and also had higher soluble solids. Both of these attributes are desirable; it would seem that further investigation of reduced irrigation on other commonly grown cultivars may identify a simple management technique to enhance the quality of NZ grown apples.

5.4 Conclusions

The 'Granny Smith' surveys identified that within-season variability between orchards (1990, 11.7%; 1991, 5.5%) in susceptibility to bruising exceeded between-season variability (2.8%) indicating that potential exists to manipulate factors that influence susceptibility to bruising. By relating standard impact bruise diameter to the damage that apples incurred during grading it was found small changes in diameter related to large changes in grader damage.

In both years of the survey the most bruise susceptible fruit were of greater mass, had more nitrogen, phosphorus, calcium and phosphorus than the least susceptible fruit. However, only in 1990 did regression analyses relate fruit mass and calcium content to standard impact bruise diameter and fruit phosphorus to grader damage. There was considerable between-orchard variation in bruise colour indicating potential to reduce the colour of bruised tissue. In 1991 bruises of lighter colour were positively associated with fruit nitrogen content.

A closer within-orchard study identified less between-tree variation in susceptibility to bruising in 'Granny Smith' (4%) than in 'Royal Gala' (11%).

There appears to be more opportunity to manipulate bruise colour of 'Royal Gala' than 'Granny Smith' apples. It was evident that harvesting early rather than later in the commercial harvest season reduced bruise damage in both cultivars ('Granny Smith', 5%; 'Royal Gala', 21%). The within-tree location of fruit from either cultivar did not consistently influence susceptibility to bruise damage. Regression analysis related (in order of importance) soluble solids, apple mass and fruit firmness, starch and crush strength to bruise severity in 'Granny Smith' ($R^2 = 0.24$). Similar associations between fruit attributes and bruise severity in 'Royal Gala' were not evident.

Apples from non-irrigated 'Braeburn' tress were 6% less susceptible to bruising than fruit from irrigated trees. The less susceptible fruit also had less calcium but tended to have more dry matter.

If the causes for the between-orchard variation in susceptibility to bruising could be identified more closely there may be considerable potential to manipulate susceptibility to bruising. Harvesting fruit early and reduced irrigation without reducing fruit mass are management strategies that orchardists could implement to reduce bruise damage.

CHAPTER SIX

HARVEST AND POSTHARVEST SOURCES OF VARIATION IN SUSCEPTIBILITY TO BRUISING

6.1 Introduction

Studies of the sources of variability of susceptiblity to bruising of apples were used to identify potential to reduce bruising by manipulation of preharvest factors (Chapter 5). In this chapter further opportunities to reduce bruise damage at harvest or early in the postharvest handling system are explored.

Generally, the NZ fresh fruit export schedule requires freshly harvested fruit to be graded and packed for immediate trans-shipment to overseas markets. Currently, there is an increasing trend for some fruit to be graded, CA-stored then subsequently packed for export. Any strategy to reduce bruise susceptibility must comply with the ENZA requirement that fruit must be coolstored within 72 h of harvest or after relatively short pre-coolstorage periods. Efforts to reduce susceptiblity to bruising at either harvest or soon after are investigated in this chapter.

Whilst still on the tree, fruit go through a diurnal cycle in both water status and temperature (Jones *et al.* 1985) which may influence susceptibility to bruising in two ways. During warm days prior to harvest, transpirational water losses from apple tree leaves can exceed xylem inflows and it is has been proposed that the tree draws water from the fruit, thereby reducing leaf water deficits and the risk of stomatal closure. Higgs and Jones (1985) documented that fruit diameter can reduce by 0.8 mm diameter from mid morning to late afternoon. Lang (pers comm. 1993) found that fruit can lose as much as 1% of their early-morning weight by mid-afternoon and suggested that this weight loss would be likely to cause reductions in turgor. Mills *et al.* (1996) found that water deficits early in fruit growth caused reductions in osmotic potential and therefore turgor potential was maintained. Late season water deficits did not induce the same fruit osmotic adjustments and therefore it is probable that at harvest, mid-afternoon reductions in weight reduce turgor and, as a consequence, also reduce tissue sensitivity to bruise damage.

A second influence of diurnal effects on susceptibility to bruising may be associated with fruit temperature. Prior to harvest fruit can be subjected to considerable fluctuations in temperature with autumn night time temperatures close to freezing and highs of 24°C by early afternoon. Oleocellosis or rind oil damage (oil gland rupture) in citrus fruit has been shown to be a problem when fruit are harvested during cold wet conditions when oil glands are more easily ruptured as a result of finger and impact pressure (Salem and Eissawy, 1978). Apples that have been stored for several days are less sensitive to bruise damage at warmer temperatures (Sekse and Opedal, 1993) and it may be that the temperature at which fruit are harvested may influence their susceptibility to bruise damage. Orchardists have often noted that apples are most susceptible to bruising if harvested early in the morning which could be explained by low fruit temperature and/or higher water content of fruit at that time. It would seem feasible that fruit harvested later in the day would be less prone to damage because of reduced turgor, elevated temperatures or a combination of both of these effects.

Growth stresses in fruit may persist if the fruit are stored in high humidity after harvest; they may even continue to swell (Wilkinson, 1965) which is probably a result of cells rounding-off as their walls soften. In contrast, if fruit are stored at low humidity, rapid water loss causes relaxation of internal stresses, increased production of ethylene and enhanced ripening (Hatfield and Knee, 1988); weight losses greater than about 6% can detrimentally influence the fruit's appearance. On the other-hand, some degree of water loss can have beneficial effects on fruit quality. It has been suggested by Hatfield and Knee (1988) that water loss after harvest may increase the cohesion of cells as ripening continues. They used this approach to explain the increased retention of firmness following weight loss observed in their experiments. Another advantage of weight loss may be derived from increase in soluble pectin associated which presumably originates from cell wall degradation; these increases in soluble pectin may improve the shock absorbing capacity of apple tissue. Highly turgid fruit have been reported to be more susceptible to impact damage than those at lower turgor (Johnson and Dover, 1990; Garcia *et al.* 1995). Bruise damage might therefore be reduced by allowing or even stimulating weight loss before handling, as suggested for 'Bramley's Seedling' apples by Johnson and Dover (1990). However, Samim and Banks (1993b) provided no evidence that 'Granny Smith' apples became less susceptible to bruising as they lost water with increasing time after harvest. Weight loss should be optimised so that bruise damage can be reduced but long term storage potential or other essential quality attributes are not compromised. Control of weight loss after harvest, but before grading and packing within ENZA's guidelines could potentially become an important tool packhouse operators might use to reduce susceptibility to bruising.

If the temperature at which fruit are harvested is important it is also likely that fruit temperature at which fruit are graded could influence tissue sensitivity to bruise damage. The primary (reversible) stage of chilling injury in horticultural crops involve phase transitions in the double layers of the cell membranes and cell organelles, increased membrane permeability and a decrease in protoplasmic streaming (Lyons, 1973). It is likely that these changes begin to occur at apple coolstorage temperatures (Watada, pers comm. 1993) and may affect the potential of membranes to absorb impact energy without damage. At lower temperatures pectin fractions in the cell wall may begin to gel (Werner and Frenkel, 1978) perhaps reducing the capacity to flex under external loading and making fracture more likely. Jeffery and Banks (1994) found that the firmness of mature kiwifruit fruit decreased following warming providing evidence for a direct, physical effect of temperature on fruit firmness raising the possibility that bruise susceptibility could also be affected by temperature. Many researchers have documented various effects of temperature on the bruise susceptibility of apples (Section 2.5.3.5); some inconsistencies in these findings can be explained by the techniques used or the extended periods for which some of the fruit were in storage before use.

Hyde and Ingle (1968) found that storage time influenced bruise diameter and depth after apples had been stored about 11 weeks. Schoorl and Holt (1977) found that with two cultivars, bruise volume increased with increasing storage time and another cultivar produced variable results. Lau (1983) reported that if CA-storage conditions were imposed in four days, bruise susceptibility of 'Golden Delicious' apples decreased when compared to apples that took 21 days to establish CA-storage conditions. Olsen and Bartram (1978) found that CA-storage for 6 months reduced grading damage but after periods longer than this the possibility of bruising increased. Zhang *et al.* (1992) found that apples stored in lower humidity (50%) were less bruise susceptible than those stored at higher humidities (100%) but fruit from the low humidity were shrivelled. Johnson and Dover (1990) found that it took 20 days at low humidity to produce a significant reduction in bruise volume which equated to a 2% weight loss. Garcia *et al.* (1995) found that bruise susceptibility reduced after time in storage and that storage humidity 16 h prior to testing can also influence bruise susceptibility. Samim and Banks (1993b) found no evidence that bruise susceptibility of freshly harvested apples reduced after periods in store. Despite the somewhat variable effects of water loss on bruise susceptibility in previous work, there seems likely to be an opportunity for weight losses to be manipulated to balance or override the effects of enhanced ripening on susceptibility to bruising.

Mature 'Splendour' apples are sought after by consumers for their crispness and juiciness but are amongst the most bruise sensitive apples that have been grown in NZ. At harvest maturity they still have a considerable area of lightish green background colour and the very dark colour of bruised tissue in this cultivar makes bruises particularly obvious. For these two reasons, 'Splendour' apples are no longer regarded as suitable for export. Any improvements to handling procedures to reduce damage to this cultivar could be of benefit to the NZ apple industry. These same features make 'Splendour' an ideal cultivar for susceptibility to bruising studies.

At packhouses apples are often precooled prior to grading and packing. ENZA stipulates that, depending on cultivar, apples must be coolstored within either 48 or 72 h of harvest. Through effects on both weight loss and ripening the period that fruit are left before pre-cooling may have a significant effect on their subsequent susceptiblity to bruising at grading. Sensitivity of apple tissue to impact damage would be expected to reduce with weight loss but increase with enhanced ripeness. These effects do not appear to have been investigated.

Bruise colour intensity has been reported to be less in fruit which are bruised at lower temperatures (Ingle and Hyde, 1968); in contrast, Prange (1994) found that at 20°C visible bruise damage was less than damage incurred at 0°C. Samim and Banks (1993a) reported that reduced water status of 'Granny Smith' apples and time in storage (up to 200 h) did not influence bruise colour. Some of the considerable differences may relate cultivar variation in levels of precursors and enzyme activity associated with the development of bruise colour. Given the importance of bruise colour to both detection and perception of bruises it would seem that further investigations in this field would be worthwhile.

Overall, it appears that at or after harvest it may be possible to manipulate water loss, ripening and fruit temperature to reduce susceptibility of apples to bruising before grading and packing. Various combinations and durations of temperature and storage time could have differing effects on susceptibility to bruising. The work in this chapter describes a series of investigations to determine the potential to reduce susceptibility to bruising of several important NZ cultivars by the manipulation of time of harvest, time in storage time, temperature and weight loss soon after harvest.

6.2 Materials and methods

6.2.1 Time of harvest during day

One hundred and twenty mature ‘Golden Delicious’ apples were harvested from a block of ten trees at FCU orchard at each of three harvest times: 0600, 1100 and 1600 h. The average temperature of a sample of ten exposed fruit was 6, 19 and 22°C at those times. Six groups of 20 fruit were randomly selected from each harvest and weighed. Twenty fruit had a standard impact (Method 2; Section 3.2.2) applied immediately after harvest in the field. The other 5 groups of fruit were equilibrated to either 0, 2, 6, 12 or 20°C for 2 h and the standard impact was applied to fruit at each temperature. Bruise dimensions were measured (Section 3.3). The experimental design was randomised with internal replicates without blocks and it had factorial combinations of harvest and temperature at the time of bruising.

6.2.2 Temperature

Seven hundred and twenty mature ‘Granny Smith’ apples were harvested from the FCU and randomly allocated to four temperature treatments, each with three replications. Fruit were left for 24 h at 0, 10, 20 or 30°C, before a standard impact (Method 2; Section 3.2.2) was applied. Fruit from each temperature treatment were then subjected to grading in a standard manner (Method 3; Section 3.2.3) and bruising levels assessed (Section 3.3), bruise dimensions were measured (Section 3.3) recorded and fruit firmness (Section 3.5) was assessed after each treatment. The experimental design was randomised, but without blocks.

6.2.3 Storage time after harvest

Eleven hundred ‘Royal Gala’ apples were harvested at the FCU orchard and were randomly allocated to 4 groups for each of four time treatments (0, 1, 3, and 9 days). Apples were stored loose in cartons in a laboratory at ambient temperature (14 to 18°C) prior to the susceptibility to bruising being assessed after each storage time (Method 3; Section 3.2.3). Bruise dimensions were measured (Section 3.3) and data were analysed according to the randomised, internally replicated experimental design. Grader bruise area and number of grader bruises were back-transformed for presentation (Section 3.11.2).

6.2.4 Temperature and weight loss

One hundred and twenty mature 'Royal Gala' apples were harvested from the FCU orchard, weighed and randomly allocated to 4 treatment groups, each of thirty fruit. A standard impact was applied (Method 1; Section 3.2.1) and grader damage (Method 3; Section 3.2.3) was assessed (Section 3.3) for each of the temperature treatments. Bruising treatments were applied to fruit in treatment 1 immediately after harvest (fruit temperature = 20°C). Fruit in treatments 2, 3 and 4 were transferred to a coolstore at 3°C. After 24 h, fruit in treatment 2 were subjected to the bruising treatments at 3°C. Fruit in treatments 3 and 4 were rewarmed to 20°C for 24 h and fruit in treatment 3 were bruised. Fruit in treatment 4 were recooled to 3°C for 24 h and then bruised. In each of the four treatments all fruit were placed on export trays; half of the fruit in each treatment (15 fruit) were enclosed in perforated plastic bags to allow gas exchange but maintain high humidity of the air surrounding the apples and thereby maintain fruit water status. After each treatment; all fruit were reweighed and a limited number of apples were cut longitudinally to the core and the resultant gap measured 30 minutes later with micro-callipers (Section 3.9). Bruise dimensions and areas (Section 3.3) and bruise colour (Section 3.4) were measured on the exposed bruised tissue of longitudinally bisected bruises (Section 3.4). The experiment had a randomised design with internal replicates but without blocks. Grader bruise area and number of grader bruises were back-transformed for presentation (Section 3.11.2).

6.2.5 Storage time and temperature

Mature 'Splendour' apples were harvested from the FCU orchard, weighed and groups of 20 fruit were randomly selected and allocated to five time treatments (12, 20, 54, 114, or 414 h) at three storage temperatures (0, 10 and 20°C). At each time and storage temperature combination, 20 fruit had a standard impact (Method 1; Section 3.2.1) applied. The fruit were then reweighed and after 24 h at ambient temperatures, bruise dimensions (Section 3.3) and bruise colour were assessed (Section 3.4). The experimental design was randomised, with internal replicates but without blocks with factorial combinations of time and temperature.

6.2.6 Delay in pre-cooling

Three hundred and twenty mature 'Royal Gala' apples were harvested from trees at the FCU orchard and weighed. These fruit were sorted into similar pairs based on weight and colour and then the pairs of fruit were randomly allocated to 8 groups of ten fruit each in each of four replicates. Each group was placed on an export tray, 5 of which were enclosed in a perforated plastic bag to allow gas exchange with the outside air but still maintain high humidity of the air surrounding the apples. Pairs of trays (with and without bags) were then randomly allocated to 5 delay treatments (0, 24, 48 and 72 h at 20°C) before pre-cooling to 3°C.

At 96 h, (72 h plus 24 h cooling to 3°C) all fruit were reweighed at 3°C. A standard impact (Method 1; Section 3.2.1) was applied and firmness, starch index, soluble solids, and gap assessed (Sections 3.5, 3.6, 3.7 and 3.9). After rewarming to ambient temperatures (24 h) bruise dimensions were measured (Section 3.3). The experimental design was a randomised, split-plot (humidity) with external replicates.

6.3 Results and discussion

6.3.1 Time of harvest during day

There were significant time of harvest and temperature effects on standard impact bruise diameter (Table 6.1). The time of harvest and temperature interaction was less significant indicating that the main effects were largely independent.

A 6.5% (1.30 mm) reduction in standard impact bruise diameter was achieved by delaying harvest until 1100 h and a 7.3% (1.47 mm) reduction in bruise diameter

Table 6.1 Analysis of variance for standard impact bruise diameter of 'Golden Delicious' apples bruised at three harvest times and after fruit had equilibrated at five temperatures (0, 2, 6, 12 and 20°C).

Source	DF	SS	MS	F value	Pr>F
Time of harvest	2	9.70	4.85	7.24	0.0009
Temperature	4	25.36	6.33	9.45	0.0001
Time of harvest*temperature	8	11.33	1.41	2.11	0.034
Error	284	190.32	0.67		
CV = 4.29%					

occurred when harvesting was delayed until 1600 h when compared to size of bruises incurred after harvesting at 0600 h (Table 6.2). The pooled data contained bruise dimensions from five temperature treatments and were therefore only suitable for within row comparisons.

Standard impact bruise diameter and depth were 4.5% and 5% less respectively on fruit equilibrated at 20°C before impact than on fruit held at 0°C (Table 6.3). These findings are in agreement with those of Sekse and Opedal (1993) who using fruit that had equilibrated in the 4 to 20°C temperature range for several days found that increasing temperatures reduced bruise susceptiblity. Other researchers (Schoorl and Holt, 1977; Saltviet, 1984; Zhang *et al.* 1992) have investigated the effect of temperature on susceptibility to bruising but have generally used apples that have been stored for varying periods and because of maturation and water loss changes those results are not directly applicable to this study.

Table 6.2 Standard impact bruise dimensions applied to 'Golden Delicious' apples either A) after three harvest times (n = 60) or B) after equilibration to one of 5 temperature for 2 h (data pooled across temperature treatments; n = 300).

Attribute	Time of harvest		
	0600 h	1100 h	1600 h
Apple temperature (°C)	6	19	22
A			
Bruise diameter (mm) SED=0.79	19.90 a	18.60 b	18.43 b
Bruise depth (mm) SED=0.33	7.75 a	7.53 ab	6.65 b
B			
Bruise diameter (mm) SED=0.67	19.30 a	19.09 a	18.86 b
Bruise depth (mm) SED=0.38	6.85 b	7.03 a	6.95 ab

Values within rows followed by different letters are significantly different at 0.05.

Viewed from the perspective of data as columns it was clear, that fruit harvested early in the morning were much more sensitive to temperature effects than those fruit harvested later in the day (Table 6.4). The range of standard impact bruise diameters between temperatures for 0600 h harvested fruit was 1.6 mm whereas for those harvested at 1600 h it was only 0.75 mm. Early harvested fruit would be expected to be more turgid than later harvested fruit but the absence of turgor data means that this proposition could not be formally tested in this experiment. If turgid fruit are more susceptible to impact damage then they would also be likely to be more susceptible to temperature effects. Early harvested fruit were clearly more sensitive to temperature influences than later harvested fruit.

Table 6.3 Standard impact bruise diameter and depth of 'Golden Delicious' apples for data pooled according to temperature treatment.

Attribute	Fruit temperature				
	0°C	2°C	6°C	12°C	20°C
Bruise diameter (mm) SED = 0.51	19.47 a	19.23 ab	19.01 b	19.14 b	18.59 c
Bruise depth (mm) SED = 0.29	7.05 ab	7.10 a	6.98 ab	6.91 b	6.70 c

Values within rows followed by different letters are significantly different at 0.05

Harvesting fruit later in the day resulted in substantial reductions in susceptibility to bruising as measured by the standard impact bruise diameter. However, it was of interest to determine if this reduction was a response to higher tissue temperature or reduced turgidity or a combination of both of these effects. Closer examination of the time of harvest and temperature interaction indicated that time of day effects on standard impact bruise diameter were greatest at the lower temperatures; these were fruit in which turgor was likely to be maximised by the low temperature (Table 6.4). However, given that the only statistically significant difference in standard impact bruise diameter between harvest times occurred when the fruit from each harvest were equilibrated at 2°C, further work would be required to confirm this indication. As the pooled data (Table 6.2) did show a statistical difference it was concluded that the reduction in standard impact bruise diameters of fruit harvested later in the day were a result of lower turgor as well as higher fruit temperature.

A study into the steepness of decline in susceptibility to bruising as temperature increased was attempted to determine the temperature range at which fruit are most sensitive to bruise damage.

Table 6.4 Standard impact bruise diameter of 'Golden Delicious' apples harvested at three times during the day, equilibrated at 5 temperatures for 2 h before bruising.

	Time of harvest Bruise diameter (SED = 0.29)		
Temperature (°C)	0600 h	1100 h	1600 h
0	19.72 a AB	19.50 a A	19.17 a A
2	19.89 a A	19.16 ab A	18.63 b AB
6	18.89 a C	19.06 a A	19.06 a A
12	19.26 a BC	19.12 a A	19.02 a A
20	18.12 a C	18.61 a B	18.42 a B

Values within rows followed by a or b are significantly different at 0.05.
Values within columns followed by A or B are significantly different at 0.05.

Bourne (1982) used a firmness-temperature coefficient equation to calculate the percent reduction in firmness of fruit tissue as temperature increased by 1°C over the range 1 to 20°C. For the six apple cultivars he studied there was a 0.36% reduction in fruit firmness for every 1°C increase in temperature. The firmness of 'Golden Delicious' was most sensitive (0.73% per degree) to temperature whilst 'Rome' was the least sensitive (0.08% per degree). Replacing firmness with bruise severity indices in Bourne's equation not only facilitates an evaluation of the steepness of reduction in susceptibility to bruising as temperature increases in this study but also allows a comparison with the study by Zhang *et al.* (1992) study in which the same cultivar and a similar temperature range and cultivar were used. The analogous form of Bourne's equation would be:

$$\textit{Bruising-temperature coefficient} = \frac{\textit{Diameter at } T_2 - \textit{Diameter at } T_1}{\textit{Diameter at } T_1 * (T_2 - T_1)} * 100\% \ /^{o}C$$

Where: T_1 = lowest temperature

T_2 = highest temperature

Diameter = standard impact bruise diameter (mm).

Over the 0 to 20°C temperature range a 0.2% and 0.49% reduction in standard impact bruise diameter was calculated for every 1°C increase in temperature for this and Zhang's study, respectively. Apart from any other experimental factors being different, Zhang's group CA-stored their fruit for seven months before the temperature treatments were applied. This would be expected to encourage variation in weight loss and ripening between the two experiments which probably explains the twofold difference in susceptibility to bruising between the two bruising-temperature coefficients. Zhang's study showed a greater reduction in bruise damage (0.7% per degree) occurring as temperature increased from 0 to 14°C whilst the current study showed the greatest value (0.36% per degree) in the bruising-temperature coefficient between 12 and 20°C. These data are in conflict if a general trend is sought. However, they indicate that any increase in temperature up to 20°C would reduce bruise damage but increments from initial low temperatures may have a greater effect on CA-stored fruit and freshly harvested fruit should be handled at higher temperatures (20°C). It was clear that the relationship was unlike the linear relationship between temperature and firmness documented by Bourne (1982).

There are obvious practical implications for orchardists of the evidence gained from this study. In commercial practice, fruit harvested early, during cooler mornings are placed in fruit bins and generally remain in the orchard until being collected later in the day. This time in the orchard would give fruit time to warm and as a result be less susceptible to bruising if handled later in the day. Therefore any real benefit in harvesting later in the day would be derived from the fruit being subjected to less handling damage rather than grading damage. Banks *et al.* (1992) found that about 100 mm^2 of bruise area can be incurred by fruit during harvesting. In that study, the harvests probably occurred at different times of the day and therefore the data would be representative of a wide range of harvest times and fruit temperatures. Any reduction in handling damage would depend on the susceptibility to bruising of the cultivar being harvested and the ambient temperature at harvest. It was clear that harvesting 'Golden Delicious' apples later in the day when ambient temperatures were closer to 20°C should result in considerable reductions in handling damage.

The bruising-temperature coefficient over the 0 to 20°C temperature range for the 0600, 1100 and 1600 h harvest times was 0.44, 0.22 and 0.20% respectively. As temperature increased from 0 to 20°C, fruit harvested early in the day showed a greater reduction in bruise damage than fruit harvested later in the day.

6.3.2 Temperature

Analysis of variance of pooled treatment means determined that there were minimal differences in standard impact bruise diameter incurred by 'Granny Smith' apples that had been stored at various temperatures prior to grading.

When subjected to standard impacts at 20°C, 'Granny Smith' apples incurred bruise diameter and depths that were about 5% and 5.7% less than if they were bruised at 0°C (Table 6.5). These data are consistent with those of Zhang *et al.* (1992) who found 'Golden Delicious' and 'Red Delicious' apples were more susceptible to bruising at 0°C than either 14 or 21°C.

Saltveit (1984) found that 'Starkrimson Delicious' and 'Golden Delicious' apples coolstored for 26 weeks were less susceptible to bruising when cold than when warm. However, the large impact energy used (0.5 *J*) was so severe that the test may have been describing different fruit characteristics than those critical to normal bruise susceptibility. Furthermore, 26 weeks in coolstore probably would have caused ripening to significantly affect tissue responses to impact.

In this case, grader damage reduced by 24% and bruise number/fruit reduced by

21% when 'Granny Smith' apples were graded at 20°C as opposed to grading at 0°C (Table 6.5). Pang (1993) found with a similar experimental design that fruit graded at warmer temperatures incurred less bruising than when they were graded at cooler temperatures (0°C).

Standard impact bruise diameter was not correlated with grader bruise area. This was in contrast to a previous study (Section 5.2.2; 1991 orchard survey) where standard impact bruise diameter was significantly related ($R^2 = 0.49$) with grader bruise area. 'Granny Smith' were used in both studies but in the previous work slightly larger fruit (average apple mass = 0.178 kg) were used while in this study (average apple mass = 0.160 kg). In both studies the same grader was used and similar number of fruit were graded simultaneously; it is therefore difficult to explain the lack of a correlation. In this study, standard impact bruise diameter was only weakly correlated with grader bruise number/fruit ($r = 0.23$) and standard impact bruise depth was poorly correlated with grader bruise number/fruit ($r = 0.13$).

Table 6.5 Standard impact bruise and grader bruise dimensions of 'Granny Smith' apples bruised at either 0, 10, 20 or 30°C.

Attribute	Temperature (°C)			
	0	10	20	30
Bruise diameter (mm)	17.21 a	16.26ab	16.37 ab	16.14 b
Bruise depth (mm)	6.83 a	6.72 a	6.44 b	6.50 b
Grader bruise area (mm^2/apple)	87 a	96 a	66 b	76 ab
Grader bruise number/apple	1.16 a	1.08 ab	0.92 c	0.96 bc
Average bruise size (mm2)	75 a	88 a	71 a	79 a

Values within rows followed by letters are significantly different at 0.05.

The immediate commercial implication of these data is that if 'Granny Smith' apples are coolstored, rewarming to greater than 10°C before grading should reduce the bruise damage incurred during grading.

6.3.3 Storage time after harvest

There were significant differences in grader damage incurred by 'Royal Gala' apples that had been stored for varying periods of up to nine days at ambient temperature prior to grading (Table 6.6).

Grading mature 'Royal Gala' apples after 1, 3 or 9 days storage at ambient temperatures reduced bruise area per apple by 25%, 29% and 61% respectively compared to fruit graded immediately after harvest (Table 6.7). Bruise number per apple showed similar trends, reducing by 32%, 34% and 61% after those times.

Most of the reduction in susceptibility to bruising had been achieved by grading the apples one day after harvesting. By day 9, grader bruise area and the bruise number per fruit had decreased further but the apples had signs of shrivel, were soft and were unsuitable for commercial use.

Table 6.6 Analysis of variance for grader bruise area of 'Royal Gala' apples stored at ambient temperatures for varying periods prior to grading.

Source	DF	SS	MS	F value	Pr>F
Days before grading	3	510.95	170.32	21.31	0.0001
Error	1103	141.33	0.12		
CV = 57%					

Table 6.7 Bruise area and number of bruises on 'Royal Gala' apples graded after 1, 3 or 9 days storage at ambient temperatures.

Attribute	Time (days)			
	0	1	3	9
Bruise area/fruit (mm^2)	31 a	23 b	22 b	12 c
Bruise number/fruit	0.64 a	0.43 b	0.42 b	0.24 c

Values within rows followed by different letters are significantly different at 0.05.

Susceptibility to bruising reduced as storage time increased prior to grading, an overall effect that would have resulted from the two separate mechanisms. In the first, because apples were losing weight which would have reduced turgor, increased storage time would make fruit less susceptible to impact damage. In the second enhanced ripening would have been expected to increase susceptibility to bruising. The relative rate of these two process, coupled with the steepness of their relationship with bruise susceptibility would determine whether increased storage time would increase bruise susceptibility or decrease it. The two effects would be expected to contribute to changes in susceptibility to bruising.

The decrease in bruise susceptibility in this experiment indicates that weight loss was the predominant influence on bruise susceptibility in this study. Other experiments were designed to explore further the interaction between weight loss and ripening and its effects on susceptibility to bruising.

6.3.4 Temperature and weight loss

There were statistically significant effects on the standard impact bruise diameter of freshly harvested 'Royal Gala' apples that had been subjected to various cooling and warming treatments (Table 6.8).

Despite the experiment running for 72 h, 24 h of which fruit were held at 20°C, the placing of fruit in plastic bags did not have a statistically significant influence on weight loss of fruit (Table 6.9) perhaps because the Friday trays themselves represented a substantive sink for moisture over the duration of the experiment. The interaction between fruit temperature and bagging treatments on standard impact bruise diameter was not statistically significant.

Table 6.8 Analysis of variance for standard impact bruise diameter of 'Royal Gala' apples stored either in plastic bags or not and bruised during a sequence of warming (20°C) and cooling (3°C).

Source	DF	SS	MS	F value	Pr>F
Temperature treatment	3	19.93	6.44	3.89	0.012
Plastic bag treatment	1	1.01	0.59	0.59	0.44
Temperature*plastic bag treatment	2	1.95	0.97	0.57	0.57
Error	72	122.91	1.70		
CV = 9.54%.					

'Royal Gala' apple tissue was not as sensitive to bruise damage at various temperatures as were freshly harvested 'Golden Delicious' (Section 6.3.1) and this may relate to differences in fruit density. According to Klein (1987) 'Delicious' apples were of lower density than 'Gala' apples. It was noted in the time of harvest experiment (Section 6.3.1) that 'Golden Delicious' apples harvested early in the morning displayed a greater tissue sensitivity to temperature changes than those harvested later in the day. By the time 72 h had elapsed the 'Royal Gala' in the current experiment may have been losing sensitivity to temperature changes.

The duration of the experiment was 72 h with a further 24 h period at 20°C. At the end of the experiment weight loss of the final recool treatment was 0.17% of apple mass (mean fruit mass = 0.156 kg). The daily weight loss (0.06%) for the 3 days duration of the experiment was similar to that documented by Hatfield and Knee (1988). Johnson and Dover (1990) found that a weight loss of 1% after 10 days did not produce a significant change in bruise volume when compared to fruit stored in high humidity (weight loss of 0.03%). But in their high humidity treatment there was clearly a trend that supported the hypothesis that even a small amount of weight loss would reduce bruise susceptibility. This trend in susceptibility to bruising became statistically significant after 20 days and coincided with a 2% weight loss. The weight loss documented in this experiment was low and may explain the nil effect.

The gap test generated two problems; firstly, this data group had a particularly high CV (27%) which was linked to the difficulty in obtaining perfectly symmetrical fruit of uniform mass. Even slightly asymmetrical fruit generally had stresses that were released when fruit were sliced longitudinally to the core which exaggerated gap measurements (data not shown). Furthermore, despite considerable attention when cutting, freshly harvested fruit split through the core causing larger gaps. The gap data showed a reverse trend to that expected, although ripening may explain the increase in gap as time progressed. A larger sample of symmetrical fruit of uniform mass than that used in this investigation would be required if conclusions were to be drawn from this type of test measurement.

Bruising at either 3 of 20°C did not influence the final bruise lightness, chroma or hue angle. Sekse and Opedal (1993) observed a reduction in discolouring in 'Gravenstein' when bruised at higher temperatures. However, it was difficult to ascertain from that study whether there was a direct temperature effect on the biochemistry of colour development or that lighter bruise colour was caused by the reduction in bruise size making bruises less visible.

Table 6.9 The effect of a sequence of warming (20°C) and cooling (3°C) treatments on 'Royal Gala' fruit attributes.

Attribute		Temperature treatment			
		Initial 20°C	Cool 3°C	Rewarm 20°C	Recool 3°C
Bruise diameter (mm)	+ bags	13.46 b	14.56 a	12.81 c	13.82 b
	- bags		13.79 a	12.85 a	13.77 a
Bruise depth (mm)	+ bags	5.93 a	6.08 a	5.62 a	5.99 a
	- bags		5.75 a	5.82 a	6.23 b
Weight loss (% apple mass)	+ bags	nil	0.091 a	0.13 b	0.162 c
	- bags		0.098 a	0.14 b	0.175 c
Gap (mm)	+ bags	0.81 a	0.98 a	1.08 a	-
	- bags		-	0.99 a	-
Grader bruise area (mm^2)	+ bags	25 a	25 a	16 b	28 a
	- bags		24 a	11 b	21 a
Number of grader bruises/fruit	+ bags	0.40 a	0.40 a	0.25 b	0.48 a
	- bags		0.36 a	0.22 b	0.32 a
Bruise lightness	+ bags	33.62 a	35.00 a	33.45 a	34.64 a
	- bags		32.68 a	33.60 a	31.78 a
Bruise chroma	+ bags	7.05 a	8.17 a	7.47 a	8.02 a
	- bags		6.85 a	7.06 a	6.40 a
Bruise hue angle	+ bags	82.51 a	80.76 a	77.94 a	82.13 a
	- bags		80.11 a	81.82 a	77.66 a

Data in the initial 20°C temperature treatment column were not subjected to bagging treatments. There were no significant differences between the plastic bag treatments in any of the measured fruit attributes. Values within rows followed by different letters are significantly different at 0.05.

When fruit were bruised immediately after harvest at 20°C, standard impact bruise diameter immediately was significantly less than when fruit were bruised after cooling to 3°C (Table 6.9). Bruising after the rewarming treatment produced the smallest standard impact bruise diameter (12.81 mm). Recooling to 3°C resulted in increases in bruise diameter by 8% to 13.8 mm from the low of the previous treatment. Standard impact bruise depth did not alter for the first two treatments but declined when fruit were rewarmed and then increased again after recooling.

After grading on the FCU grader, both the area and number of bruises caused by grading reduced only when fruit had been rewarmed to 20°C. 'Royal Gala' apples graded on the FCU grader sustained about 36% less damage if they were graded following rewarming than if they were graded immediately after harvest (Table 6.9). Rewarming the fruit reduced grader-induced damage, whilst re-cooling reinstated their high level of susceptibility to bruising. This clearly shows that there was a direct effect of temperature on susceptibility to bruising rather than a change in susceptibility resulting from enhanced ripening or reduced turgor with time.

6.3.5 Storage time and temperature

There were significant storage time and temperature effects on standard impact bruise diameter of 'Splendour' apples and these two factors interacted (Table 6.10).

After 414 h, 'Splendour' apples stored at 0°C were slightly more susceptible to bruising as measured by the standard impact bruise diameter (4%) than at the start of the storage period (Fig. 6.1A). Storing and bruising these apples at 10°C produced no change in susceptibility to bruising whilst storing at 20°C produced a 5.5% decrease in standard impact bruise diameter. Similar trends were evident for standard impact bruise depth (Fig. 6.1B).

Table 6.10 Analysis of variance for standard impact bruise diameter for 'Splendour' apples held at three temperatures (0, 10 and 20°C) for varying periods (12, 20, 54, 114 or 414 h).

Source	DF	SS	MS	F value	Pr > F
Time	4	6.21	1.55	2.41	0.05
Temperature	2	36.04	18.02	27.91	0.0001
Time*temperature	6	10.11	1.68	2.61	0.018
Error	243	156.90	0.66		

CV = 5.6%.

Wilkinson (1965) reported that in some instances if apples are coolstored at high humidities they can continue to expand without an increase in weight. Such an effect would increase the inherent stresses and strains within the fruit and also decrease wall-to-wall contact, decreasing the strength of bonds between cells. Such a tendency would be reduced in fruit stored at lower humidities as water would be lost much more rapidly. In addition to this, as apples continue to ripen, cell walls would soften and round off. Either water loss or ripening or a combination of these effects is reflected in the susceptibility to bruising patterns of the three treatments.

Fruit stored at 0°C did not lose water rapidly in coolstore (0.52% of weight in 414 h; Fig. 6.1C) compared to the weight loss of fruit at 10°C and 20°C. These differences can be attributable to the differences in the low water vapour pressure deficit which prevailed during storage in these three treatments. Also, at 0°C, ripening would have progressed at a slower rate than the other treatments. Thus, initially (by 114 h) cells in these apples may have expanded thereby increasing susceptibility to bruising. Presumably these apples did not ripen rapidly and continued weight loss could account for the decline in susceptibility in bruising recorded at 414 h. Hyde and Ingle (1968) stored fruit for about 11 weeks (1850 h) before obtaining significant reductions in bruise diameter. Holt and Schoorl (1984) also found no change in the bruise resistance coefficient of three cultivars during a storage period of 20 weeks.

A study by Garcia *et al.* (1995) perhaps highlights the value of careful bruise dimension measurement in such investigations. This group used a 0.03 *J* impact energy and measured bruise dimensions with a stereoscopic microscope and found that 'Golden Delicious' apples after 16 h at either high (100%) or low (40%) relative humidities had significantly different bruise volumes. Those fruit stored at low humidities had a 0.4% moisture loss and had 5.7% lower bruise volumes. It was noted, however, that the firmness of these apples at harvest was low (24 N) which would be expected to be associated with higher bruise susceptibility. Zhang *et al.* (1992) found that 'Golden Delicious' and 'Red Delicious' were less susceptible to bruising if stored at 50% humidity for about 42 days. But this group did not find a convincing relationship between storage time and bruise susceptibility probably because experimental fruit had been stored for 9 months prior to treatment.

'Splendour' apples stored at 10°C experienced a slightly higher weight loss than those stored at the lower temperature and these fruit would have continued to ripen. The balance between lower cell volume due to weight loss and some softening of cell walls due to ripening, was reflected in little or no change in bruise diameter.

The reduction in susceptibility to bruising of 'Splendour' apples stored at 20^{O}C is probably accounted for by a combination of larger weight loss (3.55%) and enhanced ripening. These apples were losing water quite quickly and initially susceptibility to bruising declined. However, as the apples ripened the strength of cell-cell bonds weakened and cell walls began to decrease in thickness. As a consequence, susceptibility to bruising increased but not to levels recorded when

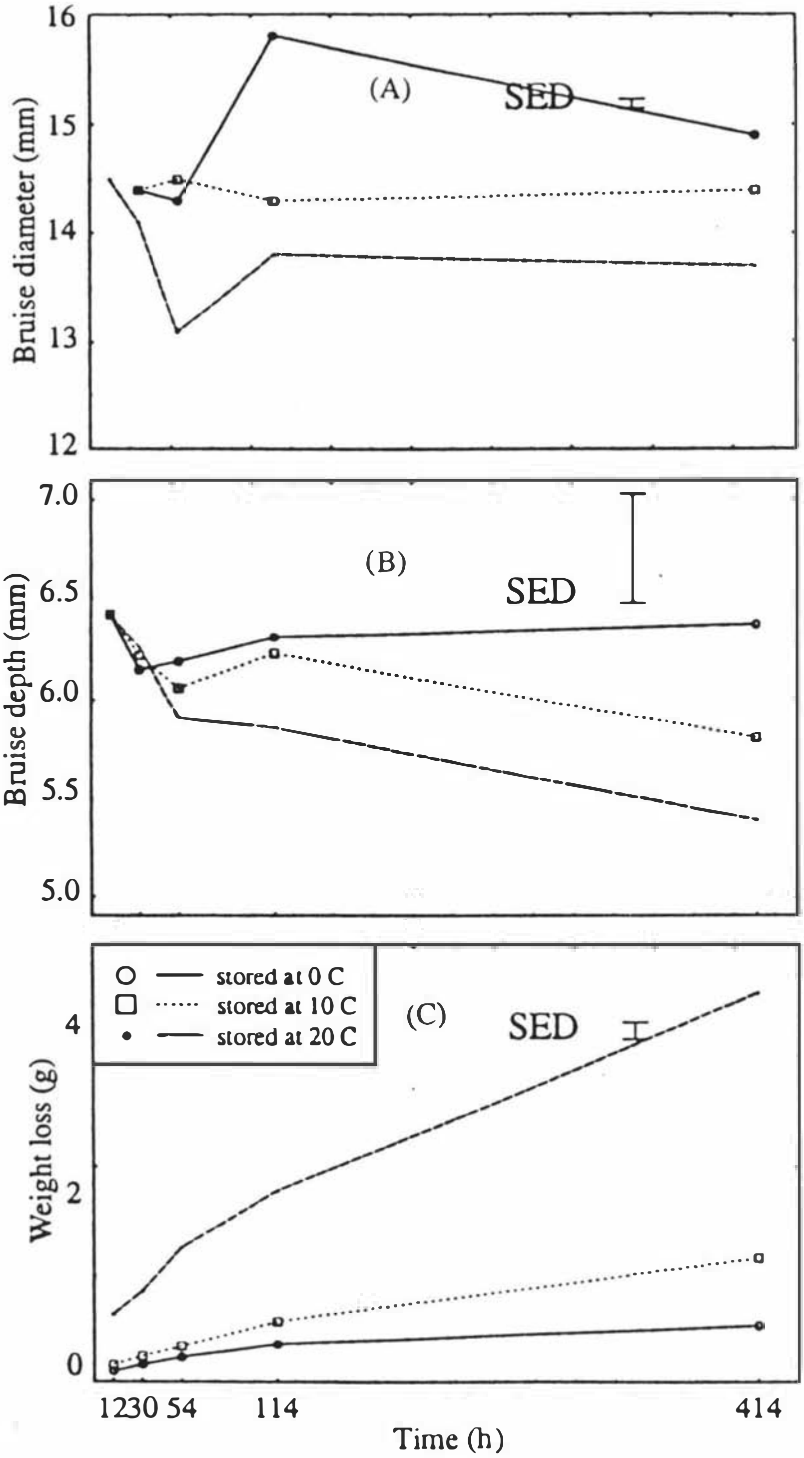


Fig. 6.1 Standard impact bruise diameter (A), depth (B) and weight loss (C) of 'Splendour' apples coolstored at 0, 10 or 20°C for either 12, 30, 54, 114 or 414 h before being bruised.

the apples were fresh.

Bruise lightness and hue angle increased from bruising at 12 h to 414 h at each of the storage temperatures but there was no similar trend in bruise chroma (Fig. 6.2). According to data on 'Granny Smith' tissue colour (Section 4.2.3.2) the magnitude of the differences in bruise lightness and hue angle indicate that the changes in bruise colour would have been clearly visible. The increase in lightness and hue angle may in part be explained by lower water content (Samim and Banks, 1993a); apple tissue bruised after 414 h may have had damaged tissue that contained less water and as a consequence, be of lighter colour. However, those apples stored at 0°C and 20°C recorded similar increases in hue angle although those stored at the higher temperature had lost 7 times more weight. Observations made in other experiments (data not shown) indicate that the browning reaction initially proceeds at a slower rate in cool tissue but within 24 h at ambient temperatures bruise colour reaches values similar to tissues bruised at warmer temperatures. Reductions in the brownness of damaged tissue after time in store must be explained by some time-dependent factor, presumably related to ripening.

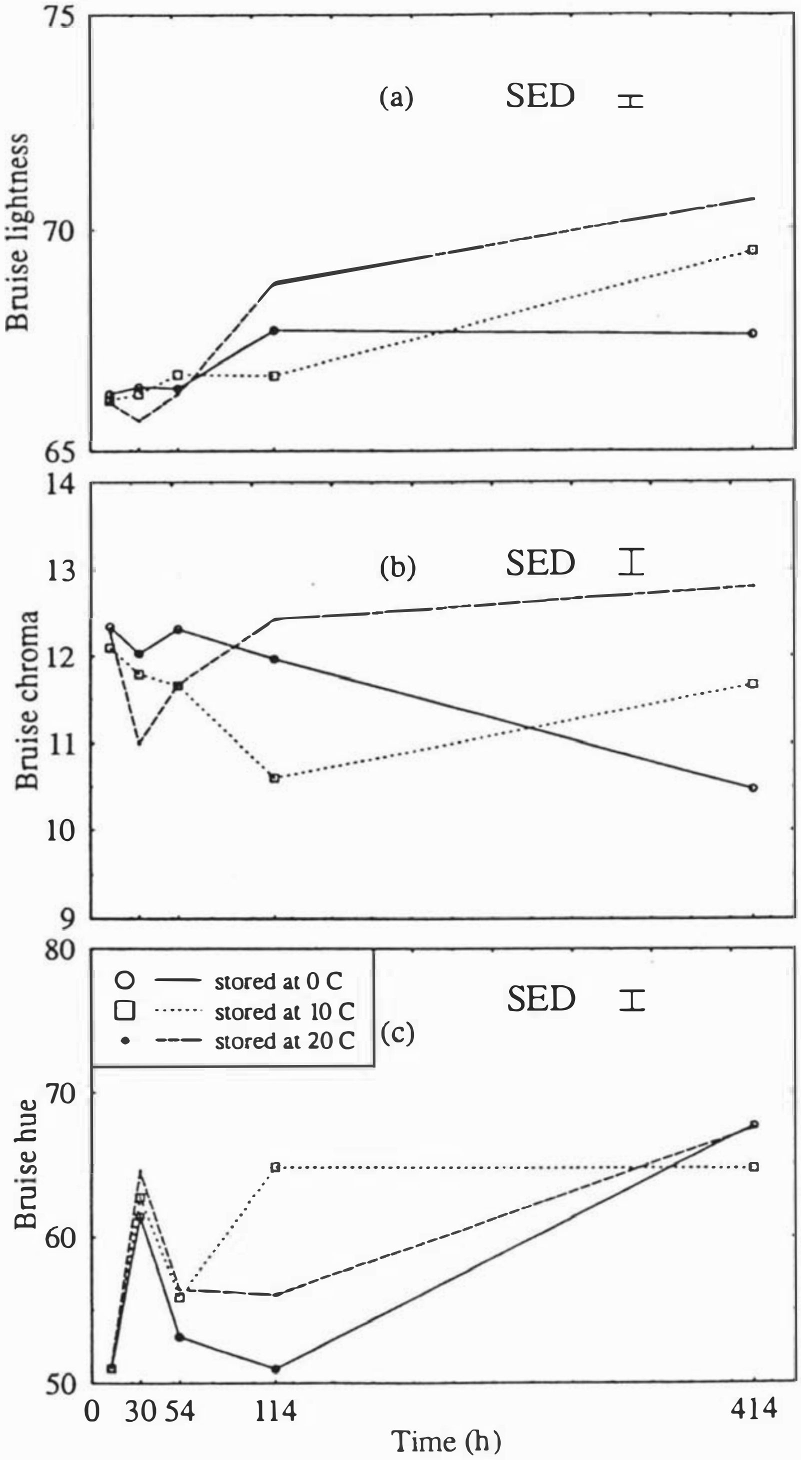


Fig. 6.2 Bruise lightness, chroma, and hue angle of 'Splendour' apples coolstored at 0, 10 or 20°C for either 12, 30, 54, 114 or 414 h before being bruised.

6.3.6 Delay in pre-cooling

There were statistically significant effects of pre-cooling periods on the standard impact bruise diameter of freshly harvested 'Royal Gala' apples (Table 6.11).

Table 6.11 Analysis of variance of standard impact bruise diameter of 'Royal Gala' apples subjected to various pre-cooling periods (0, 24, 48 72 h).

Source	DF	SS	MS	F	Pr>F
Replications	3	3.96	1.31	2.23	0.085
Pre-cooling treatment	3	15.05	5.12	8.65	0.0001
Plastic bag treatments	1	0.11	0.11	0.19	0.66
Pre-cooling*plastic bag treatments	3	2.71	0.90	1.53	0.207
Error	303	179.45	0.59		

CV = 5.58%.

Pooling of the temperature treatment data across plastic bag treatments (Table 6.12) revealed that a delay before pre-cooling of 24 h resulted in approximately a 3.4% and 6.2% reduction in standard impact bruise diameter and depth, respectively. The reduction in bruise diameter and depth was 4.1% and 8.1% respectively after a 48 h delay before pre-cooling. Pooled data showed that the reductions in both bruise dimensions in the 24 to 48 h period were not significant: apparently most of the potential benefit had been achieved by a 24 h delay. Bruise dimensions did showed an upward trend for the 72 h delay, but this was not statistically significant.

During the 24 h delay prior to pre-cooling, the largest weight loss and change in turgor (gap measurement) were recorded (Table 6.12). These differences in weight loss were not associated with changes in bruise diameter at any of the delays before pre-cooling.

Table 6.12 Bruise dimensions, weight loss, starch, soluble solids, firmness and gap of 'Royal Gala' apples stored at 20°C for 0, 24, 48 or 72 h before pre-cooling and bruising 96 h after harvest.

Attribute		Delay before pre-cooling (h)			
		0	24	48	72
Bruise diameter (mm)		14.01 a	13.54 b	13.43 b	13.62 a
Bruise depth (mm)		6.64 a	6.23 bc	6.10 c	6.35 a
Firmness (N)		69.19 a	68.83 a	69.74 a	69.38 a
Soluble solids (°Brix)		11.06 a	11.01 a	11.23 a	11.21 a
Starch index		3.19 b	3.57 b	4.25 a	4.25 a
Gap (mm)	+ bags	1.12 a	1.01 a	1.01 a	0.99 a
	- bags	1.10 a	0.95 b	0.92 b	0.88 b
Weight loss (%)	+ bags	0.10 a	0.29 b	0.31 b	0.26 b
	- bags	0.23 a	0.73 b	0.96 b	1.19 b

Values within rows followed by different letters are significantly different at 0.05.

Despite the plastic bag treatments producing statistically different weight losses and gap measurements at each of the delay periods there were no consistent differences due to weight loss in any of the measured fruit attributes. These results are not consistent with observations made by Garcia *et al.* (1995) who documented a significant reduction in bruise susceptibility of 'Golden Delicious' apples after a 0.4% weight loss in 16 h after harvest. However, this group used a low impact energy and 'Golden Delicious' apples which were probably more bruise susceptible than the 'Royal Gala' apples used in this study.

Soluble solids and starch began to increase after the 24 h delay, indicating continued ripening which might well have enhanced susceptibility to bruising. However any such effects were probably negated by the continued weight loss.

6.4 Conclusions

Overall, this series of investigations has substantiated the proposition that harvest and postharvest factors could be manipulated to reduce the bruise damage that apples incur during postharvest handling. Conclusive evidence was obtained that the temperature at which the relatively bruise susceptible 'Golden Delicious' was harvested could affect propensity to bruise damage. Harvesting fruit later in the day resulted in less bruise damage. This effect appeared to be due primarily to effects related to temperature rather turgor. Apples harvested early in the morning showed a greater sensitivity to temperature effects than fruit harvested later in the day indicating a role for turgor in these effects. 'Royal Gala' apples graded immediately after harvest incurred 25% more grader damage than if stored for one day at ambient temperatures before grading. Although some further reduction in bruise damage was achieved by storing apples for 3 or 9 days, these further delays resulted in excessive weight loss. Similarly 'Splendour' apples bruised immediately after harvest were more susceptible to bruising (9.6% larger bruise diameters) than those bruised after being stored at 20°C for 30 h. 'Granny Smith' apples stored at 0°C for 24 h incurred bruises of greater diameter and depth and more grader bruises compared to fruit bruised at 20°C. Likewise 'Royal Gala' apples sustained 36% more damage if graded at 3°C rather than 20°C. Grading these apples after they were cooled a second time after rewarming resulted in similar amounts of damage to that incurred by apples after the initial cooling. This confirmed that the reduction in bruising was a result of increased temperature *per se.*, rather than enhanced ripening.

CHAPTER SEVEN

DISCUSSION

7.1 Introduction

Excessive bruise area on apples (> 100 mm^2) incurred at either harvest or during postharvest handling can result in the downgrading of fruit from export to juicing grade, causing considerable financial losses to New Zealand orchardists. Display of mildly bruised apples at retail outlets can erode the high quality profile that is required for marketing success. The physical causes of bruising that occurs during harvesting, grading, and postharvest handling have been investigated in previous publications and procedures that may reduce the incidence and severity of bruises have been identified. In an alternative approach to reducing bruise damage, this study has explored variability in susceptibility to bruising to identify the potential scope for manipulation of management factors within the bounds of current growing, harvesting and storing procedures to reduce bruise severity.

7.2 Bruise susceptibility and its assessment

Researchers have used many techniques (Section 2.5.2) to apply standard impacts to apples and generally despite several problems (Section 2.4.1.3) have represented bruise susceptibility as volume of bruised tissue per unit of energy. In a review of techniques, a study of graded apples identified common bruise sizes (Section 4.1.2). These data were considered in the light of data from Banks's (1991) study that identified drop heights commonly found on graders. This led to standard impacts to apples being generated (with consideration of several parameters; Fig. 7.2.) by using an impactor of similar mass (0.160 kg) and radius of curvature to apples (70 mm diameter) and an impact energy of 0.32 *J*. This technique of generating bruises that were related to grading damage contrast the work of Saltveit (1984) and Holt and Schoorl (1977) who employed impactors and impact energies that generated bruises that had little resemblance to the damage that apples incur during grading.

The mass and radius of curvature of the impacting ball were constant and its surface was smooth. Equatorial skin surfaces on apples were impacted, which resulted in accurate, repeatable results with diameter having a lower coefficient of variation than the more commonly used bruise volume (3.4% and 13.5% respectively; Table 4.3). The use of bruise diameter as a bruise severity index had distinct advantages over bruise volume (Section 4.1.2) but it did not take into account the three dimensional aspects of bruise shape.

The assumption that all bruises in a particular study are a common shape (Holt and Schoorl, 1977, spherical; Diener *et al.* 1979, partial sphere; Chen and Sun, 1981; semi-oblate spheroid) was not substantiated by observations made during this study. According to Protter and Morrey (1966), if the 3 dimensional coordinates ($x = A$; $y = B$ and $z = C$) of a shape are equal then it is a sphere, if $A = B$ and $C > A$ then it is a prolate spheroid and if $A = B$ but $C < A$ then the shape is an oblate spheroid. In the 1990 survey, bruise shape varied considerably; the most bruise susceptible fruit had diameter/depth ratios of 0.48 whilst the least bruise susceptible had ratios of 0.51 (Table 5.1). Therefore, in this experiment three bruise volume formulae would have been required, one based on a sphere (ratio = 0.5), one on a prolate spheroid (ratio > 0.5) and another on a oblate spheroid (ratio < 0.5). Furthermore, as observed by Garcia *et al.* (1988), some bruises are cone shaped, or as observed in this study, others are shaped similar to the base of a cone. Therefore, because of potential variation in bruise shape, the use of a single volume formula in some experiments may confound calculations of between treatment group differences. Relying principally on bruise diameter avoided these types of errors and the risk of drawing the wrong conclusions about treatment effects due to variable bruise shapes. As data on bruise depth data were included in all instances, bruise shape comparisons were possible; a suitable compromise was achieved.

At an impact energy of 0.32 *J* and with a sample of 20 fruit, slightly less than 1 mm difference in bruise diameter was required to detect a difference between treatment means. As small changes in bruise diameter were required to show treatment effects, accurate measurement of bruise dimensions were important. Support for accurate bruise dimension measurement comes from the work of Garcia *et al.* (1995) who found bruise volume differences between two relative humidity treatments using 135 fruit per treatment with a low impact energy (0.04 *J*). Assuming a constant bruise depth between treatments and using the same bruise volume formula of Chen and Sun (1981) it was calculated that an increase from 8 to 8.2 mm in bruise diameter was required to show differences between treatment means. That a stereoscopic microscope was used to determine such small changes in bruise dimensions could be considered to be an elaborate technique. However, a 0.2 mm difference in bruise diameter due to treatments equates to a 3% increase in bruise diameter and had these fruit been graded on the FCU 'Treeways' grader bruise damage there would have been at least a 12% increase in grader damage (Fig. 5.2; 1991 data).

Other researchers appear to have either overlooked, or because of inherent difficulties do not appear to have attempted to establish, a link between a bruise severity index and the damage that apples incur during grading. This seemingly natural progression in application of bruise severity data would allow orchardists and packhouse managers to deduce a commercial value of attempts to manipulate susceptibility to bruising. It was anticipated this approach would be facilitated because bruises were generated by a standardised impact designed to be representative of grader bruises. That the relationship between damage resulting from grading fruit (from a considerable number of impact energies) and bruise diameter generated in a standard manner (from one impact energy) was of medium strength ($R^2 = 0.49$) supported the approach. The slope of the relationship between bruise diameter and grader damage would be influenced by a number of factors. Apple cultivar and its maturity, the type of grader, its maintenance with respect to padding to absorb impact energy, the grading speed used, loading density of fruit on the grader and the range in apple mass from each orchard lot of apples would be important variables.

7.3 Apple bruising at cell level

At cell level, variability in susceptibility to bruising is the result of numerous factors that interact in a complex way to absorb impact energy. Results from this study and factors identified by other researchers that influence susceptibility to bruising are summarised in Fig. 7.1. For the sake of clarity, maturity and temperature effects have been omitted and the implications of turgor have been simplified. The complexity of this summary and the potential for substantial interactions between individual factors illustrates the difficulty in quantifying the influence of any of these factors in determining susceptibility to bruising.

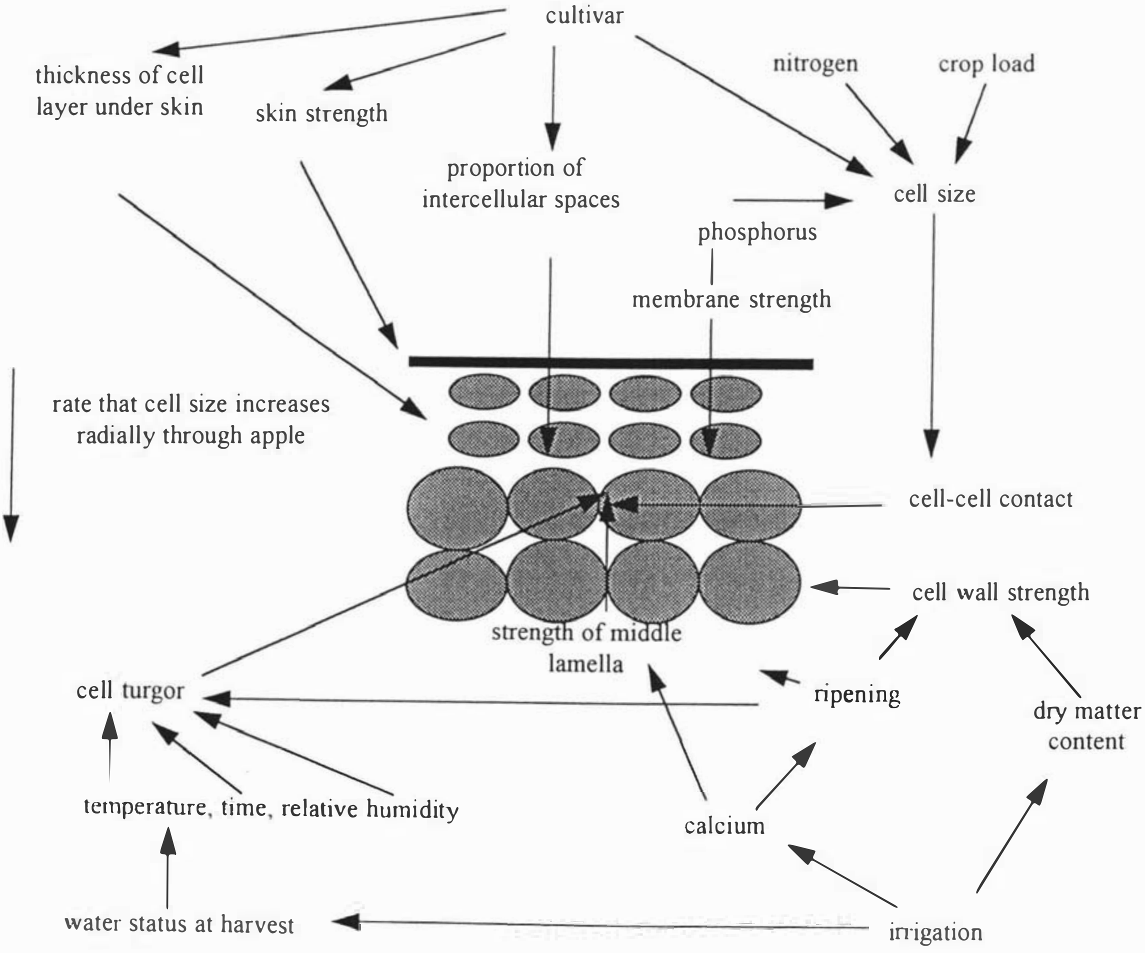


Fig. 7.1 Factors influencing susceptibility to bruising at cell level.

7.4 Preharvest factors influencing susceptibility to bruising

7.4.1 A conceptual model

In efforts to reduce bruise damage, orchardists focus on Stages 1 to 4 of the handling sequence in the order as presented (Fig. 2.1). Until this study, manipulation of preharvest factors was a largely unexplored option for orchardists to reduce damage. A considerable number of preharvest factors influence the susceptibility of apples to bruising (Fig. 7.2) some of which could be manipulated relatively easily and these opportunities are discussed in the following sections.

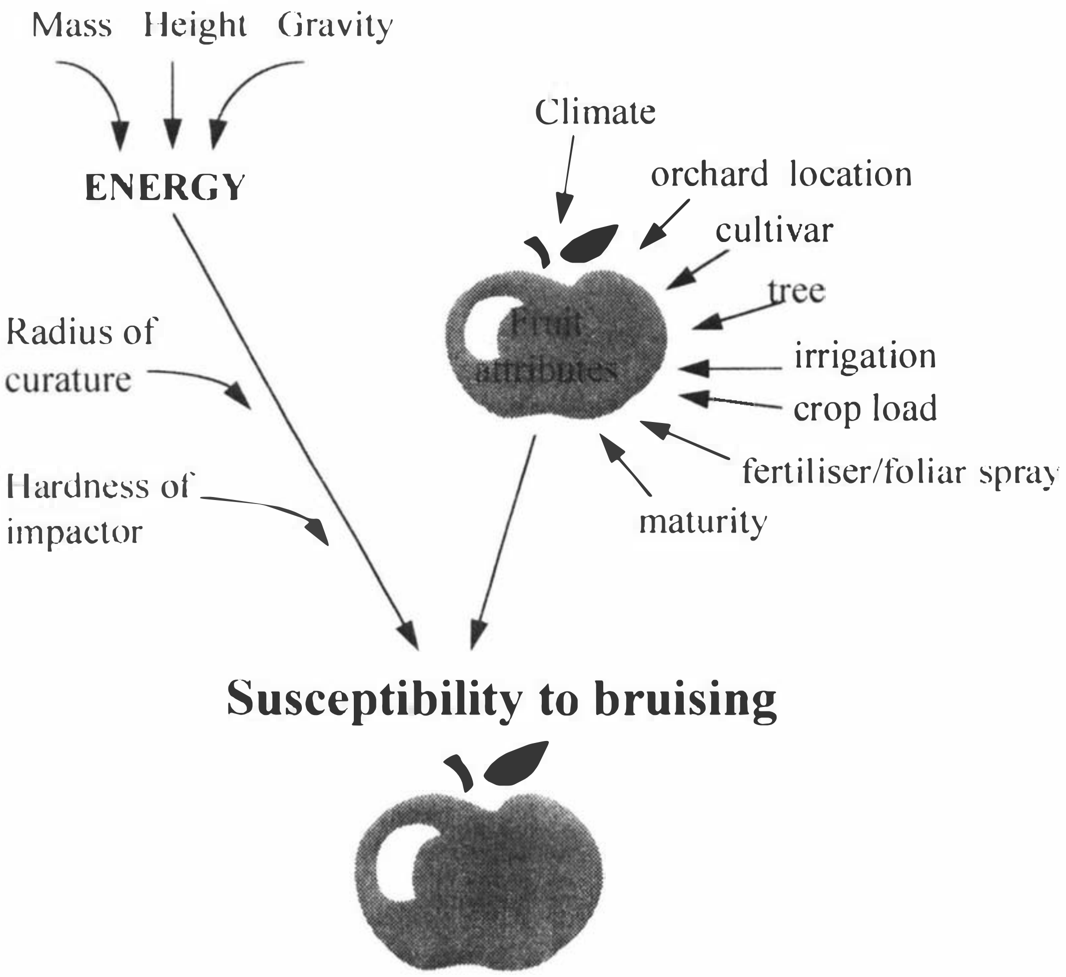


Fig. 7.2 Conceptual model of preharvest influences on susceptibility to bruising.

7.4.1.4 Irrigation

Reduced irrigation of 'Braeburn' apple trees produced fruit that were less susceptible to bruising (6%), had lower calcium content and tended to have higher dry matter content than fruit from irrigated trees (Section 5.4). The role of calcium in cell wall strength is discussed in the next section. Apples with increased apple dry matter content are likely to have more cells and/or thicker cell walls; either factor would be expected to enhance resistance of tissue to impact. Garcia *et al.* (1995) found that reduced or nil irrigation two weeks prior to harvest did not significantly reduce bruise susceptibility. It would be reasonable therefore to assume that long term water stresses that influence structural attributes of the fruit, rather than water status *per se.*, would be required to influence fruit attributes that are associated with reduced susceptibility of fruit to bruising. ENZA offers orchardists incentives for larger fruit for some cultivars. The financial inducement to produce large fruit may preclude the use of reduced irrigation to reduce susceptibility to bruising in such cultivars. Whilst reduced irrigation did not influence 'Braeburn' mass in this study, its effect on other cultivars would need to be verified. Apart from reducing susceptibility to bruising, reduced irrigation has other positive benefits on fruit attributes and therefore warrants further exploration as a valuable management tool for orchardists to improve apple quality.

7.4.1.5 Fertiliser/foliar sprays

Correlative evidence added support to the hypothesis that mineral content of apples were associated with susceptibility to bruising (Section 5.2.2). In both years of the survey, the most bruise susceptible 'Granny Smith' apples had more phosphorus, nitrogen, calcium and magnesium. Regression analysis identified that in the 1990 survey, 'Granny Smith' calcium content was not as important as apple mass in predicting standard impact bruise diameter. In 1991, where a greater range in fruit mass was utilised, no relationship between fruit mineral content and susceptibility of bruising was evident. Between-season variation in fruit mineral contents and bruise susceptibility were also evident in Johnson and Dover's (1990) study.

The potential effect of calcium on susceptibility to bruising is of interest primarily because calcium has been shown to increase fruit firmness, through its effects on cell wall strength and cell-cell bonds (Fig. 7.1). Increasing firmness has occasionally been negatively associated with bruising (Section 5.2.2). Elevated calcium tissue levels could be expected to reduce tissue sensitivity to bruising, but this was not the case in the 1990 survey. This apparent paradox is based on the unpredictable relationship between firmness and bruising; whilst calcium strengthens cell walls and cell-cell bonds it may reduce cell wall elasticity thereby making apple tissue brittle and more sensitive to impact damage. Firmness testing and bruising stress tissue in different ways; tissue with higher calcium content may be firmer but it need not necessarily be less bruise susceptible. Non-irrigated 'Braeburn' showed reduced susceptibility to bruising which was also associated with lower calcium levels compared to fruit from irrigated trees. This finding contributes to the supposition regarding the effect of calcium contributing to cell wall rigidity, thereby decreasing the ability of cells to transfer impact energy without damage.

In the 1990 orchard survey (Section 5.2.2) grader damage was moderately related to fruit phosphorus content. Whilst having many metabolic functions, phosphorus also plays a role in membrane structure where different ratios of phospholipids influence physical properties of membranes. Low energy impacts sometimes do not cause cell wall rupture but impacted tissue still shows typical browning (Ruiz, 1990). The strength of membranes would therefore be critical in determining the extent of enzymatic browning. Low impact energies can be generated during grading and the total bruise area on an apple may comprise a large number of small bruises. Thus, if these bruises were closely studied and cell wall fracture was not evident, the resilience properties of cell membranes would play an important role in determining the extent of bruising and therefore bruise area. It is therefore suggested that whilst higher levels of phosphorus may decrease membrane permeability (Johnson and Yogaratnam, 1978) there may be other influences of increased phosphorus on membrane elasticity or resilience that increase tissue sensitivity to impact damage.

Apart from foliar sprays it would seem that ground cover management and nitrogen fertiliser application rate would offer opportunities to influence susceptibility to bruising. However, Johnson and Dover (1990) found these factors had no effect on bruising levels of ‘Bramley’s Seedling’ apples after one year of a three year trial. However, prior to testing these fruit had been CA-stored and therefore ripening or water loss may have obscured treatment effects; bruise susceptibility of fruit from these treatments immediately after harvest would have been of greater interest.

Foliar sprays may offer opportunity to manipulate susceptibility but in this study a preharvest foliar spray programme that applied either phosphoric acid or calcium chloride to ‘Granny Smith’ and ‘Royal Gala’ apples did not significantly influence the mineral contents of fruit or their susceptibility to bruising. This result may perhaps in part explain the difficulty that the FCU management has had in increasing the mineral content of apples by this approach, the reasons for which are unknown.

Calcium has been associated with cell wall and membrane integrity and it may be that the effects of higher calcium levels in fruit may manifest themselves in different ways depending on the stage of ripening. In the 1990 survey and irrigation study, when tested immediately after harvest, more bruise susceptible fruit had higher levels of calcium. Had these fruit been bruised after periods in store, some water loss together with higher tissue calcium levels (reducing ripening rate) may have actually reduced susceptibility to bruising if these fruit been compared with those of lower calcium content.

Further studies will be required to identify a causal relationship between higher tissue levels of fruit calcium and phosphorus and susceptibility to bruising. The importance of calcium and phosphorus in enhancing other aspects of fruit quality has been well documented and the manipulation of these elements to reduce susceptibility to bruising would require careful consideration.

7.4.1.6 Maturity

The effect of enhanced ripening on increasing susceptibility to bruising in this particular orchard substantiates evidence obtained by a considerable number of other researchers. Harvesting 'Granny Smith' and 'Royal Gala' at the beginning rather than at the end of the commercial harvest season reduced susceptibility to bruising by 5% and 21% respectively (Section 5.3.2.2).

Ripening causes a weakening of cell walls which is also associated with conversion of starch to sugars, causing turgor pressure to increase; these effects combine to increase tissue sensitivity to impact damage (Fig. 7.1). Garcia *et al.* (1995) related weight loss over 16 h to deformation at skin puncture (DSP; $R^2 = 0.35$) and probably rightfully associated DSP with turgor. However, in another study this group also concluded that turgor changes were not associated with increased sensitivity to bruise susceptibility because DSP did not change during the 2 week harvest period but bruise susceptibility increased. It could be argued that the balance between ripening, which would decrease cell strength and any turgor increase may maintain tissue pressure against the apple skin (the strength of which may also be reducing) and produce little change in DSP. Until methods are used that unambiguously measure turgor of whole fruit the division of turgor and ripening effects on susceptibility to bruising may not able to be conclusively answered.

At orchard level, harvesting fruit early in the season but within ENZA maturity guidelines would appear to be a simple option available to orchardists to reduce bruise damage. However, because there are financial incentives for producing large fruit from some cultivars and in certain instances fruit of increased blush, there will always be a requirement for some fruit to be harvested later in the season. In these instances, fruit losses due to bruising need to be balanced against increased value of the export grade fruit. To be able to reduce susceptibility to bruising of fruit without negatively influencing fruit size would be particularly advantageous to growers. In these instances reduced irrigation and harvesting fruit later in the day may warrant further consideration.

7.4.1.7 Apple tissue attributes

In this study the relationship between susceptibility to bruising and other fruit attributes produced variable results and these attributes seldom explained more than about 25% of the variation in the data set. A consequence of this was that multivariate analyses (principal components and canonical correlations) did not add to the understanding that could be derived by correlation or regression analysis. Correlation coefficients, although small were in most cases highly significant.

Fruit mass

Although in the within-orchard study fruit from several trees had similar mass but different susceptibility to bruising there was generally positive influence of fruit mass on susceptibility to bruising (r = 0.21 and 0.23; Table 5.10,'Granny Smith' and Table 5.14, 'Royal Gala'). Whilst the relationship with standard impacts was established, the relationship between heavy fruit and the damage that occurs during handling and grading would be expected to be considerably stronger. Virtually all regression equations indicated that fruit mass was positively associated with standard impact bruise diameter.

Within a particular cultivar, larger fruit would be expected to have larger cells with fewer cell-cell bonds in a given volume of tissue that fruit with smaller cells. Therefore, cell wall strength would play an important role in determining the strength of tissue from larger apples (Fig. 7.1). Evidence of the effect of cell size on susceptibility to bruising comes from Patocka *et al.* (1992) who in a between-cultivar study showed that as cells immediately under the skin surface increase in size so does susceptibility to bruising. The potential to manipulate cell size has been identified by Sharples (1968) who found in a UK study of 'Cox's Orange Pippin' orchards that cell number of fruit from different orchards varied considerably. Variation in seed count, spur size, fruit/leaf ratio, mineral nutrition and temperature could explain such differences (Blanpied and Wilde, 1968). Efforts to increase cell number with foliar applications of kinetin or nutritive supplements have not been successful (Martin *et al.* 1964) although since that study, development of other foliar sprays may warrant consideration. To contemplate producing fruit with smaller cells (without reducing fruit mass) to reduce susceptibility to bruising would require further investigation.

Crush strength

The twist test was used to determine if it could be used as an indicator of susceptibility to bruising (Section 3.5). The blade, used in the test, shears and crushes apple tissue and, because bruising is caused by the crushing and shearing of apple tissue, the apparatus appeared to have merit. However, the penetration of the twist blade into the apples creates a tissue shear that is perpendicular to the rows of cells that offer resistance during apple-apple impact. Tissue was then crushed and sheared until complete failure and peak resistance was measured. That the crush strength of cells 3 - 5 mm below the skin was not more strongly related to susceptibility to bruising was surprising. However, it perhaps highlights the importance of the elasticity and strength of apple skin and the thin layer of cells immediately below the surface in determining resistance to bruising.

Firmness

Other researchers have either not found (Klein, 1987), or occasionally found (Johnson and Dover, 1990) a relationship between fruit firmness and bruise susceptibility. In these studies fruit firmness was negatively associated with susceptibility to bruising (pooled data, control trees; 'Granny Smith', r = -0.37; Table 5.10 and 'Royal Gala', r = -0.20; Table 5.14) and reasonably consistently related throughout harvest (Table 5.20). Standardised regression rated firmness and mass of 'Granny Smith' apples equally (standardised variates; firmness, -0.18; mass, 0.18) in contributing to standard impact bruise diameter. Clearly, firmer fruit are less prone to damage than softer fruit.

Starch index and soluble solids

Starch index was positively related to susceptibility to bruising (Table 5.10, 'Granny Smith', r = 0.38; Table 5.14, 'Royal Gala' r = 0.49) but not consistently related as harvests progressed (Table 5.20). Whilst this relationship may be correlated to enhanced ripening and weakening of cell structures it may also be that starch grains provide a within-cell energy absorbing device: disruption of the starch grains at impact may reduce external damage to cell walls. Soluble solids generally increase as starch converts to sugars, that soluble solids was less strongly correlated with susceptibility to bruising ('Granny Smith', $r = 0.18$; 'Royal Gala' no association) than starch, supports this proposition. Further support for this proposition can be gained from the 'Royal Gala' pre-cooling experiment where after 72 h at 20°C both susceptibility to bruising and starch index increased but soluble solids did not change. This may mean that at low levels of maturity the strength of the tissue may rely on starch content as well as cell wall and cell-cell bonds whilst at late maturity only the latter two factors are important in conferring resistance to bruising.

In summary, regression of bruise diameter on other fruit attributes explained only a small proportion the variation in data sets and clearly other factors need to be added before a model with accurate predictive value could be developed. In these studies starch index and soluble solids which represent a "maturity" aspect of the tissue were consistently rated. Firmness rather than crush strength was also entered and gave a "physical strength of tissue" perspective. Possible additions to the model should be "turgor" and perhaps tissue dry matter could provide a "cell structure" perspective. "Mineral contents" would also require inclusion and finally a perspective of "skin strength" should be added. It is therefore proposed that the following equation should explain a large proportion of the variation associated with bruise damage.

Bruise severity = "maturity" + "physical strength of tissue" + "turgor" + " cell structure" + "mineral contents" + "skin strength".

More accurate predictive models would facilitate further research because the effects of manipulating management factors could be more accurately described. Fruit attributes that respond to treatment effects and also reduce susceptibility to bruising could then become the focus of further investigations.

7.5 Harvest and postharvest factors influencing susceptibility to bruising

7.5.1 A conceptual model

Fruit water status and temperature at grading, fruit storage temperatures, storage time after harvest, and duration before pre-cooling are factors that could easily be manipulated to reduce bruise damage. These options arise from the dynamic integration of three factors: rate of fruit water loss, fruit temperature and rate of ripening, all of which must be considered in any discussions on harvest and postharvest susceptibility to bruising and are presented in a conceptual model (Fig. 7.3).

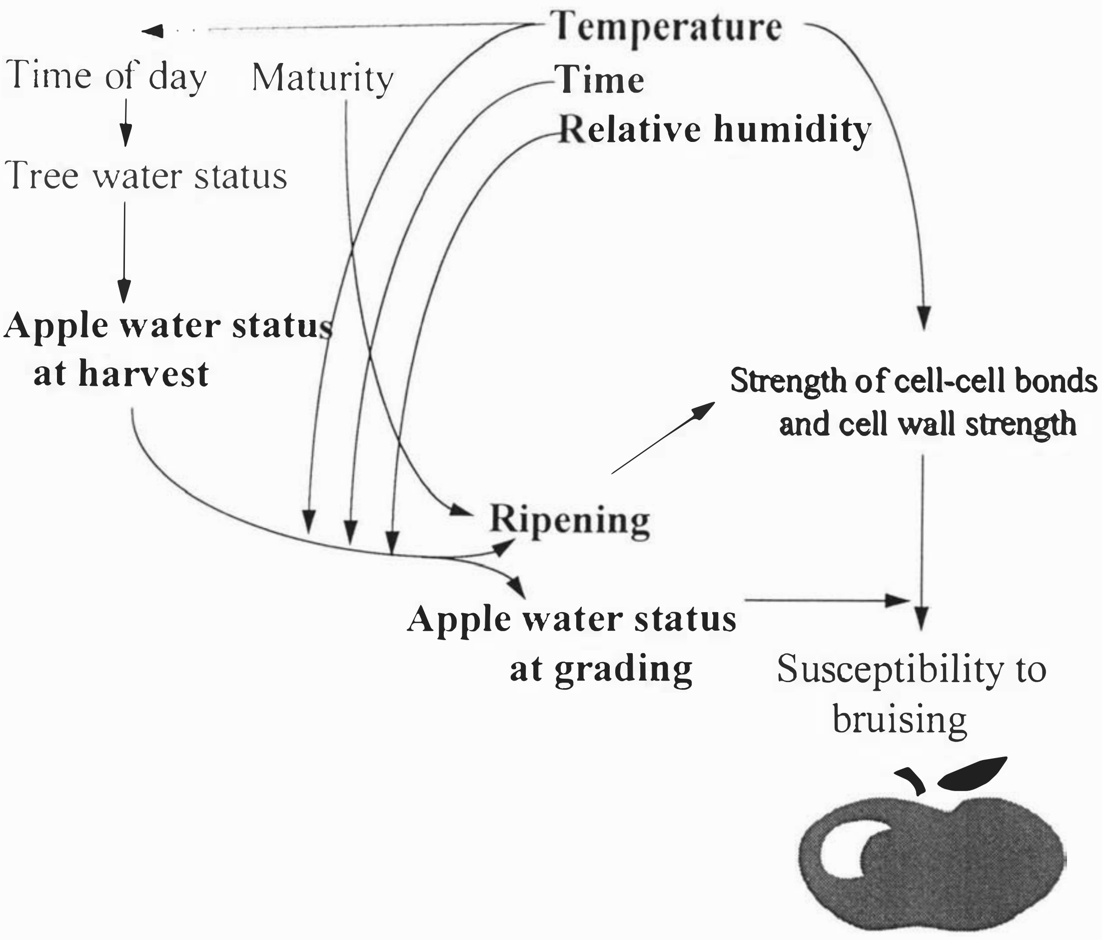


Fig. 7.3 Conceptual model of harvest and postharvest factors that influence susceptibility to bruising.

7.5.1.1 Fruit water status at harvest.

It is proposed that tree water status may influence apple water status at harvest and, as a consequence, influence susceptibility to bruising. If apples of the bruise susceptible cultivar 'Golden Delicious' were harvested early in the morning more bruise damage was incurred than if these fruit were harvested later in the afternoon (Section 2.5.3.4). Increased leaf transpiration rates caused by high afternoon temperatures were deduced to reduce fruit turgor thereby reducing tissue sensitivity to impact damage. In conflict with these results, Garcia *et al.* (1995) who found that non-irrigation of 'Golden Delicious' apples for two weeks prior to harvest did not reduce susceptibility to bruising. It would be reasonable to expect that non-irrigation late in harvest would reduce fruit turgor. However, from this group's data it was not possible to determine climatic conditions prior to harvest or the soil water holding capacity. Either precipitation, high humidity or low temperatures may have reduced tree water demand, conversely soil water reserves may have been sufficient to maintain tree water status and therefore fruit turgor until harvest.

Whilst water status of 'Golden Delicious' apples at harvest was deduced to influence susceptibility to bruising, other less bruise susceptible cultivars may show reduced responses.

7.5.1.2 Temperature

Using a range of techniques to bruise apples, a considerable number of researchers have documented variable effects of temperature on the susceptibility of apples to bruising (Section 2.5.3.5) which can be explained either by the techniques used to impact apples or the duration that fruit were in store. There are three effects which warmer temperatures (20°C) might have on the bruise susceptibility of fruit:

i) increase the limited fluidity of pectin gels that constitute the cell wall
ii) enhance rate of ripening
iii) reduce fruit turgor by increasing evaporation rates.

When 'Granny Smith' apples were graded at 20°C, they were 5% less susceptible to bruising than those graded at 0°C (Table 6.5). It could be argued this reduction was caused by enhanced ripening and/or reduction in turgor, whilst fruit were held at 20°C for 24 h. However, when apples from the bruise susceptible cultivar 'Golden Delicious' were harvested and subjected to 2 h (negligible ripening/turgor effect) temperature treatments, there was a significant influence on bruise diameter (Table 6.4). Also, by harvesting later in the day at warmer temperatures, susceptibility to bruising reduced by 7.3% (Section 6.3.1) when compared to harvesting earlier in the day, although a proportion of this reduction was deduced to result from a reduction in turgor. Further evidence of a temperature effect was obtained by subjecting 'Royal Gala' to bruising after warming and cooling treatments (Table 6.9). Despite a reduction in susceptibility to bruising during the course of the experiment (which would be attributable to enhanced ripening and/or reductions in turgor) susceptibility to bruising increased after fruit were again recooled to 3°C.

A bruising-temperature coefficient (mm diameter / °C; modified from Bourne, 1982; Section 6.3.1) showed that greater reductions in susceptibility of 'Golden Delicious' apples to bruising were evident between the 14-20°C than 0-14 °C. However, 'Granny Smith' apples (Table 6.5) showed a greater change in susceptibility between 0-10°C than 10-20°C. As temperature effects on tissue sensitivity were not linear, the use of a coefficient approach to explain these effects was of limited value. Each cultivar at particular maturities and/or water status would be expected to have a slightly different bruising-temperature curve within the temperature range used in this study (0 to 20°C).

Evidence that the stability of water soluble pectin gels can be influenced by temperature comes from Werner and Frenkel (1978) and provides an explanation for temperature effects found in these studies. Fruit ripening is accompanied by an increase in water soluble pectins and therefore fruit of different maturities may exhibit variable responses to temperature changes. An interesting situation arises if the relationship between calcium levels, pectin gels and temperature is considered. Calcium stabilises cell walls and therefore tissue with high levels of calcium may not experience the increase in fluidity at warmer temperatures when compared to fruit with lower calcium content. There is also the consideration that fruit with higher dry matter content may be less affected by temperature than fruit with lower dry matter content.

In practical terms harvesting the least bruise susceptible fruit (cultivar or maturity stage) early in the day and leaving larger, bruise susceptible fruit for harvest later in the day would be a management option that could be used by orchardists. It is recognised that in certain instances, inclement weather, limited numbers of pickers and packhouse schedules may preclude such considerations. Another opportunity for the industry to use these data to advantage arises from the developing trend for apples to be CA-stored in bins prior to packing either for export or the local market. Although the temperature effect would have to be verified on fruit that had been CA-stored, it may be beneficial if these fruit were rewarmed towards ambient temperature prior to grading. This application may be suitable for local market fruit which are not generally coolstored after packing, but because export fruit are packed into export cartons and coolstored for export shipment there are other quality considerations. Presumably, because short rewarming periods may reduce long term storage life and quality, ENZA requires CA-stored fruit to be packed and returned to coolstore within 12 h. Opportunities for warming fruit within that time period may be limited.

7.5.1.3 Ripening and water status

After harvest, the relative humidity of the store and the time and temperature that fruit are stored at would influence fruit water status which in turn would influence the damage that fruit would incur when subsequently handled (Fig. 7.2). Furthermore, if apples are coolstored in air then cell wall pectins decrease more than if apples are CA-stored (Siddiqui *et al.* 1996) which would also be expected to influence susceptibility to bruising.

Storing ‘Royal Gala’ at ambient temperatures for either 24 or 48 h prior to pre-cooling induced a weight loss of 0.3% which corresponded to a 3.7% reduction in susceptibility to bruising (Section 6.3.6). These data were substantiated by reductions in grader damage incurred by 'Royal Gala' apples after being stored at ambient temperatures for either 24 or 48 h before grading (Table 6.5). Whilst ripening may have progressed in 24 h, the key effect in reducing susceptiblity to bruising would have been a reduction in water status of fruit. This inference may be used to explain reductions in susceptibility to bruising found after short periods at ambient temperatures.

The interaction between ripening and water loss over longer periods is somewhat more complicated and the integration of these factors determines apple tissue sensitivity to impact damage. When stored at 0°C, 'Splendour' apples continued to ripen, had small weight losses and susceptibility to bruising increased (Fig. 6.1). As fruit ripen, esterification of cell wall material reduces wall strength but releases water, respiration also releases water and fruit may also be stored in high humidity. These phenomena may enhance susceptibility to bruising and may explain why numerous workers have reported enhanced or no change in susceptibility to bruising after storage. On the other hand, in slowly ripening fruit, water losses by transpiration as well as losses to the storage environment would be expected to reduce susceptibility to bruising. Lau (1983) found that rapid rather than slow establishment of CA-storage conditions reduced the susceptibility of 'Golden Delicious' apples to bruising which highlights the importance of reduced ripening in storage to reduce susceptiblity to bruise damage. Therefore, important criteria in determining bruise susceptibility of apples after periods in store would be the type and humidity of storage conditions, rate of establishment of CA conditions as well as the period that fruit were in store. Physical attributes of fruit that would also influence water loss would be the permeability of apple skin and the wax layer known to develop on some cultivars.

7.6 Bruise colour

In 1991, between-orchard differences in bruise hue angle were substantial and the variation was largely attributable to orchard location and management inputs. The within-orchard study revealed that between-tree variation in bruise hue angle in 'Royal Gala' was also large. In the 1991 survey, lighter bruise colour was associated with higher fruit nitrogen content. Mosel and Herrmann (1974) found that a nitrogen deficiency could cause an increase in phenolic content and Lea and Beech (1978) found that additions of nitrogen and potassium fertilizer to potted cider trees subsequently increased the phenolic content of cider by 17% when compared to cider made from apples from unfertilised trees. Increasing nitrogen fertiliser applications to decrease bruise visibility appears an attractive option. In this study nitrogen was not associated with increased susceptibility to bruising, however, increased nitrogen content of apples may influence fruit quality (Marcelle, 1995). Boron was not measured in this study but has been associated with the phenolic content of potatoes (Mondy and Munshi, 1993). Through an influence on phenolic content of apples, boron could potentially be linked to bruise colour.

The 'Granny Smith' orchard survey (Table 5.6) identified that there was considerable scope to reduce bruise colour. Apart from manipulation of fruit nitrogen (or perhaps boron) contents, other possibilities to manipulate bruise colour may lie in the investigation of tree cultural practices (Section 7.3.1.7).

7.7 Apple bruising at orchard and packhouse

By combining the effects on susceptibility to bruising found in this study it is possible to obtain an overview on the extent that orchardists may be able to reduce bruise damage. Some effects such as orchard variability cannot yet be utilised to reduce susceptibility to bruising but are included in the model on the assumption that a reasonable proportion of the variation was a result of management practices. It is also recognised that some of the effects listed (Table 7.2) are from different cultivars and would not be strictly additive. For instance, reduced irrigation may reduce fruit water status; and storage for 24 h before grading or pre-cooling may not further reduce susceptibility to bruising for such fruit. As the 24 h delay before grading or pre-cooling duplicate the same effect they are averaged for use in this model. The longest coolstore period in this trial was 17 days where 'Splendour' showed a 4% increase in susceptibility to bruising. Other researchers (Hyde and Ingle, 1968; Klein, 1987) have shown that longer periods in store (11 and 6 weeks respectively) significantly reduce susceptibility to bruising and these data are averaged for use in this model.

Table 7.2 Cumulative effect of manipulating factors identified in this study to influence susceptibility to bruising.

Factor manipulated to influence susceptibility to bruising	Percent increase in bruise diameter	Initial bruise diameter = 12.5 mm
Harvest from most susceptible orchard	6.5%	13.31
Harvest at late maturity rather than early (average of 'Granny Smith' and 'Royal Gala'	13%	15.04
Irrigate all season rather reduce irrigation to a level that does not decrease fruit size	6%	15.94
Harvest early morning rather than later in the afternoon.	7.3%	17.1
Precool immediately after harvest rather wait 24 h	3%	17.51
Coolstore for 6-11 weeks	5%	18.41
Grade coolstored fruit at < 6°C rather than at > 12°C	5%	19.31

By assuming an initial bruise diameter of 12.5 mm, the result of adopting procedures that have been shown in this study to increase susceptibility are calculated as an increase in standard impact bruise diameter.

Notwithstanding the approximate description involved in the model, the cumulative effect of the above procedures was predicted to increase bruise diameter by 54% (6.82 mm). Relating a 54% increase in bruise diameter to grader damage (Fig. 5.2) is not possible because of the limited range in bruise diameter. There is little doubt, even adopting a conservative approach to the relationship between increases in bruise diameter and increases in grader damage, considerable reductions in bruising levels in the industry could be achieved.

7.8 Further work

7.8.1 Representation of bruise severity

Problems associated with using bruise volume as a bruise severity index could perhaps be overcome by using image analysis to trace both the longitudinal and equatorial bisected bruise perimeters with bruise volume being inferred rather than calculated. Increased accuracy of bruise damage measurement would be of considerable value in further research work.

There would also be a need to test the relationship between susceptibility to bruising and handling damage in a wider range of conditions. Different apple growing areas are likely to produce fruit that differ in their susceptibility to bruising and various types of graders will generate varying amounts of apple damage.

7.8.2 Between and within-orchard variability

Elucidation of the management factors that may explain between and within-orchard variability in both susceptibility to bruising and bruise colour would be of considerable benefit. Ideally the model:

Bruise severity = "maturity" + "physical strength of tissue" + "turgor" +
"cell structure" + "mineral contents" + "skin strength".

would be used to measure and determine the effect of several easily manipulated management inputs on susceptibility to bruising. "Turgor" could perhaps be measured by the recently published method of Jobling *et al.* (1997).

7.8.3 Maturity

Orchardists and pickers have preconceived notions on the susceptibility to bruising of certain cultivars at different maturities. Each export cultivar should be impact tested at early, mid and late season so that more accurate bruise susceptibility data can be made available to orchardists. The implications of maturity and fruit mass on bruise susceptibility should be more comprehensively delineated for those cultivars where large or more highly blushed fruit attract incentive payments. Such studies would provide orchardists and ENZA with information that could be used to determine the financial aspects of handling these more valuable fruit.

7.8.4 Temperature

Further studies on the relationship between temperature and susceptibility to bruising (particularly after CA-storage) could identify relationships that may have immediate commercial implications.

7.8.5 Bruise colour

The association between fruit nitrogen levels and bruise colour requires further investigation with a range of cultivars. Methods of application of nitrogen (autumn foliar spray or spring fertiliser application), effect on susceptibility to bruising and storage life as well as the implications of reduced bruise colour may have to consumers would be important considerations.

7.8.6 Cumulative effects

In the calculation of the cumulative effects of reducing susceptibility to bruising identified in this study it was recognised that fruit from different cultivars of variable maturity were used. It would be of considerable value if the cumulative effects of implementing strategies to reduce susceptibility to bruising could be determined using an individual cultivar.

7.9 Conclusions

Overall this NZ study has confirmed that there is scope to manipulate factors to reduce susceptibility to bruising. Preharvest factors that could be manipulated relatively easily are irrigation and maturity at harvest. Harvesting fruit later in the day when fruit are warmer could also be a management strategy to reduce bruise damage. Fruit mineral contents (calcium and phosphorus) were occasionally positively related to susceptibility to bruising but at this stage do not appear to offer opportunities to reduce bruise damage. Apples with higher fruit nitrogen content developed bruise tissue that was lighter in colour than bruise tissue from apples with lower nitrogen content. It appears that increasing nitrogen content of apples may be a simple method to reduce bruise colour in 'Granny Smith' apples.

Postharvest efforts to manipulate susceptibility to bruising were successful and clearly offer potential to orchardists and packhouse managers to reduce bruise damage. Handling fruit at warm temperatures or after storage at ambient temperatures for one day reduced bruise damage.

Small reductions in standard impact bruise diameter were related to large reductions in handling and grader damage which justifies efforts by orchardists and packhouse managers to implement, wherever possible, the strategies to reduce susceptibility to bruising that were identified in this study.

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APPENDIX 1

Circles of increasing diameter (normally on a transparent sheet) used to estimate the size of individual bruises on apples (mm^2).