ANATOMY AND HANDLING OF MACADAMIA NUTS: IMPLICATIONS FOR QUALITY

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B.Sc.(Environmental Science), B. Sc. (Hons.) USC
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December 2005
DECLARATION

I certify that the work presented in this thesis is original, to the best of my knowledge and belief, except where acknowledged in the text.

I certify that the material in this thesis has not been previously submitted, either in whole or in part, for a degree at this or any other university.

David Walton

ABSTRACT

Macadamia (Macadamia integrifolia, M. tetraphylla and hybrids) is a high quality nut with a nutritious, edible kernel. Macadamia is an important horticultural crop in Australia and other countries and Australia is now a world leader in production of macadamia. Research priorities for macadamia have recently shifted from cultural issues to improving quality. Examples of quality issues are insect damage, immature kernels, whole kernel, shoulder damage, weight of pieces, oily and dusty kernels and whether kernels display after-roast-darkening (ARD). The aim of this study was to investigate how kernel ultrastructure, differences in site and season, mechanical dehuskers, delaying harvest, dropping macadamia nut-in-shell (NIS) and the on-farm postharvest handling chain affect kernel quality. The principal quality parameters assessed were roasting quality, oily and dusty kernels, whole kernel, shoulder damage and pieces. Roasting quality was measured by ARD, patchiness of colour and surface damage.

High whole kernel cultivars HV A38 and HAES 835, and low whole kernel cultivars HAES 344 and HAES 741 were examined by TEM and SEM for differences in cuticle structure and morphology at the interface between half kernels. The low whole kernel cultivars had thicker epicuticular wax than the high whole kernel cultivars. Adaxial surfaces of manually separated kernels of HAES 344 and HAES
741 showed less tearing of epicuticular wax, indicating easier separation than for HV A38 and HAES 835.

Nuts were dropped four times from a height of 2 metres onto a bed of NIS at 3% moisture content (MC), 7% MC, 9% MC, 17% MC and 20% MC (controls were not dropped). Over a 2 year study period, NIS dropped at low (3%) and at high (17% or 20%) MC consistently showed significant ARD ($P<0.05$). Nuts dropped at 3% and 7% also displayed significant shoulder damage, oiliness and dust ($P<0.05$). Dropping from 4m onto a metal plate at 20% and 10% also caused significant loss of roasting quality, shoulder damage, oiliness and dust ($P<0.05$). However, dropping did not reduce whole kernel. Significant ARD for high MC dropped kernels (20%) is a particularly important finding as it has long been assumed that nuts at high MC are not prone to damage from handling. Numerous drops from low heights can cause significant loss of macadamia quality. Dropped kernel examined by SEM showed an abraded cuticle, the result of dropping damage. ARD of dropped kernels is probably due to biochemical changes induced by membrane damage and breakdown of cell compartmentation.

Nuts-in-husk were placed on the ground for 3 weeks and 5 weeks in part shade and full shade before dehusking to simulate delayed harvest while controls were dehusked immediately. After 3 weeks delayed harvest, nuts had significant ARD, whole kernel was reduced significantly, and shoulder damage and pieces increased significantly ($P<0.05$). Significant loss of kernel quality can result if harvest is delayed for as little as 3 weeks. ARD of delayed harvest kernels is probably due to the initiation of germination while nuts are on the ground.

Nuts were dehusked by Shaw type or an “Admac” dehusker, and quality was compared with hand dehusking as a control. Nuts were dehusked at high MC (22%)
and intermediate MC (10-11%) after drying under ambient conditions. Nuts mechanically dehusked at both MC suffered significant shoulder damage (P<0.05). Mechanical dehuskers are a major cause of shoulder damage.

Nuts were sampled at five stages in the on-farm handling chain of a commercial macadamia operation from the dehusker to the farmgate. The operation included dropping into 4 silos and a truck. Quality decreased rapidly as nuts progressed along the chain. Significant ARD occurred by the time nuts were dropped into the second silo and significant severe patchiness of colour and severe surface damage were also found (P<0.05). Shoulder damage increased significantly with each drop after Silo 2, and unsound kernel (discolouration and microbial infection) and pieces also increased significantly (P<0.05). Serious loss of quality can occur during on-farm handling of NIS, repeated dropping being a major cause of damage. ARD is probably due to 2 types of biochemical changes, 1) those resulting from the impacts of dropping and 2) those caused by the tendency to germinate at high moisture content in storage silos.

Quality loss in roasted and raw kernel from dropping mandates that the number of drops of NIS be minimised, as even small drops cause significant damage. Easy let-downs to reduce impacts are recommended in all handling equipment and drop heights should be reduced. Delaying harvest reduces kernel quality, therefore nuts should be harvested at intervals of 2 weeks or less. Potential damage from mechanical dehuskers necessitates frequent dehusker adjustment. Whole kernel is chiefly genetically determined, emphasising the importance of cultivar choice. Significant quality can be lost on-farm from excessive dropping and storing nuts too long at high MC. Further research could be conducted into the effect of dropping, delayed harvest and dehuskers on the shelf life of macadamias.
Key Words: Macadamia integrifolia, macadamia, whole kernel, kernel breakage, cuticle, shoulder damage, oily kernels, dusty kernels, after-roast-darkening, delayed harvest, dehusking, dropping impacts, quality changes on-farm

LIST OF PUBLICATIONS ARISING FROM THE THESIS


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ABBREVIATIONS

ABBREVIATIONS OF UNITS

°C  degrees Celsius

g   grams

m   metres

me  milli-equilavents

mL  millilitres

h   hours

OTHER ABBREVIATIONS

aw  water activity

db  dry basis

ERH  equilibrium relative humidity

FFA  free fatty acids

FTICR-MS  Fourier-transform ion cyclotron resonance mass spectrometry

GC  gas chromatography

GCMS  gas chromatography mass spectrometry

HPLC  high performance liquid chromatography

MC  moisture content

NIS  nut-in-shell

PSV  protein storage vacuole

RH  relative humidity

SEM  Scanning Electron Microscopy

TBA  thio barbituric acid

TEM  Transmission Electron Microscopy

TZ  tetrazolium
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CHAPTER 1.
INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction to the thesis

_Macadamia_ F. Muell., (Proteaceae) is cultivated for its edible kernels. Nine macadamia species have been described, with seven occurring in Australia and two in Sulawesi (Douglas, 1995; McDonald and Ismail, 1995). The two commercial macadamia species, _M. integrifolia_ Maiden and Betche and _M. tetraphylla_ L.A.S. Johnson, are both indigenous to coastal rainforests of the east coast of Australia (Gross, 1995). _M. integrifolia_ is characterised by round nuts with a smooth shell, three leaves at each node and leaf margins without spines, and is found between 25.5° and 28.3°S. _M. tetraphylla_ has a slightly more southerly distribution (27.6°-29°S) and is distinguished by spindle shaped, rough shelled nuts, four leaves at each node and serrated, spiny leaf margins (Gross, 1995; Nagao and Hirae, 1992). Both species and their hybrids are grown for food and the mature embryo of macadamia comprises the edible ‘kernel’ (Stroschen, 1986). In this report the name used for the commercial nuts will be ‘macadamia’ because it is recognized common usage, unless context dictates the scientific nomenclature. ‘Nut’ or the commercial term ‘nut-in-shell’ (NIS) will be used to refer to the seed, _i.e._, the seed coat or ‘shell’ containing the embryo, or ‘kernel’.

Macadamia is cultivated mainly in Australia, the USA (Hawaii and California industry) and South Africa. There are also expanding industries in Brazil, Guatemala and Kenya, and smaller industries in New Zealand, Malawi, Paraguay and other countries. World production for 2003-04 was projected to be 93,000 tonnes of nut-in-
shell (NIS), an increase of 11% over 2002-03 (USDA, 2005). In 2003 Australian production was reported as above 10,000 tonnes of kernel (Hargreaves, 2003), while Hawaii produced over 5,000 tonnes (Vidgen, 2003) and South Africa over 3,000 tonnes (Lee, 2003). Current annual value of the Australian crop (both domestic and export markets) is estimated at $120 million, making it one of Australia’s most valuable export horticultural products (Anon., 2005). Although macadamia is an indigenous Australian species, early development of the crop took place in Hawaii. Many of the cultivars in use have been developed in Hawaii by the Hawaii Agricultural Experiment Station (HAES) (Ito, 1983). In Australia, other cultivars have been developed more recently for Australian conditions (Bell and Bell, 1987). Macadamia cultivars are primarily propagated by grafting, and all scions within a cultivar have the same genotype.

There has been much research conducted on cultural issues for macadamia, e.g., Stephenson and Gallagher (1986a, b; 1990a, b; 2000), Stephenson et al. (1996; 1997; 2000), Trueman and Turnbull (1994a, b), Wallace et al., (1996), Trueman et al. (2000, 2002), Trueman, (2003a, b). Much research in recent years has focussed on improving the quality of the kernel in response to increasing worldwide production and market competition, e.g., Mason et al. (1995, 1998, 2004). Quality involves many issues such as appearance, texture, flavour and shelf life (Kramer, 1972). One aspect of appearance is whether kernels are whole or broken into halves, that is, whether the embryo has separated into two cotyledons. Whole kernel on average is worth 12% more than halves (Twentyman, pers. comm.), and whole kernel is likely to be a more important quality issue as production increases. It is not known whether breakage is related to kernel anatomy and whether it varies with site or season. Another issue is
whether the dehusking machines necessary for removing the fibrous husk of macadamia affect quality. A further problem is that macadamia NIS is dropped many times after harvest, and the effect of impacts from dropping is unclear. During the harvest season abscised nuts may lay on the ground for varying periods of time such as from one week to eight weeks awaiting harvest. This delay in dehusking and drying is known to affect some aspects of quality after one month (Mason and Wells, 1984) but the effect on quality of shorter delays is unknown. On roasting, some kernels assume an excessively dark appearance, a condition known as After Roast Darkening (ARD). The effect of dehuskers, dropping of NIS and delayed harvest on the quality of roasted kernel, particularly ARD, is largely unknown. This thesis will detail experiments conducted to provide more information on these aspects of macadamia quality that can be applied to improve quality.

Previous reviews have focused on such issues as cultivation (Cavaletto, 1983; Nagao and Hirae, 1992) and physiology of macadamia (Nagao and Hirae, 1992; Himstedt, 2002; Huett, 2004). There is a need to understand the factors that impact on quality. An increasingly important quality and marketing issue for the macadamia industry as production increases is maintaining high levels of whole kernel. Macadamia nuts are subjected to many impacts and stresses in postharvest procedures and there is concern over excessive browning when kernels are roasted. More information is needed on issues such as how kernel (embryo) structure is related to whole kernel and quality, and how postharvest handling procedures such as dehusking fruit and dropping nuts affect quality including roasting quality. This review of the literature will examine how macadamia nut development and structure, handling methods, nut chemistry, drying, roasting and ARD relate to kernel quality.
1.2. Literature Review: Development, Structure and Quality of Macadamias

1.2.1. Classification of the macadamia fruit

There has been some dispute over the correct classification of the macadamia fruit. It is popularly called a ‘nut’ and it has in the past been described as a drupe or a nut (Stroschen, 1986). However, while ‘nut’ is popular terminology, the macadamia fruit is not a nut. A nut is a dry indehiscent fruit while the macadamia fruit is dehiscent (Stroschen, 1986). The mistake of classifying macadamia fruit as a drupe no doubt came about by botanists mistaking the unusually hard, thick shell of the seed for the stone of a drupe and identifying the seed coat as the endocarp (Hartung and Storey, 1939). A follicle is defined as ‘a simple, dry dehiscent fruit, with one carpel, splitting along one suture’ (Rost et al., 1998). The dry pericarp of the macadamia fruit dehisces and splits along the suture of the pericarp (Figure 1.2 B). Therefore the macadamia fruit is correctly classified as a follicle (Francis, 1928; Hartung and Storey, 1939; Joubert, 1986; Strohschen, 1986). The ‘nut’ contained in the pericarp is a true seed, with seed coat, hilum and micropyle (Hartung and Storey, 1939). For practical purposes, however, the popular nomenclature ‘nut’ will be used in this review to refer to the hard seed of macadamia. The term ‘kernel’ will be used to refer to the commercial, edible embryo unless referring to anatomy, when ‘embryo’ will be used.

1.2.2. Fruit development and embryo structure

The ovary of macadamia contains two orthotropous ovules at anthesis (Stroschen, 1986). The ovary contains two suspended, sessile orthotropous ovules on the margins of its ventral suture (Hartung and Storey, 1939). The ovules develop on either margin of the suture and protrude into the ovarian cavity (Hartung and Storey, 1939). They are attached near the ovary apex (Francis, 1928). At anthesis the ovary wall is
composed of parenchymatous tissue and has an outer and inner one-layered epidermis (Stroschen, 1986). In some ovaries the epidermis is partly replaced with a periderm, while a main vascular system develops within the middle of the fruit wall (Stroschen, 1986). Division of the zygote takes place 4-5 weeks following anthesis (Sedgley, 1981; Nagao and Hirae, 1992, Figure 1.1).

Both ovules increase in size following anthesis, but one more than the other (Sedgley, 1981). Growth occurs in all tissues in both ovules, particularly the nucellus and outer integument, the latter developing vascular bundles (Sedgley, 1981). Shortly after anthesis the integuments surround the nucellus incompletely and a true micropyle is not formed (Stroschen, 1986), however, both integuments proliferate towards the micropylar end of the ovule (Sedgley, 1981). Both integuments increase in length so that at 10-11 weeks after anthesis they completely surround the nucellus and a true micropyle is formed (Stroschen, 1986).

Although the two ovules appear to be alike in every respect until the time of fertilization (Hartung and Storey, 1939), in almost all cases only the larger of the two ovules is fertilized (Sedgley, 1981). However fertilization of only one ovule is not mandatory, as sometimes both ovules are fertilized, resulting in two hemispherical fruits (Francis, 1928). While such fruits often contain sound kernel, their shape predisposes the contents to severe damage during processing and this trait has been greatly reduced by cultivar selection (McConachie, pers. comm., 2000). Fertilization of one ovule seems to suppress fertilization of the other, preventing either pollen tube penetration, sperm cell release or syngamy, despite no anatomical differences between the ovules other than size (Sedgley, 1981).

One of the two ovules of the macadamia ovary usually aborts during early fruit development (Stroschen, 1986). This is similar to almond, where only one ovule
develops (Hawker and Buttrose, 1980). The aborted ovule in *Macadamia* may be found clinging to the inner layer of the mesocarp or the seed (Hartung and Storey, 1939). At about 4 weeks following anthesis the embryo sac of the smaller ovule may be clearly visible but shortly thereafter is crushed by the developing larger ovule (Sedgley, 1981).

Stroschen (1986) believed that fruit enlargement is virtually completed by about 20 weeks. Other authors consider the total length of the fruit growth period from anthesis for macadamia to be between 25 and 31 weeks (Joubert, 1986). This difference is probably related to using different criteria for defining stages of development. Fruit diameter of macadamia increases rapidly at 2-3 weeks after anthesis and this rapid growth continues until approximately 12-15 weeks (Nagao and Hirae, 1992, Figure 1.1). Fresh fruit weight increase follows a simple sigmoid curve, with rapid weight increase occurring at 5 to 6 weeks after anthesis and continuing until reaching a maximum at 18 weeks (Sakai and Nagao, 1984, Figure 1.1). Sakai and Nagao (1984) agree with Stroschen (1986) on this period of 20 weeks for maximum fruit enlargement. While they found that maximum fruit diameter occurred at 14-16 weeks, maximum fresh weight was attained at 18 weeks, and no further weight increase occurred (Sakai and Nagao, 1984). A similar time scale was also identified by McConchie *et al.* (1996) who found that maximum wet and dry weights were achieved by 21 weeks. By contrast almond takes only 12 weeks to reach full weight (Hawker and Buttrose, 1980).
The relationship between embryo and endosperm development and nutrition is very important for macadamia crop production. The route of entry of nutrients into macadamia to nourish the embryo is poorly understood, but Sedgley (1981) suggested some possibilities. She hypothesised that projections and thickenings of the embryo sac, synergid (persistent) and embryo wall may increase the area of cell wall across which nutrients can pass into the embryo sac. In almond, well developed vascular tissue in the testa is an important path for nutrient transport (Hawker and Buttrose, 1980)

**Endosperm and embryo development**

Following fertilization, cells in the chalazal region become meristematic and produce a massive nucellus tissue (Stroschen, 1986). By about 11 weeks after anthesis the expanding embryo sac fills the cavity left by the breakdown of older, highly

\[\text{Fig. 1.1. Growth and development of macadamia fruits. Source: Nagao and Hirae (1992)}\]
cytoplasmic cells (Stroschen, 1986). At this time also a hypostase begins to form between the chalaza and the cavity, gradually developing into a massive cell block (Stroschen, 1986). The embryo sac exhibits protuberances in this area, possibly the nutritive tissue referred to above (Stroschen, 1986). Endosperm cell formation begins at about 4 to 8 weeks after anthesis (Hartung and Storey, 1939; Sedgley, 1981). A free nucleate endosperm is formed at first as division of the endosperm nucleus precedes the division of the zygote nucleus, the latter occurring at 4-5 weeks (Sedgley, 1981). From 8 weeks (Hartung and Storey, 1939) to about 10-11 weeks after anthesis (Stroschen, 1986) the free nuclear endosperm becomes cellular. Cellular endosperm gradually extends from the upper end of the ovule through the vacuolar space towards the chalazal region and by 12 weeks only a small amount of free nuclear endosperm remains (Stroschen, 1986). The embryo is subglobose, while the cotyledons are semiglobose and large (Francis, 1928). The radicle and plumule form a small, subglobose unit whose acuminate lower end extends into the micropyle (Francis, 1928).

Two massive cotyledons are produced (Stroschen, 1986) and the embryo unit is inserted between the cotyledons (Francis, 1928). Francis (1928) does not include the cotyledons in the embryo in this description, but Stroschen (1986) properly includes the cotyledons in the term embryo. The expanding embryo fills most of this cavity by about 11 weeks following anthesis and at 12 weeks, only a small amount of free nuclear endosperm remains in the basal part of the ovule (Stroschen, 1986). By contrast, the endosperm of pecan (Carya illinoensis) has attained maximum proportions at the time of shell hardening, about 14 to 16 weeks after fertilization (Haulik and Holtzhausen, 1988). At 12-13 weeks a cuticle can be observed between the outer and inner integuments of the macadamia embryo (Stroschen, 1986).
The reduction of fruit expansion at 15 weeks corresponds with the hardening of the seed coat (Nagao and Hirae, 1992, Figure 1.1). By around 20 weeks after anthesis, the cellular endosperm is completely replaced by the cotyledons (Hartung and Storey, 1939). Basal lobes are produced where the young plant body is attached to the cotyledons, enveloping the radicle (Stroschen, 1986). Most of the growth of the embryo takes place in the 13 weeks after flowering (Jones, 1939, Figure 1.1). The macadamia mature embryo, consisting mainly of large cotyledons, constitutes the edible macadamia kernel and is the main focus of the research reported in this thesis. The growth and structure of the macadamia embryo until 20 weeks after anthesis are well understood, as is growth until maturity at 33 weeks. However, the structure of the mature embryo (kernel) and how this affects quality has not previously been investigated. The ultrastructure of macadamia and how anatomy of the embryo relates to quality are investigated in Chapter 2 of this thesis.

**Husk development**

The characteristic resilient, dense nature of the husk of macadamia (Figure 1.2.A) results from its fibre content. At anthesis the ovary wall consists of parenchymatous tissue with an outer and inner epidermis (Stroschen, 1986). A main vascular system develops in the middle part of the fruit wall, which branches toward the periphery of the ovary wall 4-5 weeks after anthesis (Hartung and Storey, 1939; Stroschen, 1986). Cells in both the inner and outer part of this parenchymatous complex exhibit dark staining cell contents, which are probably tannins (Francis, 1928; Hartung and Storey, 1939). The vascular elements of the ovary wall become capped with fibre cells at about 14 weeks after anthesis, resulting in a fibrous outer mesocarp complex (Stroschen, 1986). Most of the dry weight of the husk is achieved by this time (McConchie et al., 1996). The inner epidermis does not differentiate as the ovary
develops, but disintegrates shortly before maturity with the result that an endocarp does not form (Stroschen, 1986). This contradicts Atwell et al. (1999) who describe the hard macadamia shell as an endocarp.

The inner part of the fruit wall has a soft inner layer with a typically pale appearance and remains soft due to its parenchymatous origin and nature (Stroschen, 1986). Adjacent to the loculus, these cells become smaller, resulting in a compact tissue lining the fruit cavity, and at maturity the fibrous, horny nature of the pericarp is revealed as it dries and splits along the single suture (Figure 1.1.B). The husk does not dehisce until after abscission in most cultivars (Stroschen, 1986; Trueman et al., 2000). This suture would appear to relate to the single suture of the carpel (Hartung and Storey, 1939). This split confirms the dehiscent nature of the Macadamia fruit, an important feature for classification of the fruit as a follicle (Stroschen, 1986). The husk (pericarp) of the macadamia fruit is described as fibrous and horny (Cavaletto, 1983; Stroschen, 1986) and must be removed after harvest. The nature of the husk necessitates considerable mechanical force for husk removal, an operation that may cause damage to kernel. In addition, delays in harvesting abscised fruits leads to drying and increased toughness of the husk, making dehusking more difficult. The effect of mechanical dehuskers on macadamia quality is investigated in Chapter 5 of this thesis.

**Testa (shell) development**

The hard testa or shell (Figure 1.2.B) is composed of the integument of the fertilized, mature ovule (Francis, 1928). In unimproved cultivars the most prominent feature of the fruit is the extraordinary development of the testa, which can be as thick as 5mm (Francis, 1928). In early development of the fruit, both ovules have outer and inner integuments, though at this stage these do not enclose the nucellus sufficiently to
form a micropyle (Sedgely, 1981; Stroschen, 1986). The outer integument achieves extreme thickness due to cell divisions and branching of the vascular system (Stroschen, 1986). At 10-12 weeks after anthesis the nucellus is completely surrounded due to continued growth of both integuments and at this stage a micropyle is formed (Stroschen, 1986). This occurs at a time when the embryo is differentiating to form cotyledons and the embryonic axis is developing (Hartung and Storey, 1939). At this time, cells in the inner epidermis of the outer integument become meristematic and a tissue 5-7 layers thick is produced, however, this is reduced to one layer in the region of the micropyle (Stroschen, 1986). It is this activity which produces the distinctive enamel-like layer of the testa (Hartung and Storey, 1939; Stroschen, 1986). Francis (1928) identified crystals of calcium oxalate in these cells. Similar accumulation of calcium oxalate has been described as a regular process in spruce seeds belonging to maturation and defense mechanisms (Tillman-Sutclia and Kauppi, 1999). The function of the calcium oxalate in macadamia may be to protect the embryonic axis region. Mature embryos tend to cling to this enamelled area, possibly due to the presence of the vestigial inner seed coat (Hartung and Storey, 1939). This adhesion to the enamelled area may be the major cause of ‘shoulder damage’ in macadamia.

The inner integument completely disintegrates apart from a few lignified remnants of cells in the chalazal region and at this opposite, chalazal end of the nut the shell of macadamia is lined with small, flattened, slightly lignified cells which are dark-staining, giving this region its smooth, brown layer (Stroschen, 1986). It is not clear whether this brown layer is also derived from the inner epidermis of the outer integument, however, Francis (1928) termed these two layers the tegmen, or inner
seed coat. These contrasting layers produce the characteristic bi-coloured internal appearance of macadamia testa (Figure 1.2.C).

![Image of mature Macadamia fruit morphology]

**Fig. 1.2** Mature *Macadamia* fruit morphology  
**A.** Raceme of *Macadamia* fruit showing green pericarp.  
**B.** Left to right: dehiscent fruit; seed (‘nut’), h, hilum; m, seed micropyle (white dot at bottom of seed); s, suture between hilum and micropyle.  
**C.** Clockwise: seed in pericarp (‘husk’); pericarp interior with tannin coated endocarp; open testa (‘shell’) showing enamel layer on inner surface of testa, m, micropyle at enamel end; h, hilum at opposite end; embryo in position in testa with cotyledon apex extending towards micropyle (m).

The outer integument continues to elongate quickly and at about 20 weeks post anthesis it overgrows the inner integument, which at this stage is disintegrating. At this time the inner integument is virtually non-existent (Stroschen, 1986). This means that in macadamia, the testa is derived from the outer integument only. Initial increase in fruit dry weight is due mainly to rapid increase in testa weight (McConchie *et al.*, 1996). Reduction of rapid growth of the fruit at about 15 weeks coincides with hardening of the outer integuments (Stephenson and Gallagher, 1986b). The hilum is
lateral, and located towards the apex of the seed. It joins the pericarp near its suture adjacent to the stylar end (Francis, 1928). The micropyle is found towards the opposite end of the seed (Figure 1.1.C). The testa is thinner along a line joining the micropyle and the hilum, and the micropyle is highlighted by a trace of white enamel protruding from it (Francis 1928; Figure 1.1.B). In this way the micropylar plug is formed from the material of the white enamel layer, which is derived from the inner epidermis of the outer integument (Stroschen, 1998). A natural fissure or suture exists along the line joining the hilum and micropyle.

**Testa structure and properties**

The tissue of the testa, the exterior of which can be seen in Figure 1.2.B and C, consists of sclerenchyma tissue interspersed with occasional vascular bundles (Francis, 1928). The sclerenchymatous tissue contains thick-walled stone cells of different sizes and shapes (Stroschen, 1986). The nuclei in these cells have disintegrated leaving spaces (Hartung and Storey, 1939).

A number of researchers have examined macadamia nut shell, both because of the crop’s economic importance and because of the engineering challenge presented by this unique seed (Jennings and Macmillan, 1986; Chun-Hui and Yiu-Wing, 1994/1995). The shell has very interesting microstructure and mechanical properties. It is similar to woods in general, a cellular solid with relatively low density and high strength (Chun-Hui and Yiu-Wing, 1994/1995). However, the macadamia nut shell is different in that it is reasonably isotropic and uniform, whereas the common features of various woods are highly anisotropic (Chun-Hui and Yiu-Wing, 1994/1995). The cells in woods can be considered two-dimensional, with cells elongated parallel to the trunk, and greatest strength in the axial direction. In macadamia shell, the cells are in the three-dimensional category, and have random orientation (Chun-Hui and Yiu-Wing, 1994/1995). This structure gives macadamia shell impressive properties when compared with man-made materials. Shells have about the same hardness as annealed,
commercial purity aluminium, which has almost exactly twice the density of macadamia shell, and are stronger in tension than concrete (Jennings and Macmillan, 1986).

These testa features help explain a number of important characteristics of macadamia. First, the nuts are very difficult to crack, and extraction of kernels requires considerable force. Second, the testa is an effective protector of the embryo from predation and damage under natural conditions although insects and rodents may penetrate it at some stages (Jennings and Macmillan, 1986). It is not known if this hard, unyielding testa is a cause of damage to the kernel during impacts.

If the suture of the testa is considered a meridian, the wall thickness is not uniform, but thicker near the two poles and thinner at the equator (Chun-Hui and Yiu-Wing, 1994/1995). The cells of the shell are nearly hollow with an inner core of rods, presumably of lignin, the rods being loosened from the cell walls and thus providing space in the cell. This structure is a factor controlling the tensile strength of the nutshell and so influencing fracture (Chun-Hui and Yiu-Wing, 1994/1995). The near-hollow cells also toughen the material by allowing a certain degree of stress relaxation and redistribution at the fracture tip and in addition, large cavities affect the material’s strength, increasing fracture toughness (Chun-Hui and Yiu-Wing, 1994/1995). All these properties will influence the cracking properties of the nutshell. Also, the thinning of the shell near the suture line creates a weak zone (Chun-Hui and Yiu-Wing, 1994/1995; Braga et al., 1999). The fairly uniform cell structure and thinning at the equator influence difficulty of cracking, and makes Position 3 (Figure 1.3) the most efficient cracking orientation. The suture line makes Position 1 (Figure 1.3) the next best, while the nut has maximum strength in Position 2 (Figure 1.3), in line with the equatorial axis (Braga et al., 1999). Nuts can be oriented in Position 3 during hand
cracking, but the random nature of mechanical cracking does not allow this. Therefore the extremely tough shell of macadamia nuts requires application of considerable force to the nut during commercial cracking with risk of kernel damage.

![Diagram of Macadamia Nut Cracking Orientations](image)

**Fig. 1.3.** Three possible orientations for cracking *Macadamia* nuts (Source: Braga *et al.*, 1999). The hilum is considered the North pole, orientation 2 is in the equatorial plane.

*Embryo maturation*

Embryo maturation, the final stage of macadamia fruit development, commences approximately 13 weeks before final maturity (Stroschen, 1986; McConchie *et al.*, 1996). Fruit are variously considered mature at 28 to 30 weeks (Sakai and Nagao, 1984), 30.5 to 33 weeks (Jones, 1937) and 33 weeks (McConchie *et al.*, 1996). Large quantities of oil are stored in the expanded cotyledons, reaching a level as high as 80% (Jones and Shaw, 1943; McConchie *et al.*, 1996; Trueman *et al.*, 2000). This period of oil formation appears to be associated with the time of hardening of the testa (Jones, 1937). The macadamia is the highest oil-yielding ‘nut’ on the market (Stroschen, 1986). The oil content of the kernel is very important commercially as it is
often equated with edible nut quality (Joubert, 1986; Nagao and Hirae, 1992). Oleic acid is the predominant fatty acid (c.60%), with smaller quantities of palmitoleic (c.22%), palmitic (c.9%), stearic (c.2%) and linoleic (c.2%) acids (Jones, 1937; Saleeb et al., 1973).

Oil is contained in all cells of the embryo (Francis, 1928). However, this anabolic process of oil formation does not result in an increase in overall weight, with weights at 16 weeks and at maturity at 33 weeks being almost identical (McConchie et al., 1996). Oil accumulation of macadamia kernels is accomplished well before abscission in cultivars HV A16, HAES 344 and HAES 246 (Trueman et al., 2000), confirming previous findings for HV A16 (McConchie et al. (1996) and for HAES 246, HAES 508, H2, Own Choice and Shimke (Baigent, 1983). Maximum mean nut oil content of 3.1g for HV A16 was reached by 23 weeks after anthesis, well before abscission at 33 weeks (McConchie et al., 1996). Little oil was stored in macadamia seeds for the first 90 days after flowering, followed by a 70 day period of rapid oil formation (Jones, 1937; Jones and Shaw, 1943). Early work by Jones (1937) also reported that during the final 70 days before abscission little oil is stored. By contrast, the lack of oil formation in the final 10 weeks on the tree (weeks 23 to 33) is questioned by Nagao and Hirae (1992), who maintain oil content reaches only 67% by week 30, although no cultivars are identified. The possibility that macadamias are mature for the final 10 weeks on the tree may suggest that there is room for intervention to harvest fruit by some means before they begin to naturally abscise to spread the harvest and reduce time of nuts on the ground (Cavaletto et al., 1972).

Jones (1939) observed that for some trees, oil content of ground-harvested nuts declined and reducing sugars increased just before harvest. This may have been due to the nuts beginning germination while on the ground (Jones, 1939). It is even possible
for nuts to begin to germinate on the tree (Jones, 1939). The possibility of germination raises important questions regarding roasting quality as increased reducing sugars are one of the reactants required for nonenzymatic browning of heated foods. This matter is discussed in Chapter 5 of this thesis.

**Halves and wholes**

Cotyledon separation results in the problem of reduced whole kernel percentage recovery. The ultimate causes of this kernel breakage are unclear, however, Wallace et al. (2001) demonstrated that the tendency to remain whole is clearly genetic, that is, related to cultivar. There may be some anatomical differences between cultivars influencing breakage. In some cultivars, for example, HAES 741 and HAES 344, the cotyledons separate much more readily than others (Stephenson and Gallagher, 2000). Wallace et al. (2001) demonstrated some differences between the cuticles of the high-whole cultivar HAES 835 and low-whole cultivar HAES 741. They recommended that further research was necessary to confirm these differences and clarify their relationship to whole kernel and breakage.

### 1.3. Aspects of macadamia quality

#### 1.3.1. What is quality?

The macadamia has achieved a reputation as one of the most highly regarded nuts in the world (Nagao and Hirae, 1992), and the roasted kernels of macadamia are considered by many to possess the finest flavours of all the confectionery nuts (Crain and Tang, 1975). In addition, recent studies have emphasised the healthful qualities of the food due to the high content of monounsaturated oil (Ako et al., 1995). Rapidly increasing production of macadamia kernel is shifting emphasis from improving yield to improving quality of product (Swanepoel, 1998). Defining nut quality is an important starting point for a discussion of quality. Quality has been described as the
combination of all the characteristics that give the product value or “a degree of excellence” (Cavaletto, 1981). Others have reviewed quality standards and methods from around the world for hazelnuts and their report illustrates the complexity and difficulty of assessing quality of an edible nut (Riedl and Mohr, 1979).

The macadamia industry has developed various indicators of quality. Sampling procedures have been developed to assess quality in macadamia orchards: 1) husk dry weight, 2) shell and kernel (NIS) dry weight, 3) kernel recovery (the percentage of kernel to NIS weight) and 4) specific gravity, from which oil content can be estimated (Ripperton et al., 1938; Meyers et al., 1999). Oil content is used widely by industry as an indicator of quality (Joubert, 1986; Nagao and Hirae, 1992). To the consumer, knowledge of the health benefits of macadamia oil as well as the total oil content could be an important aspect of quality influencing choice (Ako et al., 1995). While the assessments of quality above are useful to production, ultimately quality is the way the consumer perceives the product (Cavaletto, 1981). Some quality characteristics of macadamia are: 1) kernel size and shape, 2) kernel wholeness, 3) oil content, 4) kernel colour and 5) flavour (Cavaletto, 1981). Texture could be added to this list. Quality determines the degree of acceptability of a product and influences the decision of the purchaser (Erickson, 1994). Most of these parameters relate to appearance, one to taste, and another (oil content) indirectly to taste. However, acceptance of a food depends upon total appearance (Hutchings, 1994). Quality is a mix of many features, summarised by Kramer (1972) in three categories, 1) appearance, 2), flavour and 3), kinesthetics. The meaning of kinesthetics in this context is primarily texture, but many characteristics of quality overlap in a complex manner (Kramer, 1972; Figure 1.4).
There is a degree of subjectivity to some parameters of quality, e.g., appearance, flavour and texture. For pecans, attempts have been made to correlate sensory evaluation of nuts with objective chemical assessment (Forbus et al., 1980).

Evaluation of sensory attributes of quality should be carried out in a structured manner by trained sensory panels (Erickson, 1994). Sensory evaluation of quality can then be correlated with chemical measurements. Efforts have been made to correlate undesirable flavours of hazelnuts with analysis of volatile oxidation components by gas chromatography (Kinderlerer and Johnson, 1992).

There are various factors impacting on macadamia kernel quality, both physical and chemical. Hazelnuts, like macadamias, have a hard shell which must be removed by mechanical means. The drying process necessary to aid cracking also predisposes the delicate tip of the nut to breakage (Riedl and Mohr, 1979). Macadamias are very similar, needing drying to aid cracking and having a pointed,
vulnerable end. This is a possible site for damage and chemical and microbial degradation as well as loss of product and visual appeal. Chemical changes can occur because of storage time and/or conditions, impacting on flavour and palatability. Little is known about how delaying harvest affects quality, and how postharvest handling practices such as dehusking, dropping and delayed harvesting of macadamias affect quality, including the quality of roasted kernels. This review will examine the literature available on these subjects.

1.3.2. Dehuskers and macadamia quality

The fibrous pericarp (husk) of the macadamia fruit makes up as much as 40-45% of the fruit weight (Cavaletto, 1983). It is necessary to dehusk macadamias within 24 hours of harvest to avoid heat accumulation due to respiration (Cavaletto, 1983). This is an essential element of postharvest treatment of macadamias and yet there is very little literature on the effects of dehuskers on quality. The challenge is to design a dehusker which will remove the husk from fruit of variable size and moisture content with a minimum number of unhusked fruit and without cracking an unacceptable number of nuts (Luan and Ling, 1983).

Dehuskers should be adjusted to minimise damage to the kernel such as bruising (Mason, 1983a). Macadamia nut dehuskers use various methods to fracture and remove the husk, such as: impact by a blade; a rubbing action between two rough surfaces such as a rubber sheet and steel spiral roller; and passing between a spiral roller and circular blades (Luan and Liang, 1983). Nuts entering the ‘Shaw’ type dehusker pass between a steel spiral roller and small, spring-loaded adjustable, interconnected plates. The ‘Admac’ dehusker rubs the nuts between a rubber-coated spiral auger rotating in a rubber-lined cylinder. The stresses involved in dehusking
may cause damage to the kernel, and compression experienced during dehusking could be a cause of cell damage (Roudot et al. 1991).

The effect of dehusking appears to be variable and related to cultivar. Wallace et al. (2001) found no difference in whole kernel between three dehuskers in two experiments comparing five cultivars (HAES 835, HV A16, HAES 842, HAES 344 and HAES 741). However in a third trial using only cultivar HAES 246, the Shaw type dehusker caused significantly more damage than hand dehusking (Wallace et al., 2001). There is some macadamia industry opinion that there may be differences in the effect of dehuskers on whole kernel and damage at different times of the harvest season (McConachie; Pearce, pers. comm.), but this has never been tested. It is possible that dehusking at field MC causes only minimal damage to kernel due to the high moisture content of the nut and high cell turgor pressure (Pearce, pers. comm.), but this also has not been tested. This hypothesis is not supported by Pitt and Chen (1983) who predict from a model that failure of vegetative tissue occurs at a significantly lower strain rate with more turgid samples. Stress is a term referring to the force on a body tending to cause it to deform, while strain is a measure of the extent to which a body is deformed when it is subjected to as stress. High cell turgidity significantly weakens vegetative tissue, apparently because cell walls are already in a pre-stressed state before any external loads are applied (Pitt and Chen, 1983). Therefore greater bruising could be expected in handling highly turgid products (Pitt and Chen, 1983). By contrast, some fruit harvested from the ground weeks after abscission may have dry, hard husks which are more difficult to remove. This may predispose the nuts to damage from mechanical dehusking due to greater difficulty removing husk. An oily appearance of macadamia kernel has been noted in some samples of kernel stored for some time by processors (Wallace et al., 2001).
This may be due to escape of oil from cells due to strain imposed during dehusking and handling. This may be explained by damage to cells with subsequent release of oil from cell oil bodies. Comparatively little attention has been paid to the effects on quality of this important postharvest procedure for macadamias. The effect of dehuskers on quality, including at roasting, will be examined in Chapter 5.

1.3.3. Handling damage to macadamia

1.3.3.1. Introduction

The effect of physical damage due to handling has been a concern for many crops including peanut (Turner et al., 1967), navy beans (Hoki and Picket, 1973, Bartsch et al., 1986), pea bean (Perry and Hall, 1966), and various common seed grains (Bilanski, 1966). However, there have been few studies focusing on physical damage to macadamia kernels due to handling practices. Most research to date has involved cultural, post-harvest and microbiological studies. Between harvest and cracking, NIS is subjected to many physical stresses. These include dehusking of the nut, elevation and drops into various containers and conveyors for harvesting, drying, transport and processing. The increase in damage caused by individual handling operations may be small and difficult to measure (Perry and Hall, 1966).

While the Industry Code of Sound Practice recommends that drop heights be no more than 2m (Anon. a, 1992), that height is often exceeded and drops into silos and trucks of 4 to 5 metres are common (McConachie, pers. comm.). In addition, this recommendation takes no account of the effect of repeated drops from a moderate height such as 2m. Roudot et al. (1991) predicted from a model developed from apple tissue that two different types of damage are possible to plant tissue under stress: 1), collapse of cells is more likely during impact to tissue and 2), cell displacement during compression. Compression could be expected to occur during dehusking while
impact results from handling processes. Quality of macadamias can be reduced in a number of ways, e.g., loss of whole kernel, shoulder damage, production of pieces, and bruising. How dropping macadamia NIS may affect these factors has not been adequately determined.

1.3.3.2. Loss of whole kernel

The macadamia embryo (kernel) consists of two large cotyledons and these may separate during postharvest handling and processing. Whole kernel refers to the number or weight of kernels which remain whole during handling. While limited work has been conducted on the effect of dehuskers on whole kernel loss (Wallace et al., 2001), little is known about the effect of other types of physical impact on whole kernel yield.

1.3.3.3. Shoulder damage

Shoulder damage is a term used to describe torn areas on the micropylar hemisphere of the kernel which are caused by tissue adhering to the shell inner surface (Fig. 1.5). Drying causes shrinkage of the kernel leaving an air gap around the kernel. This is considered desirable, as it leaves room for deformation of the shell during cracking with minimal kernel damage (Cavaletto, 1983; Kowitz et al., 1996). Impact may cause the kernel to break away from the shell causing tearing of the kernel where it is often strongly attached in the apical (‘shoulder’) region (Cavaletto, 1979).
While the causes of shoulder damage are not completely clear, some macadamia kernels adhere strongly to the white, enamelled region of the shell (Hartung and Storey, 1939; Cavaletto, 1986). Shoulder damage appears to occur when the attached kernel tears away during posharvest procedures, leaving a lesion. Shoulder damage is proof of tissue damage and cell damage. It also involves economic loss in two possible ways, 1) total loss as tissue adhering to the shell and discarded with the shell (Liang, 1977), or 2) reduction in value when torn sections separate from the shell and contribute to pieces. It may also have less obvious economic consequences by causing buyer resistance to a less visually attractive product, and as a site for possible lipid oxidation (Burton, pers. comm.). At the site of shoulder damage, the kernel has lost its protective cuticle and therefore may be more prone to further tissue and cell damage and to microbial infection (Walton, 1990). Peanuts are also prone to damage in the
apical region during handling (Turner et al., 1967). Shoulder damage of macadamia is a problem, not only because of the damage to the kernel itself, but also because of the loss of the kernel which adheres to the shell and cannot be recovered.

1.3.3.4 Oiliness and dustiness of kernels

From a study of one macadamia processing operation Liang (1977) identified three main types of kernel loss: 1) kernel chips nearly impossible to recover and useless, 2) kernel portions discarded with shells due to strong attachment of kernel to the shell, 3) mouldy and discoloured kernels. Other more subtle forms of damage may be oiliness of the surface of kernels, and appearance of dust (fine fragments of kernel). Impact to nuts from dropping onto steel at intermediate moisture content (7-17%) has been reported to cause bruising of kernel, particularly in the shoulder area (Cavaletto, 1990). It has not been reported whether this damaged region is subsequently more prone to oxidation. Dust on macadamia kernels at cracking is evidently composed of degraded kernel tissue. Causes of oiliness and dustiness of macadamia kernel will be examined in Chapter 6.

1.3.4 The relationship of moisture content to damage

The term “moisture content” can be very ambiguous unless the method to determine it is clearly stated. Moisture content is usually determined on either wet-basis or dry basis (Kowitz and Mason, 2001). In this thesis all moisture content data is calculated on a wet basis (wb) unless otherwise stated.

Damage to seeds and nuts during handling generally increases with decreasing MC. For example, damage to pea beans was reduced by raising the MC of dropped beans (Perry and Hall, 1966). Similarly, navy beans were more susceptible to impact damage (seed coat checks and splitting, i.e. separation) at low moisture content than at higher levels, and moisture content was a major factor in controlling the damage.
process (Hoki and Picket, 1973). The resistance of 5 seed grains to impact damage (seed cracking and breaking) increased as the moisture content increased (Bilanski, 1966). Impact damage to soybeans (bruising and cracking as indicated by tetrazolium (TZ) testing) increased significantly as moisture content dropped from 13% to 8% (Bartsch et al., 1986). By contrast, peanuts incurred more damage to the apical end of the nut from impact with increasing moisture content as shown by TZ testing (Turner et al., 1967). However, although low moisture content reduced apical damage, peanuts tended to split more under these conditions (Turner et al., 1967). It is evident that for many seeds more damage occurs during handling at low MC.

In macadamia, high MC nuts (3.28% db) can withstand greater deformation without failure of the kernel (Liang, et al., 1984). Cracking macadamias at ‘medium’ kernel MC (2.3 to 4%) produced higher quality in terms of higher whole kernel and less size reduction of kernels than at 1%, a common figure for processed kernel (Liang, 1977). The best relationship between nut MC and kernel quality at cracking (in terms of wholes and halves) was found at 7% to 12% NIS MC (Sarig et al., 1980).

In a study using limited numbers of nuts, impact to macadamia NIS at intermediate moisture content (7-17%) has been reported to cause bruising of kernel, particularly in the shoulder area, the final point of attachment as the nut dries (Cavaletto, 1990). However, Cavaletto (1986) found that kernels from NIS dropped at 15% were less prone to chipping damage than those dropped at 1%. In the same study when nuts were dropped on the hilum end, the tendency was for the point to break off, resulting in a more symmetrical shape. When dropped on the micropyle end or side, typical damage was a round fracture with radiating cracks (Cavaletto, 1986). In addition, damage increased with drop height (Cavaletto, 1986).
It is undesirable to transport kernel at low moisture contents (< 7.5%) as they are more susceptible to physical damage (O'Hare, 1993; Mason et al., 1998; Mason, 2000). However, Cavaletto (1990) also found that kernels at > 10% MC can suffer bruising with subsequent browning at roasting. Bruising of macadamia kernels was greatest at 7 to 17% MC (Cavaletto, 1986). It is not clear what is the best MC for transport. While drying NIS to 7.5% on-farm is recommended, this is difficult for most farm systems to achieve using only air at ambient temperatures (Mason, 2000).

Macadamia kernels shatter easily at very low moisture contents e.g., 1.5% (Tang et al., 1982), which corresponds to NIS MC of around 3.5%. This has implications for nuts in the factory as for ease of cracking, shells need to be at low MC (Liang et al., 1984). Cracking at 3.5% NIS MC, corresponding to 1.5% kernel MC, is recommended because that facilitates shell fracture and thus reduces the risk of physical damage to the kernel (Mason et al., 1998). However, cracking nuts at very low shell MC reduces kernel quality expressed either in wholes and halves or smaller grades of nuts (Liang, 1977). The optimal MC for handling operations is a difficult issue with important implications for recovery of high quality kernel. Loss of premium priced whole kernel is completely unacceptable to processors in Australia who buy macadamias as NIS (Kowitz and Mason, 2001). Best recovery of kernel has been reported at MC range of 7-12% at cracking (Sarig et al., 1980). More information is needed on the relationship between macadamia shell and kernel MC at cracking. The effect of handling NIS at different MC on kernel quality is reported in Chapter 6.

1.3.5. How delaying harvest of macadamias affects quality

Fruits of macadamia are usually harvested from the orchard floor in Australia following natural abscission (Mason, 1983c; Mason, 2000). Abscission can occur over several months within a cultivar and varies in timing between cultivars (Trueman
et al., 2000). Careful planning of harvest frequency is essential to ensure optimum quality of nuts is achieved (Liang et al., 1996). Harvest intervals of 4 weeks or less are recommended, especially during rainy weather, to avoid kernel deterioration due to germination, fungal growth or exposure to sunlight (Mason and Wells, 1984; Nagao and Hirae, 1992; Liang et al., 1996). Most macadamia orchards have plantings of more than one cultivar, so that harvesting extends over several months and involves multiple harvest rounds over the same rows.

Delaying harvest may affect macadamia kernel quality. Nuts from 2 locations in Queensland were subjected to simulated delayed harvest of 1, 3 and 5 months on the ground in part sun and shade for 2 seasons. Kernels were rejected for germination, insect or rodent damage, mould and discolouration (Mason and Wells, 1984). Processed recovery was not affected for nuts in the shade, but decreased with time after 1 month for nuts in the sun. The major cause of kernel rejection was discolouration (Mason and Wells, 1984). Following roasting flavour scores for nuts in the shade were affected only after 5 months, but for nuts in the sun decreased with time on the ground (Mason and Wells, 1984). There is no information available on how shorter periods of harvest delay affects quality, or how specific aspects of quality such as whole kernel, shoulder damage, pieces and roasting quality are affected by delayed harvest. The issue of delayed harvest will be addressed in Chapter 5.
1.4. Chemistry and rancidity of macadamia

1.4.1. Introduction

Conditions prior to harvest, during drying, and during storage can induce chemical changes in macadamia kernels (Mason et al., 1995; Kaijser et al., 2000). These chemical changes may produce substances which give the product off-flavours (Pike, 1998). Subjective detection of these off-flavours by tasting is still used to determine nut quality at present (Fourie and Basson, 1989), and still remains the ultimate measure of rancidity, although serious efforts have been made to correlate chemical methods with tasting (Robards et al., 1988a; b). The principal volatile components of roasted macadamias that are major determinants of flavour can be identified on the basis of their GC indices and mass spectra (Crain and Tang, 1975). GC can also be used to detect volatile aldehydes which are in large part responsible for the unpleasant oxidised flavour of lipids (de Man, 1990). Hexanal has been identified as a volatile rancidity by-product of macadamias (Himstedt, 2002) and may potentially be a chemical measure of rancidity.

1.4.2. Composition of macadamia kernels

The macadamia kernel is very rich in oil, ideally containing 75-80% by weight of oil for Macadamia integrifolia and slightly less for Macadamia tetraphylla (Cavaletto, 1983; Trueman et al., 2000). Kaijser et al. (2000) report greater variation in oil content of 69-78% for New Zealand cultivars. Furthermore, different cultivars perform differently in relation to quantity of oil (Table 1.1) and composition of oil, and the same cultivar performs differently in different regions (Himstedt, 2002). Macadamia oil is one of the most highly mono-unsaturated oils available (Ako et al., 1995), and oleic and palmitoleic are the predominant fatty acids (Cavaletto, 1983).
This high degree of unsaturation has an important bearing on the health benefits of the food (Ako et al., 1995) and storage characteristics, as mono-unsaturated oils are less subject to oxidation than poly-unsaturated oils (de Man, 1990).

The macadamia kernel has a protein content of around 9.2% of dry material and 4.22 to 4.75% of total sugar, most of which is sucrose, a non-reducing sugar (Cavaletto, 1983; Fourie and Basson, 1990). These major constituents of macadamia kernels have implications for quality, which will be discussed below. The high oil content makes it possible for macadamias to become rancid, while the sugar and protein content make excessive browning of roasted kernels possible if drying and roasting methods are not appropriate (Prichavudhi and Yamamoto, 1965; Dela Cruz et al., 1966). The term rancidity refers to the off odours and flavours resulting from lipolysis (breakdown of oils chemically or by lipase into constituent fatty acids) or lipid oxidation (Pike, 1998).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Region</th>
<th>Oil content (%)</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAES 344</td>
<td>Lismore</td>
<td>74.89</td>
<td>Himstedt (2002)</td>
</tr>
<tr>
<td></td>
<td>Victoria Park</td>
<td>77.5</td>
<td>Trueman et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Gympie</td>
<td>76.69</td>
<td>Himstedt (2002)</td>
</tr>
<tr>
<td></td>
<td>Bundaberg</td>
<td>76.45</td>
<td>Himstedt (2002)</td>
</tr>
<tr>
<td></td>
<td>Winfield</td>
<td>78.5</td>
<td>Trueman et al. (2000)</td>
</tr>
<tr>
<td>HAES 741</td>
<td>Winfield</td>
<td>80.5</td>
<td>Trueman et al. (2000)</td>
</tr>
<tr>
<td></td>
<td>Victoria Park</td>
<td>77.0</td>
<td></td>
</tr>
<tr>
<td>HV A16</td>
<td>Winfield</td>
<td>81.5</td>
<td>Trueman et al. (2000)</td>
</tr>
<tr>
<td>HAES 246</td>
<td>Victoria Park</td>
<td>78.5</td>
<td>Trueman et al. (2000)</td>
</tr>
</tbody>
</table>

1.4.3. Rancidity

The development of unacceptable flavour or rancidity is a feature of nuts which have been stored under the wrong conditions or for too long (Kaijser et al., 2000). Macadamia kernels rapidly develop rancidity when stored at room temperature at
higher moisture content (Cavaletto et al., 1966; Himstedt, 2002). The moisture content was found to be the most important factor influencing the onset of rancidity in raw macadamia kernel (Cavaletto et al. 1966) and roasted kernel (Dela Cruz et al., 1966).

There are two important pathways leading to rancidity, oxidation and hydrolysis (Robards et al., 1988a). Lipolysis is known as hydrolytic rancidity while lipid oxidation is termed oxidative rancidity (Pike, 1998). Lipid oxidation products cause rancidity and can also induce various deteriorative reactions in proteins, amino acids and other food components (Whitfield, 1992). The seasonal nature of nut crops makes storage necessary (Fourie and Basson, 1989). In addition, nuts are usually non-orthodox seeds which means that they do not become dormant and therefore can be stored for only limited periods before deteriorating (Doijode, 2001). Because nuts have a high oil content, rancidity becomes an important issue during storage, e.g., lipid oxidation is the principal mode of flavour deterioration in hazelnuts (Pershern et al., 1995). Oxidative stability of macadamias may be influenced by cultivar (Kaijser et al., 2000); however, for hazelnuts caution was urged in arriving at this conclusion because of the possibility that climate is a factor in determining fatty acid composition and susceptibility to oxidation (Halleday et al., date unknown)

**1.4.3.1. Oxidation**

Oxidation leads to oxidative rancidity and is the result of oxygen attacking glycerides. Oxidation can be initiated by heat, pro-oxidants, certain enzymes (lipoxygenases) or light (Robards et al., 1988a). The rate of oxidation depends greatly on the degree of unsaturation of an oil. As an example, in the series of 18 carbon fatty acids, with zero, one, two and three double bonds, the relative rate of oxidation has been reported to be in the ratio of 1:100:1200:2500 respectively (de Man, 1990).
Triacylglycerol (TAG) composition of lipids also influences oxidation. Neff et al. (1994) found TAG composition was statistically correlated with oxidative stability of certain canola oils. Canola oil oxidative stability increased with increasing OOO content and decreased with increasing LnLO composition (Neff et al. 1994; O= oleic acid, Ln= linolenic acid, L= linoleic acid). Oxidation of oils containing linolenic acid produces objectionable flavours, a process which is known as flavour reversion. This type of oxidation is possible with less oxygen than with common oxidation (de Man, 1990). Macadamia oil typically contains from 0.7% to 2% linolenic acid (McConachie, 1997; Himstedt, 2002), making some flavour reversion possible in macadamia products.

Lipid auto-oxidation (autoxidation) is a self-sustaining free radical mechanism that produces hydroperoxides (primary products). Autoxidation is quite complex and involves many interrelated reactions of intermediates (Belitz et al., 2004). As autoxidation progresses, primary products are cleaved into various secondary and tertiary products (Pike, 1998; Robards et al., 1988a; Fig. 1.6). However, oxidation can be by autoxidation, photo-oxidation or enzymic oxidation. Because the autoxidation system is dynamic it is recommended that two or more methods be used to obtain a measure of lipid oxidation (Pike, 1998). Another factor related to rancidity of nuts is tissue damage. Ground nut foods are more susceptible to spoilage due to the greater area of enzymes and substrate brought into contact (hydrolysis) and the greater amount of oil exposed to autoxidation (Acker, 1962). Damage such as chipping and dusting of macadamias increases the surface area exposed to air and may increase development of rancidity. However, this has not been tested for macadamias. Apart from causing rancid flavours, lipid oxidation products can react with amino acid residues in the Maillard reaction, causing excessive browning (Nawar, 1996).
Light may have a deleterious effect on many foods, particularly lipids. Chahine and de Man (1971) found that a light level of 100 footcandles accelerated the oxidation of corn oil at temperatures ranging from 17 to 60°C, and oxidation was greater when samples were exposed to fluorescent light. Increasing light intensity from 100 to 500 footcandles greatly accelerated oxidative deterioration. Thus it is important to store high-lipid foods away from light, especially fluorescent light. However, in macadamia, light did not affect quality of raw or roasted kernel (Cavaletto et al., 1966; Dela Cruz et al., 1966). This difference may be due to the different fatty acids making up the triacylglycerol structures of the respective oils and differences in saturation.
Free fatty acid hydroperoxides
(Mono-, di-, epoxy and cyclic hydroperoxides)

Triglycerides

Oxidation
(autoxidation, photo-oxidation or enzymic)

Hydrolysis
(hydrothermal or enzymic)

I

Triglyceride hydroperoxides

II

Free fatty acids + glycerol

Hydrolysis

Oxidation

Free fatty acid hydroperoxides

Secondary and tertiary products:
saturated, unsaturated, di- and epoxyaldehydes
ketones
lactones
furans
monobasic, dibasic, oxo and hydroxy acids
saturated and unsaturated hydrocarbons etc.

Fig. 1.6. Overall reaction scheme for (I) oxidative and (II) hydrolytic rancidity. (Adapted from: Robards et al., 1988a)
1.4.3.2. Hydrolysis

Hydrolysis is the consequence of lipolysis or hydrothermal activity and results in release of free fatty acids (FFA) leading to hydrolytic rancidity (Robards et al., 1988a). Lipolysis is the hydrolysis of ester bonds in lipids and may occur by enzyme action, or by heat and moisture (Nawar, 1996). The release of short-chain fatty acids from the glyceride molecule can result in off-odours similar to rancid butter (Holm, 1996). If the fatty acids liberated are volatile, FFA may be a measure of hydrolytic activity (Pike, 1998). In macadamias even small differences in FFA values were highly correlated with differences in flavour scores (Dela Cruz et al., 1966). FFA’s are more prone to autoxidation than intact triglycerides. Once formed they are subject to autoxidation, production of FFA hydroperoxides and then in turn secondary and tertiary products of oxidation (Robards et al., 1988a). Figure 1.4 shows possible pathways for hydrolytic rancidity.

Lipases hydrolyze only emulsified acyl lipids; they are active only on the water/lipid interface (Belitz et al., 2004), mandating low moisture content for storage of macadamia kernels (Cavaletto et al., 1966; Dela Cruz et al., 1966). Removal of water from a product is also an effective means of reducing microbiological growth (Acker, 1962). The absolute water content of a food is not as important as the relative humidity of the air with which the food is in hygroscopic equilibrium (Acker, 1962). However, lipolysis in macadamia appears to be related to storage at excessively high temperatures rather than as a result of moulds (Cavaletto, 1983). The formation of free fatty acids by hydrolysis is unaffected by the presence of antioxidants (Robards et al., 1988a).

Physical damage may also predispose nuts to lipolysis. In hazelnuts, lipatic enzymes located just below the testa cannot attack oils in undamaged cells; however,
any lesion changes the situation (Riedl and Mohr, 1979). The damage to cells releases oil and may allow hydrolysis to begin, promoted by lipases and esterases (Keme et al., 1983). Macadamia kernels damaged by impacts may be subject to similar processes. Tissue damage can also be caused by pressure, for example, when storing hazelnuts under nitrogen pressure (Keme et al., 1983). Macadamias are often vacuum packed and it is unknown whether damage to the cell membrane may be caused by differences in pressure under these conditions.

1.4.3.3. Measurement of rancidity

A variety of chemical and instrumental methods are available for assessing rancidity of foods. Some chemical methods are listed in Table 1.2. Some methods, e.g. peroxide values, although useful for quality control, are of low specificity (Nawar, 1996; Robards et al., 1998a).

**Peroxide value, Thiobarbituric Acid test and Anisidine Value**

Peroxide value (PV), a titrimetric method, is defined as the milliequivalents (mEq) of peroxide per kilogram of fat (Pike, 1998). Peroxides and hydroperoxides, although flavourless themselves, provide an indication of impending flavour deterioration (Robards et al., 1988b). The Thiobarbituric Acid (TBA) test measures malonaldehyde, a secondary product of lipid oxidation, and has many modifications (Pike, 1998). Anisidine value determines the amount of aldehydes (mainly 2-alkenals and 2,4-dienals) in fats and oils and is a chromogenic method (Pike, 1998).

**Iodine Value**

The iodine value is obtained by a test measuring the degree of unsaturation of an oil by reaction with iodine compounds (Nawar, 1996; Pike, 1998). The higher the
Table 1.2. Units and representative values for rancidity tests (Adapted from: Robards et al., 1988a)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>Representative values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free fatty acids</td>
<td>Free fatty acids % m/m, expressed as oleic acid mequiv.kg⁻¹ peroxide</td>
<td>0.2% of free acid (if lauric or capric acid) causes off-flavour</td>
</tr>
<tr>
<td>Peroxide value (PV)</td>
<td>Freshly refined oils, &lt;1; &gt;2.5, excessive oxidation, potential lack of product stability; &gt;7.5, can indicate sufficient breakdown to aldehydes to produce rancid flavour in product</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mg.kg⁻¹ malonaldehyde</td>
<td>Chromogen determined spectroscopically at 450, 530 or 538 nm</td>
</tr>
<tr>
<td>Thiobarbituric acid</td>
<td></td>
<td>3, incipient rancidity; 3-8, rancid, near end of induction period; &gt;8, definite rancidity</td>
</tr>
<tr>
<td>Kreis</td>
<td>Red units on the Lovibond scale</td>
<td>&lt;10 generally represents an acceptable oil</td>
</tr>
<tr>
<td>Anisidine value</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

degree of unsaturation (carbon-carbon double bonds), the greater the amount of iodine absorbed. A theoretical ‘calculated iodine value’ is an AOCS recommended practice Cd 1c-85 (Pike, 1998). Iodine value is important because of the susceptibility of unsaturated bonds to oxidation (Wanasundara et al., 1997). During autoxidation the iodine value of an oil will decrease because of oxidation at the double bond site of unsaturated oil; thus a decrease in iodine value indicates oxidation (Harris et al., 1972).

Active Oxygen Method (AOM), Rancimat Induction Test and Oxygen Absorption

These tests all rely on measurement of oxidation as an indicator of susceptibility to rancidity. The active oxygen method is widely used and involves maintenance of the sample at 98°C while air is continuously bubbled through it at a constant rate. The value obtained is the time taken to reach a specific peroxide value (Nawar, 1996). The Rancimat induction test has similarities with the AOM test. Air is bubbled through the
sample at a set temperature, usually 100°C, and the increase in electrical conductivity due to generation of oxidation products is measured. The value is expressed as ‘induction time’ (Nawar, 1996). The temperature used may be varied according to experimental needs (Kaijser et al., 2000). New Zealand macadamia oils were found to have Rancimat induction times of 39 h at the standard 110°C, (Kaijser et al., 2000) compared with 15.6 to 25.3 h for hazelnuts and 3.9 to 7.8 h for walnut oil (Savage et al., 1997; 1999). These results show that in oxidation terms macadamia oil is a relatively stable oil. In the oxygen absorption test the sample is placed in a closed chamber and the amount of oxygen absorbed is determined and used as an indicator of stability of the product. This test is particularly useful in studying antioxidant activity (Nawar, 1996). Macadamia oil does not readily become rancid. The lipid fraction of macadamias exhibited a high resistance to thermal oxidation as estimated by FFA, TBA and PV tests (Rosenthal et al., 1983). This was also the result obtained by Winterton (1966) when macadamia oil was aerated for 280 hours before a rancid odour was detectable.

**Free Fatty Acids**

Free Fatty Acids (FFA) is a measurement of hydrolytic activity in a fat. Measures of fat acidity normally reflect the amount of fatty acids hydrolyzed from triacylglycerols. FFA is expressed as a percentage by weight of a specified fatty acid e.g., percent oleic acid (Pike, 1998). The Australian Macadamia Society (AMS) considers 0.2 to 0.6% FFA acceptable (McConachie, 1996). However, there is another recommendation that FFA should be no more than 0.3% (McConachie, 1996). The FFA content of vegetable oils is used by commercial oil refiners as an index of the oil quality (Halleday et al., date unknown). The measurement of FFA’s is the simplest measure of hydrolytic rancidity (Robards et al., 1988a). In addition, lipase activity in
foods can be measured very sensitively by fluorochromic methods, however, these methods detail only the level of lipase activity and not individual fatty acids (Belitz et al., 2004). This is a similar problem to the lack of specificity of peroxide values. The odour and taste thresholds of these fatty acids vary greatly and can increase by different amounts at the same lipase activity (Belitz et al., 2004). Storage of raw macadamia kernels for one year at ambient temperatures in cellophane bags resulted in rancid kernels with high FFA levels (Rosenthal et al., 1983). More precise profiling of the fatty acids could be provided by gas chromatography, which yields a more useful measure of hydrolysis (Belitz et al., 2004).

The chemical methods listed here provide limited information. The present reliance on PV and FFA analysis as indicators of rancidity of macadamias has been described as unreliable, with sensory evaluation the only reliable test (Mason et al., 1998). However, a correlation of chemical tests with instrumental methods may provide a more reliable prediction of rancidity.

Instrumental methods

Numerous instrumental methods are available for evaluation of rancidity. Chromatographic methods provide extensive analysis for a clearer profile of rancidity and enable a correlation of sensory evaluation with instrumental analysis (Robards et al., 1988a). The advantage of chromatographic methods is that they are not subjective. They will consistently and reliably detect subtle differences in rancid products more reliably than organoleptic tests (Dupuy et al., 1977). Both gas chromatography (GC), GC-mass spectrometry (GC-MS) and high performance liquid chromatography (HPLC) are useful for measurement of rancidity as they are highly sensitive and able to separate complex mixtures (Robards et al., 1988a). GC-MS enables identification as well as quantification of volatiles. The combination of HPLC with Fourier
transform infrared spectroscopy or mass spectrometry (FTICR-MS) represents a powerful means of separating and identifying labile oxidation products, however, the high cost of such instruments may limit their use to larger laboratories (Robards et al., 1988a). Fard et al. (2003) found that FTICR-MS provided more details of macadamia oil composition than GC-MS alone.

The analysis of headspace volatiles by GC provides a sensitive means of monitoring oxidative changes during a period of storage (Halleday et al., date unknown). Of the various compounds formed during oxidation of lipids hexanal is one of the most common, and measurement of headspace hexanal is one of the methods of determining the extent of oxidation (Pike, 1998). Hexanal has been identified as an important indicator of rancidity identified by GC of macadamia (Himstedt, 2002).

HPLC is used to determine lipid composition in conjunction with headspace analysis for volatile by-products of rancidity (Shahidi et al., 1997). Savage et al. (1999) used HPLC to determine tocopherol content of walnuts. Changes in tocopherol content of almond, pecan and macadamia as determined by HPLC have been used as an indication of oxidative activity by measuring depletion of an antioxidant (Fourie and Basson, 1989). Gas chromatograph analyses are more numerous than other chromatographic methods (Robards et al., 1988a), and examples appear in Table 1.3. Quinn and Tang (1996) used GC to measure phenolic compounds of macadamias. In Chapter 3 of this thesis GC-MS analysis is used to test for volatile peroxidation by-products of macadamias as indicators of rancidity of bruised kernels.

Other instrumental methods of analysis for antioxidants are in use, for example, Vieira and Regitano-d’Arce (1999) employed ultraviolet spectrophotometric evaluation of corn oil stability. However, ultraviolet spectrophotometry is limited in
usefulness because of problems with correlation of magnitude of absorbance with degree of oxidation (Nawar, 1996).

**Table 1.3.** Various examples of the use of GC to measure rancidity

<table>
<thead>
<tr>
<th>Subject</th>
<th>Targeted compounds</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heated vegetable oils</td>
<td>Volatile carbonyl compounds</td>
<td>Stashenko et al., 1997</td>
</tr>
<tr>
<td>Comparing GCMS and TBA</td>
<td>aldehydes</td>
<td>Liu et al., 1997</td>
</tr>
<tr>
<td>Hazelnuts</td>
<td>Volatiles from oxidation</td>
<td>Halleday et al. (date unknown)</td>
</tr>
<tr>
<td>Almonds</td>
<td>Oxygen</td>
<td>Harris et al., 1972</td>
</tr>
<tr>
<td>Macadamias</td>
<td>Phenolic compounds</td>
<td>Quinn and Tang, 1996</td>
</tr>
<tr>
<td>Macadamias</td>
<td>Volatiles from oxidation</td>
<td>Himstedt, 2002</td>
</tr>
</tbody>
</table>

**Sensory evaluation of rancidity**

Sensory evaluation based on a hedonic scale remains the ultimate test of rancidity as palatability is the determiner of success of any food product (Robards et al., 1988a). Instrumental methods attempt to correlate with sensory attributes and serious attempts have been made to correlate objective methods of evaluation with subjective sensory methods (Forbus et al., 1980). An example is the determination of peroxide values, free fatty acid values, carbonyl factors, Hunter colour values, and direct GC analyses of volatile compounds being compared with sensory scores of stored pecan kernels (Forbus et al., 1980). In this case content of volatiles determined by direct GLC appeared to be the best non-sensory indication of pecan kernel quality (Forbus et al., 1980). Gas chromatography proved to be a valuable chemical technique for judging quality loss in almonds, however, a taste test for flavour using a trained panel was more reliable (Harris et al., 1972). For vegetable oils, a high degree of correlation was obtained between predicted flavour scores.
based on GC analysis of oil volatiles and actual taste panel scores (Dupuy et al., 1977). However, such correlations may not always be completely reliable because taste panels are themselves subject to the inherent weakness of subjective variation (Dupuy et al., 1977). Sensory evaluation is time consuming, costly and not practical on an industry scale (Forbus et al., 1980). There is a need to develop objective tests such as GC to a practical and repeatable level at industry scale. GC testing of damaged macadamia kernels for rancidity is evaluated in Chapter 3 of this thesis.

1.4.4. The importance of antioxidants

Antioxidants are considered by biochemists and clinicians as substances that can protect the living tissues against damage by reactive oxygen species (ROS) (Wanasundara et al., 1997). This definition has been broadened to any substance that, when present at low concentrations compared to those of an oxidizable substrate, significantly delays or prevents oxidation of that substrate (Halliwell et al., 1995). However, the action of antioxidants is not permanent as they delay oxidation without preventing it altogether (Robards et al., 1988a). Antioxidants capable of delaying the onset of oxidative rancidity will have no effect on FFA formation due to chemical hydrolysis (Robards et al., 1988a). Free radicals and ROS are key chemical species that contribute to changes in food quality and development of disease (Wanasundara et al., 1997). Oxidation of unsaturated lipids is a major cause of food quality deterioration (Wanasundara et al., 1997). Living species have developed antioxidants to counter the negative effects of oxidative chemical species and many can be found in lipids (Table 1.4).
Table 1.4. Types of lipid oxidation inhibitors found in plants and seeds and their mode of action (Adapted from Wanasundara et al., 1997).

<table>
<thead>
<tr>
<th>Type of inhibitor</th>
<th>Mode of action</th>
<th>Chemical compound/group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antioxidants</td>
<td>React with free radicals, interrupt the propagation of the chain reaction</td>
<td>Flavonoids, lignans, tocopherols, tannins, carotenoids, sterols, maillard reaction products</td>
</tr>
<tr>
<td>Synergists</td>
<td>Enhance activity of antioxidants</td>
<td>Flavonoids, tocopherol, amino acids, peptides, phytic acid</td>
</tr>
<tr>
<td>Retarders</td>
<td>Reduce hydroperoxides without forming free radicals</td>
<td>Catalase, peroxidases, amines, alkaloids, chlorophyll</td>
</tr>
<tr>
<td>Metal scavengers</td>
<td>Inhibit the ability of heavy and trace metals to catalyse production of free radicals</td>
<td>Flavonoids, amino acids, peptides, phytic acid, maillard reaction products</td>
</tr>
<tr>
<td>Singlet-oxygen</td>
<td>Inactivate singlet oxygen that initiates the free-radical chain reaction</td>
<td>Superoxide dismutase, ascorbic acid, carotenoids</td>
</tr>
</tbody>
</table>

Many oils and lipid bearing foods have been investigated in relation to the content of antioxidants and effect of processing on the antioxidants. However, the factors that determine the oxidative stability of macadamia kernels are largely unknown (Quinn and Tang, 1996). Several phenolic compounds known for antioxidant properties have been identified at very low concentrations (0.004%) in macadamia oil. However, possible synergistic effects of these low concentrations or the effect of other unidentified compounds are not known (Quinn and Tang, 1996). Kaijser et al. (2000) also identified the phenolic compounds α-tocopherol and δ-tocopherol in New Zealand cultivars of macadamia at slightly higher levels than Quinn and Tang (1996). For other species such as walnuts (Savage et al., 1999) and hazelnuts (Savage et al., 1997) tocopherols have been shown to contribute to kernel stability, but in macadamias it appears the levels of α-tocopherol and δ-tocopherol are too low to influence kernel stability (Kaijser et al. 2000). Another compound identified was α-tocotrienol and it is possible that the total of tocopherols and tocotrienols may contribute to oxidative stability (Kaijser et al., 2000). The storage life of roasted
macadamia kernels has been increased by the addition of antioxidants such as BHA and BHT to the roasted product after roasting and more protection was provided than by vacuum packing (Cavaletto and Yamamoto, 1971). This suggests that natural antioxidant levels would also have a significant effect on delaying rancidity of macadamias.

Processing may have an effect on the phenolic compounds present in macadamia oil. Shells contain many times (seventeen) more phenolic compounds than kernels. When producing cold-pressed oils kernels and fragments of shell are crushed together, which may increase the levels of phenolic compounds in oil, although this is untested (Quinn and Tang, 1996). However, the hypothesis is supported by Rancimat induction times for commercial crude macadamia oils being significantly greater than for refined oil (Quinn and Tang, 1996). Refining may remove the slightly acid phenolic compounds when free fatty acids are removed (Quinn and Tang, 1996).

Sesame oil, which has high oxidative stability, has a suite of antioxidants and the stability of sesame oil may be due to a synergistic effect between the antioxidants (Shahidi et al., 1997). These authors found a decrease in endogenous antioxidants paralleled by an increase in hexanal in the oil. It is the volatile aldehydes such as hexanal which contribute to the characteristic oxidised flavour of rancid lipids, including macadamia oil (de Man, 1998; Himstedt, 2002). The role of antioxidants in moderating and controlling rancidity is complex and subject to change. An example is that by-products of the Maillard reaction, a common cause of browning in roasted foods (Belitz et al., 2004) are featured in three categories of inhibitors in Table 1.4. Most macadamias are sold as roasted product and quality of roasted macadamias is investigated in Chapter 5 and Chapter 6 of this thesis.
1.5. Drying effects on quality

Drying is one of the most important steps in the macadamia processing chain for determining the quality of saleable product. Despite this there is a lack of useful information on drying conditions as reflected in the relatively small number of papers published in the literature (Mason and Van Blarcom, 1993). Drying determines storability, palatability and roasting qualities of kernels (Cavaletto, 1983).

1.5.1. Drying theory

Water content of a food is not as critical a factor in spoilage as availability of the water. Water molecules within food are interlinked by hydrogen bonds and can interact with other food constituents (Coultate, 2002). Though water relationships in food are complex and difficult to define, water is present in two forms: (1) bound water, which is held by strong chemical forces with other constituents and is unchanged by processes such as drying and (2) free water, the balance of water within the nut, including both adsorbed and absorbed water (Coultate, 2002). Adsorbed water is held on the surface of other molecules by weak attractive forces while absorbed water is held loosely within the extra-cellular spaces by weak capillary forces. It is free water that is most readily removed by the drying process while bound water can only be removed by high temperatures which also induce chemical changes and loss of quality (Mason et al., 1998). The term Water Activity ($a_w$) refers to this free water or unbound water. $a_w$ will increase with equilibrium relative humidity (ERH), and ERH for a given $a_w$ can be readily calculated, e.g., at $a_w$ of 0.3 for macadamia ERH will be 30% (Beuchat, 1978).

There is an optimum $a_w$ at which a dry food has the longest shelf life, close to the monolayer moisture level, usually around 0.2 to 0.3 for most foods (Labuza and Contreras-Medellin, 1981; Coultate, 2002). This is the point where all free water has
been removed and only bound water remains (Coultate, 2002). The functional connection between moisture content and ERH is expressed as experimentally determined sorption isotherms (Acker, 1962). From these how much moisture a food can contain when in equilibrium with a certain ERH at a set temperature can be determined (Acker, 1962). Knowledge of sorption isotherms is critical for food storage and they have been determined for macadamias (Palipane and Driscoll, 1992). There can be a large difference between the sorption isotherms for roasted nuts and raw nuts, with the former showing a reduced capacity for water adsorption. This is attributed to a decrease in the available sites in the substrate for water adsorption due to chemical changes induced by roasting (Martinez-Navarrete and Chiralt, 1996).

Dried macadamia nuts will rehydrate at elevated RH. The moisture content during storage in a closed system will equilibrate depending on temperature and RH (Kowitz and Mason, 2001). Water adsorption isotherms on rehydration differ from those for desorption, a phenomenon known as hysteresis (Acker, 1962; Palipane and Driscoll, 1992). Macadamia kernels with a moisture content of 1.5% have water activity of about 0.3 (Beuchat, 1978). Because of this, dry kernels (e.g., 1.5%) must be protected from moisture because exposure to RH greater than 30% will result in moisture gain (Cavaletto, 1983).

1.5.2. Drying macadamias

Correct moisture content is important for food products for microbial stability, texture and product quality (shelf life) (Labuza and Contreras-Medellin, 1981). Drying of macadamia nuts on-farm has been reviewed by Kowitz and Mason (2001). At harvest, macadamias can have a moisture content as high as 30%, and it is essential to reduce this to a level at which hydrolytic activity and mould development are prevented (Mason, 2000). Moisture content is a critical factor influencing
macadamia stability (Cavaletto et al., 1966). However, drying must be accomplished in ways that do not compromise other quality parameters. The aim must be to have a drying regime that permits the highest moisture removal rate and energy efficiency within operational restraints, including quality of product (Davidson et al., 2000).

There are several suggested drying regimes for macadamias (Table 1.5).

Table 1.5. Various drying regimes for macadamia nut-in-shell

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>X d @ 38°C b</td>
<td>X d @ 52°C c</td>
<td>X d @ 60°C d</td>
<td>----</td>
<td>Cavaletto, 1981</td>
</tr>
<tr>
<td>4-5d @ambient</td>
<td>2-3d @ 38°C</td>
<td>4-5d @ 50°C</td>
<td>1-2d @ 60°C</td>
<td>Cavaletto, 1983</td>
</tr>
<tr>
<td>2d @ 38°C</td>
<td>2d @ 45°C</td>
<td>2d @ 60°C</td>
<td>----</td>
<td>Anon., 2002</td>
</tr>
<tr>
<td>5-7 d @ 32°C</td>
<td>1-2 d @ 38°C</td>
<td>1-2 d @ 44°C</td>
<td>Finish @ 50°C</td>
<td>Mason, 1983a</td>
</tr>
<tr>
<td>3-4d @ 30°C</td>
<td>2-3d @ 40°C</td>
<td>X d @ 50°C a</td>
<td>----</td>
<td>Mason, 1983b,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mason et al., 1995</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Trueman, 2003a</td>
</tr>
</tbody>
</table>

a, Dried at 50°C until kernel MC of 1.0-1.5% achieved.
b, Dried at 38°C until kernel MC of 8% is achieved.
c, Dried at 52°C until kernel MC of 5-6% achieved.
d, Dried at 60°C until kernel MC of 1.0-1.5% achieved.

At present, macadamia nuts are dried to around 3.5% NIS MC before cracking, which corresponds to a kernel MC of around 1.5%. This renders the shell brittle and easy to crack, but unfortunately also predisposes the kernel to shattering (Tang et al., 1982). Drying high moisture macadamia NIS rapidly, for example at 50°C, causes the kernel to become extremely brittle and susceptible to physical damage such as chipping and breakage (Tang et al., 1982). Drying nuts too quickly can also cause loss of the characteristic macadamia flavour (Tang et al., 1982).

An additional problem of rapid drying can be browning of the centre of the kernel. A low initial drying temperature is essential to prevent browning in the centre of kernels due to reactions between proteins and reducing sugars enhanced by enzymatic activity at high moisture content and temperature (Prichavudhi and Yamomoto, 1965). Reducing sugars in the centre of kernels can be as much as doubled in brown areas of kernel compared with outer regions (Cavaletto, 1983).
Reducing sugars increase with increased drying temperature and specific gravity (Yuliarti, 1998). However, there was no reduction in eating quality of roasted product following rapid drying, and no significant difference between reducing sugars at drying temperatures ranging from 32°C to 56°C and a range of relative humidities, perhaps due to the low relative humidity used (Mason and Van Blarcom, 1993). The difference from Prichavudhi and Yamomoto (1965) may be explained by the fact that Mason and Van Blarcom (1993) used higher temperatures (from 50°C to 71°C).

Similarly, Yuliarti (1998) found no reduction in eating quality of roasted product following rapid drying time of only 31 hours at 52°C and 10% RH. However, there is a need for more work to confirm these results (Yuliarti, 1998).

Temperature of drying is an important factor in drying time and quality of the dried product. One current recommended practice for drying macadamias is an incremental process, 2 days at 38°C, 2 days at 45°C, and 2 days at 60°C (Anon., 2002). This is a variation of a method developed by Prichavudhi and Yamomoto (1965), who used higher temperatures. However, drying methods vary from processor to processor, and it is not easy to obtain details of these operations.

Thus the potential may exist to reduce drying times using lower RH (Van Blarcom and Mason 1987; Yuliarti, 1998). More research on this important subject could reap considerable benefits and efficiencies, particularly during peak seasons, as the present stepwise recommended drying process is very time consuming. The effect of different drying regimes on quality will be reported in Chapter 7 of this thesis.
1.6. Roasting macadamias

Roasting of macadamia kernels is widely practiced and has been reviewed by Weinert (1993). Some workers consider that roasting improves shelf life due to the fact that it reduces the binding sites for water in the kernel (Martinez-Navarrete and Chiralt, 1996). However, some have found that roasted kernels have reduced shelf life (Isaacs et al., 1991; Lemmer and Kruger, 2000). In addition, roasting is considered to improve palatability (Leverington, 1971). Roasting of macadamia commenced in Hawaii (Moltzau and Ripperton, 1939). The fledgling Australian industry at first adopted Hawaiian roasting practice until studies such as those of Leverington and Winterton (1963) and Winterton (1966) modified procedures. Most kernels initially were roasted in oil, but Leverington and Winterton (1963) developed a dry air roasting regime.

There are a number of factors that are known to influence the quality of roasted product, such as temperature and duration of roasting, and moisture content of kernels at roasting. It is essential that kernels are below 1.5% MC at roasting to avoid excessive browning (Prichavudhi and Yamamoto, 1965), further, Dela Cruz et al. (1966) state that kernels should be at no more than 1.1% MC at roasting for maximum sensory and chemical quality. Moisture content at the time of roasting is also important in determining the final colour. Kernels with MC higher than 2% do not have crisp texture, brown too rapidly and do not have good shelf life (Cavaletto, 1983). Kernels should also be of a high oil content, as indicated by specific gravity of less than one, as there is an inverse relationship between oil content and sugar content. High reducing sugar content leads to dark kernels at roasting (Cavaletto, 1983).

The time/temperature relationship is proposed as the most important factor in the prevention of rancidity in roasted nuts (Leverington, 1962). Too high a temperature
will not cook the kernels through to the centre by the time a desirable colour is obtained (Leverington, 1962). When this happens, the binding sites for water in the centre of the kernels are not reduced effectively by roasting (Martinez-Navarrete and Chiralt, 1996).

The genotype may also have an influence on the quality of roasted macadamia. Some workers have recommended that *M. integrifolia* and *M. tetraphylla* kernels should be separated before roasting because of different roasting characteristics and resultant variable quality of roasted product (Grimwood, 1971). It has further been recommended that cultivars which are hybrids of *M. integrifolia* and *M. tetraphylla* also be roasted separately and that standards for *M. integrifolia* be applied to its cultivars and those for *M. tetraphylla* be applied to hybrids (Lee, 1998). Despite this, the influence of hybridization on kernel quality is not always clear (Lemmer et al., 1998). Some cultivars considered *M. integrifolia* have produced variable browning results when roasted (Lemmer et al., 1998). Examples of the confusing situation are that known hybrids produced superb quality and high uniformity when roasted at the correct temperature and time, while HAES 741 and HAES 791 differed from HAES 508, HAES 246 and HAES 788 in respect to the roasting time to desirable colour. Cultivar HAES 788, classified as *M. integrifolia*, exhibited roasting characteristics of both groups (Lemmer et al., 1998). Difficulties such as this suggest the desirability of segregating cultivars for roasting, and having defined standards for each cultivar. There is also a need for flexibility when roasting, and varying time of roasting as necessary to achieve the desired colour.
1.6.1. Oil roasting of macadamias

Most roasted macadamias in Hawaii were roasted in oil (Grimwood, 1971). One problem with oil roasting can be that degradation of roasting oil due to heating can lead to peroxidant contamination of kernels (Winterton, 1966; Grimwood, 1971). This can be counteracted to some extent by treating roasted kernels with antioxidants (Cavaletto and Yamamoto, 1971). This practice was not considered necessary for kernels roasted correctly (Winterton, 1966). Another problem with oil roasting is that kernels can lose substantial quantities of endogenous oils to the frying oil (Cavaletto and Yamamoto, 1971). However, an advantage of oil roasting is that a more even colour of product is obtained (Grimwood, 1971). Various methods have been reported for oil roasting macadamias (Table 1.6). When oil roasting, temperatures between 115ºC and 125ºC achieve better control of colour-time relationships than at 135ºC (Mason et al., 1995). Roasting at 135ºC produced inferior flavour compared with roasting at 115 to 125ºC (Mason et al., 1995).

1.6.2. Air roasting of macadamias

Most roasted macadamias produced in Australia are air-roasted (Burton, pers. comm.). Various air-roasting regimes have been reported for roasting macadamia kernel in air (Table 1.7). Macadamia processors in Australia tend to use low temperatures when roasting to minimize the risk of dark kernels, considered to be partly due to kernels of mixed cultivars (Burton, pers. comm.). The roasting regimes presented in Table 1.6 and Table 1.7 were those used by experimenters under laboratory conditions. For processors, batch sizes and the scale of roasting equipment are very different, and equipment used also varies. An example of dry roasting methods used by a processor are presented in Table 1.8.
### Table 1.6. Roasting regimes for roasting macadamias in vegetable oils

<table>
<thead>
<tr>
<th>Cultivar or species</th>
<th>Oil type</th>
<th>Temperature (ºC)</th>
<th>Duration (min)</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. integrifolia</td>
<td>Unknown</td>
<td>127</td>
<td>25</td>
<td>Winterton, 1966</td>
</tr>
<tr>
<td>HAES 246</td>
<td>Coconut</td>
<td>127</td>
<td>15</td>
<td>Cavaletto &amp; Yamamoto, 1971</td>
</tr>
<tr>
<td>M. integrifolia</td>
<td>Coconut</td>
<td>135</td>
<td>12-15</td>
<td>Grimwood, 1971</td>
</tr>
<tr>
<td>HAES 508</td>
<td>Coconut</td>
<td>127</td>
<td>15</td>
<td>Prichavudhi &amp; Yamamoto, 1965</td>
</tr>
<tr>
<td>HV A4, HV A16, HAES 344, HAES 741, HAES 800, H2</td>
<td>Coconut</td>
<td>125</td>
<td>#</td>
<td>Isaacs <em>et al.</em>, 1991</td>
</tr>
<tr>
<td>HV A4, HV A16, HAES 741, HAES 800, HAES 246, HAES 344</td>
<td>Coconut</td>
<td>125</td>
<td>10-15 #</td>
<td>Fedric, 1997</td>
</tr>
<tr>
<td>Hybrids♦</td>
<td>Coconut</td>
<td>127</td>
<td>12</td>
<td>Lemmer <em>et al.</em>, 1998</td>
</tr>
<tr>
<td>HAES 246, HAES 508</td>
<td>Coconut</td>
<td>115, 125</td>
<td>19-35, 10-14 #</td>
<td>Mason <em>et al.</em>, 1995</td>
</tr>
<tr>
<td>Hybrids</td>
<td>Coconut</td>
<td>121</td>
<td>#</td>
<td>Lemmer and Kruger, 2000</td>
</tr>
<tr>
<td>Various*</td>
<td>Coconut</td>
<td>128</td>
<td>#</td>
<td>Lemmer and Kruger, 2000</td>
</tr>
</tbody>
</table>

# To desired colour standard  ♦ Nelmak 1, Nelmak 2, Nelmak 26, Beaumont (695)  
* HAES cultivars 294, 344, 660, 695, 741, 788, 789, 791, 800, 814, 816, 863

### Table 1.7. Roasting regimes used for roasting macadamias in air

<table>
<thead>
<tr>
<th>In-shell or shelled</th>
<th>Cultivar or species</th>
<th>Temperature (ºC)</th>
<th>Duration (min)</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shelled</td>
<td>M. integrifolia</td>
<td>135</td>
<td>25</td>
<td>Leverington &amp; Winterton, 1963</td>
</tr>
<tr>
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<td>M. tetraphylla</td>
<td>127</td>
<td></td>
<td>Grimwood, 1971</td>
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<tr>
<td>In-shell</td>
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<td>110</td>
<td>60-75</td>
<td>Rosenthal <em>et al.</em>, 1984</td>
</tr>
<tr>
<td>In-shell</td>
<td>Beaumont (695)</td>
<td>102</td>
<td>70-75</td>
<td>Basker and Kadman, 1986</td>
</tr>
<tr>
<td>Shelled</td>
<td>Yonik</td>
<td>104</td>
<td>16</td>
<td>Basker and Kadman, 1986</td>
</tr>
<tr>
<td>Shelled</td>
<td>Hybrids*</td>
<td>127</td>
<td>12</td>
<td>Lemmer <em>et al.</em>, 1998</td>
</tr>
</tbody>
</table>

* Nelmak 1, Nelmak 2, Nelmak 26, Beaumont (695)
Table 1.8. Example of a roasting regime for a batch roaster used by an anonymous commercial macadamia processor

<table>
<thead>
<tr>
<th>Roast colour</th>
<th>Nut style</th>
<th>Temperature (ºC)</th>
<th>Duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Large, style 0-4</td>
<td>125</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Small, 5 - fine</td>
<td>130</td>
<td>40</td>
</tr>
<tr>
<td>Medium</td>
<td>Large, style 0-4</td>
<td>130</td>
<td>50 (25x2)*</td>
</tr>
<tr>
<td></td>
<td>Small, 5 - fine</td>
<td>135</td>
<td>50 (25x2)*</td>
</tr>
<tr>
<td>Dark</td>
<td>Small, 5 – fine#</td>
<td>138</td>
<td>40</td>
</tr>
</tbody>
</table>

* Trays mixed after 25 min
# Roasted for biscuits, confectionery

1.7. The chemical basis for food browning

1.7.1. Introduction

Browning of heated foods is a common phenomenon. It may be desirable, improving flavour and colour as in the case heated foods such as bread crust and fried potatoes (Friedman, 1996). Browning can also occur in foods that are not heated as a result of enzyme activity (Hutchings, 1994). This may be desirable, as valued products such as black tea, prunes and apple juice rely on enzymic reactions to produce some of their characteristics. Food browning only becomes a problem when the browning reaches undesirable levels or unpalatable by-products result. There are two broad types of food browning, 1) enzymatic browning (EB) and 2) nonenzymatic browning (NEB).

1.7.2. Enzymatic browning

A common example of enzymatic browning, reviewed by Palmer (1984) is browning of bruised fresh foods such as potatoes, and cut foods such as lettuce. This browning is a result of activation of the phenylalanine ammonia-lyase polyphenol oxidase pathway (Partington et al., 1999; Saltveit, 2000). Browning occurs when polyphenolic substances, usually contained within the plant cell vacuole, are oxidised by polyphenol oxidase (PPO), which is found in the cytoplasm. Tissue damage such as slicing, peeling, fungal attack or bruising will bring enzyme and substrates together
and result in browning (Coultate, 2002). Wounding of tissue produces signals propagating from injured to non-injured tissue and synthesis of phenylalanine ammonia-lyase (PAL), a first-order enzyme of the phenyl propanoid pathway (Saltveit, 2000). In biochemical terms, phenolic content and presence of oxidative enzymes such as PPO, or possibly even peroxidases, influence bruise development (Partington et al., 1999; Fukuoka and Enomoto, 2002). The end products are characteristic dark, melanin-type pigments such as in cut or bruised apple, bananas and potatoes (Coultate, 2002). Treatments to inactivate enzymes include adding cysteine or ascorbic acid, and heat treatment (Belitz et al., 2004). A 90 second heat shock at 45°C prevents an increase in PAL activity if administered to cut lettuce either 4h before or 2h after wounding (Saltveit, 2000). Some enzymes, however, can again become active after a heat treatment (Acker, 1962). In general, some protection of foods against the action of enzymes can be achieved by drying. However enzyme reactions can still occur, although at a reduced rate (Acker, 1962).

Macadamias are subject to another type of browning known as brown centres. As the name suggests, kernels have a brown coloured centre although this is not always obvious from the external appearance. In addition, these discoloured kernels often have a strong unpleasant flavour with moderate to severe sour, offensive odours (McConachie, 1992). Although the cause of this condition remains unclear, kernels with brown centres were shown to have higher levels of reducing sugars and lower levels of sucrose than unaffected kernels (McConachie, 1992). The problem may be due to unknown enzymatic degradation of oil bodies and sugars in affected kernels (McConachie, 1992).
1.7.3. Nonenzymatic browning

Nonenzymatic browning occurs in two principal forms, caramelisation and the Maillard reaction (Belitz et al., 2004). Caramelisation is a complex series of reactions involving the degradation of sugars and it occurs when sugars are heated at temperatures above 100ºC (Coultate, 2002; Belitz et al., 2004; Hutchings, 1994). However, caramelisation can also occur at lower temperatures such as prunes drying at 80ºC (Wilford et al., 1997). The resultant products are a wide range of flavour compounds and the brown pigments that are associated with caramelisation (Coultate, 2002). While heat is commonly involved in caramelisation, it can also be significant at shelf temperatures (Hutchings, 1994). The characteristic caramel pigments arise from a poorly understood group of polymerisation reactions (Coultate, 2002). This reaction can sometimes be manipulated and directed toward either aroma or brown pigment formation in controlled conditions (Belitz et al., 2004).

The other principal cause of browning in heated foods, the Maillard reaction, refers to complex heat-initiated protein-amino acid-carbohydrate reactions (Friedman, 1996; Labuza and Baisier, 1992). This reaction is still not understood fully although it has been studied extensively (Friedman, 1996; Belitz et al., 2004). The reaction requires reducing sugars and amino acids or proteins with available sites for bonding of carbohydrates (Friedman, 1996). Although lysine is often considered the amino acid most likely to be involved numerous studies have produced contradictory results and other amino acids are able to participate (Belitz et al., 2004). Although the reaction is initialized by heat, and the reaction rate increases markedly with temperature, high temperatures are not essential (Whitfield, 1992). Regulating moisture content of foods is an important way of controlling the Maillard reaction along with enzymic activities and peroxidation (Acker, 1962; Whitfield, 1992).
1.7 presents a generalised model of the relationship of water content and water activity to the reaction rates of these processes. The Maillard reaction is generally inhibited at both low (0.2) and high (0.8) water activity, reaching a peak at around $a_w$ 0.6 (Labuza and Baisier, 1992) but the actual relationships will depend on the food systems involved (Fig. 1.7 with Fig. 1.8). Macadamias are dried to 1.1% to 1.5% MC before roasting, representing $a_w$ of 0.2 to 0.3 (Beuchat, 1978). This is at the lower end of the Maillard reactivity range, so dark colours are still possible (Figure 1.8).

The Maillard reaction is often regarded negatively because it can cause deterioration of food during storage and processing and can produce deleterious products such as mutagens and carcinogens in some foods (Friedman, 1996). However, the reaction can also generate beneficial products such as antimutagens, antioxidants, antibiotics and antiallergens depending on the food (Friedman, 1996).

![Fig. 1.7. Generalised model of food degradative mechanisms as functions of water activity. Source: Labuza (1971)]
Amino acids or proteins are necessary reactants for the Maillard reaction. Macadamia kernels contain as much as 36.5% protein in the lipid-free meal (Saleeb et al., 1973) with much of the protein contained in protein bodies (Pate et al., 1986). Protein in protein bodies normally remains stable until germination (Vierstra, 1993). Macadamias probably contain sufficient amino acids to facilitate the Maillard reaction (Albertson, pers. comm.). Lysine is commonly the amino acid involved in the reaction, but arginine has also been reported to enable it (Belitz et al., 2004).

Macadamia is reported to have 73mg of lysine and 18mg of arginine per 100g of oil free meal (Saleeb et al., 1973). In addition to amino acids, kernels must have a source of reducing sugars for the browning reaction to take place. Most mature seeds have low levels of reducing sugars such as glucose and fructose (Cochrane, 1999) and this is true of macadamias. Macadamias are reported to have a glucose level of 0.08% and fructose level of 0.03% (Fourie and Basson, 1989). Similar browning reactions to those obtained with carbohydrates in the Maillard reaction are also suggested for oxidised lipids (Nawar, 1996; Hidalgo et al., 1999).
1.8. Summary

The macadamia industry in Australia is undergoing significant expansion and quality of kernels is of increasing importance to successful marketing. Much research on macadamia in the past has concentrated on cultural issues, but there has been limited research on quality issues. In particular, there is little information on the effect of handling practices on whole kernel, shoulder damage, pieces, oiliness of kernels, dusty kernels and on roasting quality. The major handling issues are impacts when nut-in-shell is dropped, the effect of dehuskers and the effect of delaying harvest on kernel quality.

The nature of the macadamia fruit may affect quality. Development of the fibrous husk necessitates mechanical dehusking and application of potentially damaging force, but little is known of the effects of dehusking. The fruit develops a very hard shell enclosing a softer embryo, the edible kernel. Many seeds are known to be damaged by impacts, especially at low MC, but the effect of impacts on macadamia quality is unknown.

Macadamia oil is mono-unsaturated and can undergo peroxidation and hydrolytic rancidity. Peroxide values and free fatty acid analysis, the chemical analyses used to evaluate macadamia rancidity, are not considered adequate to predict rancidity. It is not known whether dropped kernels are more prone to rancidity.

The amount of macadamia sold as roasted kernel depends on the market but most is eventually marketed at the retail level as roasted product (Mason et al., 1995). This makes influences on roasting quality important. A condition known as after roast darkening (ARD) of roasted kernel is of concern. Little is known of the causes predisposing macadamia kernel to ARD although browning of heated foods is often related to an increase in reducing sugars.
The following research questions have emerged from this literature review and will be investigated in the following chapters, 1) Do mechanical dehuskers affect macadamia kernel quality? 2) Does delaying harvest reduce macadamia kernel quality? 4) Does dropping macadamia NIS reduce kernel quality? 5) Is kernel from dropped nuts more subject to rancidity?
CHAPTER 2.

Ultrastructure and breakage of macadamia kernels

2.1.1. Introduction

Macadamia is an important horticultural crop in Australia, Hawaii, South Africa and other countries (Anon., 2005). The edible kernel of macadamia is composed of the mature embryo with two large cotyledons that store very high concentrations of oil (Stroschen, 1986). Much research for the crop is now focussed on maintaining and improving quality because of increasing production worldwide and resultant competition (Mason et al., 1995; Mason, 2000). An important aspect of quality is whether kernels remain whole or separate at the junction of the cotyledons. A factor which may influence kernel separation is a naturally occurring partial gap between cotyledons of some kernels. Gaps between cotyledons before cracking of nuts have been demonstrated by x-rays of whole nuts (Cavaletto, 1979; Wallace et al., 2001). Gaps may weaken the bond between cotyledons. There is also some evidence that the tendency to remain whole is influenced genetically, that is, by cultivar (Stephenson and Gallagher, 2000; Walton and Wallace, 2005).

All plant surfaces are covered by cuticle, an interface between plants and the atmosphere (Walton, 1990). All surfaces of the mature macadamia embryo (kernel) are covered with a cuticle and there is a double cuticle between the two cotyledons in the centre of the kernel between the adaxial surfaces (Walton and Wallace, 2005). Whole kernels separate into halves at the interface of the adaxial cuticles of the two cotyledons, more specifically, at the epicuticular wax of the cotyledons. It is not
known whether the ultrastructure of the adaxial cuticles of the cotyledons influences the tendency to separate. Examination of the ultrastructure of the double cuticle may provide indications of the reasons for cotyledon separation, and aid strategies to improve whole kernel production.

Another quality issue is that dusty kernels are generated during postharvest handling of NIS. This dust may result from damage to the surface of kernels caused by postharvest handling of macadamia NIS. This issue will be investigated in Chapter 6. Macadamias as NIS are subjected to as many as 20 drops after harvest (McConachie, pers. comm., 2002), and the hard shell of the nut may damage kernels during dropping. Examination of the abaxial surface of kernels from dropped and undropped NIS may provide information on the extent and nature of damage to the surface.

This study has three aims, 1) to measure the gaps between whole and separated (broken) kernels still in-shell for any relationship to whole kernel, 2) to describe the ultrastructure of the adaxial cuticle of the mature macadamia embryo of high and low whole kernel cultivars, and 3) to examine the ultrastructure of the abaxial surface of dropped and undropped kernels.

2.2. Materials and methods

2.2.1. The gap between cotyledons

One hundred nuts for each of cultivars HAES 344 and HAES 741 were harvested at Glasshouse Mountains (26°53.44'S, 152°56.16'E) in early August 2004. Nuts were dehusked by hand with aviation snips and immediately after dehusking, nuts were dried in laboratory fan-forced ovens. The drying regime was 2 days at 38°C, 2 days at 45°C followed by the required time at 58°C to dry nuts to 3% MC NIS wet basis (wb), to achieve approximate kernel moisture content of 1.5% (Anon, 1995). MC was
determined by drying nuts for 24 h in a laboratory fan-forced set at 105 °C (Atkinson, 1991). Nuts were sawn open with a “junior” hacksaw in the “equatorial” region midway between the hilum and micropyle. The kernel was then removed from the shell with minimal force, and if still whole, was bisected perpendicular to the adaxial cotyledon axis to expose the join between the halves of the kernel. Kernels that had separated were bisected in the same manner, and adjacent quarters were rejoined by pinning with an entomology pin to retain original structure and display any gap (Fig. 2.2). Whole kernels and half kernels at removal from the shell were counted, and the following measurements were recorded:

1. length of the join between the cotyledons,
2. the maximum width of gap,
3. the gap length.

2.2.2. TEM of mature macadamia embryo cuticle

2.2.2.1. The adaxial cuticle of macadamia kernel

For examining ultrastructure of the adaxial cuticle, nuts were sampled from mature trees on a commercial farm at Wolvi in S.E. Queensland (26°9.63’S, 152°48.65’E) in August 2002. Samples of the double cuticle at the cotyledon interface were cut from whole nuts of HV A38, HAES 835, HAES 344 and HAES 741 cultivars. Samples were approximately 1.5mm³. Samples were fixed in 3% glutaraldehyde in 0.1M phosphate buffer at pH 7.0 for 48 h. The fixative was changed and the samples were fixed for a further 24 h. Samples were then washed twice in 0.1M phosphate buffer for two 24 h periods, fixed in 1% osmium tetroxide in 0.1M cacodylate buffer for 24 h and washed twice in 0.1M phosphate buffer for 3 h. Samples were then dehydrated in an acetone series and infiltrated in a Spurrs resin series. Transverse sections of the cotyledon junction of the samples of 50-60 nm
thickness were cut with a Leica Ultracut-T ultramicrotome and mounted on pioloform-coated copper slot grids. The sections were stained with 5% uranyl acetate and Reynold's Lead Citrate. These sections were viewed in a JEOL 1010 transmission electron microscope operated at 80 kV. The cuticle structure of high whole kernel cultivars (HV A38, and HAES 835) was compared with known low whole kernel cultivars (HAES 344 and HAES 741) using these sections (Table 2.1).

<table>
<thead>
<tr>
<th>Cultivar</th>
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<th>Nut</th>
<th>Sections viewed</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>HAES 835</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>HAES 344</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
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<td>HAES 741</td>
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<td>1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2.2.2. **Ultrastructure of the abaxial surface of dropped and undropped kernels**

Five kernels from dropped nuts and five kernels from undropped nuts of cultivar HAES 344 were selected. Dropped nuts had been dropped four times from a height of two metres onto a bed of NIS. Samples from the abaxial surface of the kernels were cut for TEM with a two-edged stainless steel razor blade. Samples approximately 2 mm long by 1 mm wide were cut from near the ‘equator’ of both the damaged and undamaged kernels. Samples were then processed and embedded in Spurr's resin as described above in 2.2.2.1. Thin sections (1 µM) were cut on a Leica Ultracut T ultramicrotome and stained with toluidine blue for light microscopy (LM). Ultrathin sections (60 nM) were cut on a Leica Ultracut T ultramicrotome and stained as
described above. Thin samples for LM were previewed on an Olympus BH-2 microscope fitted with an Olympus DP-10 digital camera. Ultrathin samples for TEM were viewed on a JEOL 1010 transmission electron microscope operated at 80 kV.

2.2.3. SEM of macadamia embryo cuticle

2.2.3.1. Surface morphology of the adaxial cuticle

Whole kernels of high whole kernel cultivar, HV A38, and low whole kernel cultivar HAES 741 were selected and heated in a laboratory oven for 2 hours at 60°C. After removal from the oven the cotyledons were separated immediately while still warm by prying apart with a scalpel at the cotyledon junction, taking care not to damage the adaxial surface with the scalpel. While the cuticle wax was still warm the cotyledons separated readily. Half kernels which had become separated during normal processing in the laboratory were also selected as controls. Samples approximately 2 mm square and 1 mm thick were then cut from the adaxial surface for SEM examination. Care was taken to cut from a flat section of the surface of heat-separated whole kernels to try to ensure that the cotyledons had been in contact prior to separation. Obviously torn areas were avoided. Samples were also cut from half kernels for comparison with the whole, hand-separated kernels. Samples from halves were cut from concave areas of the surface that had not been in contact. Samples were mounted on stubs exposing the adaxial cuticle and coated with platinum in a BioRad Sputter Coater. These samples were then viewed in a JEOL 6300FSEM operated at 5-10 kV. Hand-separated and naturally separated adaxial cuticle surfaces were examined to compare the appearance of the cuticle.
2.2.3.2. *Surface morphology of the abaxial cuticle of dropped nuts*

A macadamia kernel of dropped NIS of cultivar HAES 344 showing dust at cracking as evidence of damage from impacts was selected. Samples from the abaxial surface of the kernel were cut for SEM with a double-edged stainless steel razor blade. Samples were also cut from an undamaged kernel as a control for comparison. Samples approximately 2 mm square and 1 mm thick were cut from near the “equator” of both damaged and undamaged kernels. Samples were mounted on stubs exposing the abaxial cuticle and coated with gold in a BioRad Sputter Coater. These samples were then viewed in a JEOL 6300FSEM operated at 5-10 kV. Dusty nut surfaces and control surfaces were examined for differences in the appearance of the cuticle.

2.2.4. *Statistical analysis*

The gap length between cotyledons was calculated as a percentage of the total length of the join between the cotyledons, that is, of the adaxial axis, by the formula:

\[
\text{Gap length } \% = \frac{\text{Gap length} \times 100}{\text{Length of adaxial axis}}
\]

Mean gap width, mean gap length and mean gap % were calculated. Data were analysed for significance using SPSS software version 10.05. Because data were non-parametric, Kruskal-Wallis and Mann-Whitney tests were used to test for significant differences \((P < 0.05)\) and a Bonferroni correction factor applied to determine the appropriate level of significance.

2.3. *Results*

2.3.1. *The gap between cotyledons*

Cultivar HAES 344 had a significantly longer gap than HAES 741 for kernels that were half at nut opening (Fig. 2.1), and 344 also produced less whole kernel (49%)
than HAES 741 (71%). Gap width for separated kernels (halves) was more than twice that for wholes for both cultivars ($P<0.001$) (Fig. 2.1); similarly, gap length for halves

![Figure 2.1](image)

**Fig. 2.1.** Differences between whole kernels and separated kernels of cultivars 344 and 741 for the naturally occurring gaps between the cotyledons. A, gap width (mm), B, gap length (mm) and C, gap length (%), gap length expressed as a percentage of the total length of the cotyledon axis. Means with different letters are significantly different ($P<0.001$ for all, except for differences between gap length of 344 and 741 halves and their respective wholes, $P=0.001$).
was more than twice that for wholes \((P=0.001)\) (Fig. 2.1). Similar differences were found for the gap length % with half kernels of both cultivars having gap length % more than twice that of wholes \((P<0.001)\) (Fig. 2.1). Examples of the differences in morphology of the gaps of halves and wholes for cultivar HAES 344 are shown in the images in Fig. 2.2. To summarise these results, cultivar HAES 344 had a wider and longer gap for halves than HAES 741, and produced 30% less whole kernel than HAES 741. The cultivar with the shortest gap and the narrowest gap (HAES 741) produced 45% more wholes.

<table>
<thead>
<tr>
<th>Half Kernels</th>
<th>Whole Kernels</th>
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<td><img src="image1.png" alt="Half Kernels" /></td>
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<tr>
<td><img src="image19.png" alt="Half Kernels" /></td>
<td><img src="image20.png" alt="Whole Kernels" /></td>
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</tbody>
</table>

**Fig. 2.2.** Macadamia kernels, cultivar HAES 344, showing the cut surface, cut perpendicular to the axis of the cotyledons to reveal gaps. Shells have been opened by sawing to eliminate stresses on kernels caused by mechanical cracking. ‘Half kernels’ are those which have already separated at nut opening. Note that gaps are generally wider and longer for half kernels than for wholes.
2.3.2. TEM of macadamia embryo cuticle

2.3.2.1. The adaxial cuticle of kernels of high and low whole kernel cultivars

In transverse sections viewed by TEM, low whole kernel cultivars HAES 344 and HAES 741 (Fig. 2.3.C, 2.3.D) displayed consistently wider, more clearly defined epicuticular wax than the high whole kernel cultivars HV A38 and HAES 835 (Fig. 2.3.A, 2.3.B). The wax layer of HV A38 was less distinctive than the other cultivars. However, HAES 344 cuticle was not always wider (Fig. 2.4). All cultivars shared some features of cuticle such as a reticulate cuticular layer and more amorphous cuticle proper (Fig. 2.4.B, 2.4.C, 2.5), overlying laminate cell walls (Fig. 2.4.A, 2.4.B, 2.4.C, 2.4.D). A pectic cuticular peg formed from an excessive outer reticulate region extends between the middle lamellae of epidermal cell junctions (Osborn and Taylor, 1990) (Fig. 2.3.D, 2.6). Numerous oil bodies appear as globose grey objects in some sections (Fig. 2.3.C, 2.3.D).
Fig. 2.3. Comparison of the epicuticular wax width of high-whole kernel cultivars (A & B) with low whole kernel cultivars (C & D). A = HV A38, B = HAES 835, C = HAES 344, D = HAES 741. w = epicuticular wax, c = cuticle, cw = laminate cell wall, cp = pectic cuticular peg, ob = oil body. A, bar = 500 nM; B, bar = 200 nM; C, bar = 1 μM; D, bar = 1 μM.
Fig. 2.4. Adaxial cuticle of macadamia kernels of cultivars A, HV A38; B, HAES 835; C, HAES 344; D, HAES 741. w = epicuticular wax, c = cuticle, cpr = cuticle proper, cl = cuticular layer, cw = laminate cell wall. All bars = 100 nM.
Fig. 2.5. Cuticle of cultivar HV A38 showing fibrillae in reticulate cuticular layer. Cw = laminate cell wall, w – epicuticular wax, f = fibrillae, cp = cuticle proper, cl = cuticular layer. Bar = 100nM.

Fig. 2.6. Cuticular peg of macadamia kernel, cultivar HAES 741. w = epicuticular wax, cpr = cuticle proper, cl = cuticular layer, rr = outer reticulate region, cp = pectic cuticular peg. Bar = 2 μM.
The cuticular layer contains distinct fibrillae (Viougeas et al., 1995) (Fig. 2.5) and the outer reticulate region (Osborn and Taylor, 1990) merges into an incrustation of the cell wall (Fig. 2.6). The intense, dark staining of this region in Fig. 2.6 is an indication of a pectin layer, a feature that is notoriously difficult to stain in TEM (Holloway, 1982). Fibrillae in the pectic cuticular peg merge into the cell wall (Fig. 2.5, 2.6).

### 2.3.2.2. The abaxial cuticle of dropped and undropped kernels

Macadamia kernel has a well defined abaxial cuticle (Fig. 2.7). The cuticle appears as a grey layer but has dark staining regions on the surface (Fig. 2.8). Numerous protein storage vacuoles (PSVs) (protein bodies) can be seen in epidermal cells (Fig. 2.8.A). While the cuticle can be clearly distinguished from the cell wall (Fig. 2.8.A), a cuticular layer and cuticle proper cannot be defined (Fig. 2.8.B). The epicuticular wax is irregular in thickness with some large deposits (Fig. 2.8). The wax is coated with spherical, osmophilic objects (Fig. 2.7, 2.8).

![Fig. 2.7](image)

**Fig. 2.7.** Light micrograph of transverse section of the abaxial surface of macadamia kernel stained with toluidine blue: ec = epidermal cells; c = cuticle, triangles indicate dark-staining regions. Bar = 20 µM.
Fig. 2.8. TEM micrographs of abaxial cuticle of macadamia kernel: c = cuticle, cw = cell wall, w = epicuticular wax, oo = osmophilic objects, cp = pectic cuticular peg. A: psv = protein storage vacuole, Bar = 5 µM. B: Bar = 1 µM.
2.3.3. Surface morphology of macadamia cuticle

2.3.3.1. Surface morphology of the adaxial cuticle of high and low whole kernel cultivars

Adaxial cuticle surfaces of whole kernels of high whole kernel cultivar HV A38 separated after heating showed areas of torn cuticle, and epidermal cells were clearly exposed where cuticle had been torn (Fig. 2.9.A). By contrast, wax surfaces of low whole kernel cultivar HAES 741 separated after heating exhibited less tearing of cuticle and cell outlines were clearly defined by the cuticle (Fig. 2.10.A). This demonstrated that whole kernels of HAES 741 separate more readily than HV A38 when heated. Adaxial cuticles of both cultivars displayed different surface morphology for heat-separated wholes from naturally separate halves (Fig. 2.9.B and 2.10.B). Natural half kernels of both high whole kernel cultivar HV A38 and low whole kernel cultivar HAES 741 shared a similar appearance, exhibiting a sculptured, angular surface (Fig. 2.9.B, 2.10.B). This appearance suggested a crystalloid structure.
Fig. 2.9. A: adaxial surface of whole macadamia kernels of cultivar HV A38 separated after heating. Note torn areas of cuticle. B: adaxial surface of natural macadamia half, cultivar HV A38.
Fig. 2.10. A: adaxial surface of whole macadamia kernel of cultivar HAES 741 separated after heating. B: adaxial surface of natural macadamia half, cultivar HAES 741.
2.3.3.2. *Surface morphology of the abaxial cuticle of dropped and control kernels*

The control samples had a different appearance to the dropped samples (Fig. 2.11). For all samples, SEM images showed epicuticular wax similar to that defined as a crust (Barthlott et al., 2002). Wax covering of the control samples had a more amorphous appearance than the damaged samples (Fig. 2.11.A, 2.11.C, 2.12.A). The control samples also differed in the degree of crusting of the surface (Fig. 2.11.A, 2.11.C). Damaged surfaces from dusty kernel clearly displayed the outline of convex outer tangential walls of epidermal cells (Fig. 2.11.B, 2.11.D). The outline of the epidermal cells of the controls was far less clear than of the damaged samples (Fig. 2.12.A, 2.12.B). The definition of cells of control tissue was almost obscured by more amorphous epicuticular wax, whereas the cells of damaged samples were much more clearly defined (Fig. 2.11, 2.12). The epicuticular wax of all samples displayed a granular structure. These granules were considerably reduced in size and occurrence on the damaged samples (Fig. 2.11.B, 2.11.D, 2.12.B). These differences between epicuticular wax appearance between controls and damaged samples were found in all five sections of sample examined. One sample (Fig. 2.11.D) had clumps of particles, probably aggregations of dust.
Fig. 2.11. Abaxial surface of mature macadamia embryo (kernel) as shown by SEM. A: C = control (no dropping); B: D = dusty kernel (nut-in-shell dropped repeatedly). Note that amorphous wax crust of control samples (A,C) conceals epidermal cells and that cell outlines of dusty samples (dropped, B, D) are much more clearly defined (arrows).
Fig. 2.12. High magnification SEM images of change in cuticle as a result of repeated dropping of NIS. A = control, not dropped, B = kernel from dropped nut. Note the more amorphous wax covering of the undamaged control kernel, A. Note also that while little evidence of cell shape can be detected in the control, A, in the dropped sample, B, cells are much more clearly defined.
2.4. Discussion

The major findings of this chapter are: 1) there may be a relationship between the width and length of the gap between cotyledons and kernel breakage; 2) low whole kernel cultivars have thicker adaxial epicuticular wax than high whole kernel cultivars; 3) the abaxial cuticle of macadamia has a wax crystalloids of a crust type with prominent wax projections; 4) abaxial epidermal cells contain many protein storage vacuoles.

2.4.1. The gap between cotyledons

Separation of cotyledons may be due to a simple mechanism, that is, the naturally occurring gap between cotyledons. Two known low whole kernel cultivars (Stephenson and Gallagher, 2000; Walton and Wallace, 2005) were compared, and the cultivar with 30% less whole kernel, HAES 344, had significantly wider and longer gaps than HAES 741. Stephenson and Gallagher (2000) by contrast found that HAES 344 produced more whole kernel, perhaps due to HAES 741 being more susceptible to mechanical force. However, both cultivars produced acceptable whole kernel in this experiment. The reason for this may be that nuts were sawn apart with minimal force applied, compared with mechanical cracking (Stephenson and Gallagher, 2000).

Where the gap is narrow and the cotyledon surfaces flat, extruded epicuticular wax from each cuticle can fill the gap and bond halves together. Where the gap cannot be bridged, the surface area of bonding is reduced and the kernel join is inherently weak. This bonding may be due to the interlocking of like molecular substances in close proximity in the early stages of wax deposition. Many half kernels have a concave surface (Fig. 2.2). This shape greatly reduces the area of surface in contact. This surface morphology may be the result of drying to low MC, and low
whole kernel cultivars may be more subject to developing concave surfaces when
dried. Another possibility is that the high whole kernel cultivars may be more efficient
at this process than low whole kernel cultivars, resulting in reduced gaps. A study of
gap development in embryos (from 20 weeks post-anthesis until maturity) of high and
low whole kernel cultivars may reveal if gap development is related to cultivar and
filling of the shell.

These naturally occurring gaps may also aid production of the characteristic
sculptured wax surface on cotyledons. A gap wide enough to preclude bonding of wax
will also allow the characteristic sculptured wax structure of the surface of halves to
develop, while closely pressed cotyledons will not allow the characteristic structure to
form. Gaps may not develop until the nuts are dried fully. For this reason cracking at
slightly higher MC may help to prevent kernel breakage. The effect of drying on the
size of gaps could be investigated by examining gaps of moist and dry kernels.

2.4.2. Adaxial cuticle structure of high and low whole kernel cultivars

The main difference between high and low whole kernel cultivars discernible in
TEM micrographs was the thickness of the epicuticular wax between cotyledons. The
combined wax layers of the two cuticles in the adaxial region appeared generally
thicker in the low whole kernel cultivars, HAES 344 and HAES 741 although the
width of wax varied in the adaxial cuticle regions of HAES 344 examined. More
studies would be needed to confirm that HAES 344 and HAES 741 have consistently
thicker adaxial wax. The thickness of wax may mean that the amount of wax
production may be a factor in low whole kernel. The amount of wax produced may be
genetically controlled, giving the potential for genetic improvement. The thickness of
wax may also be due in part to a wider gap between cotyledons in low whole kernel
cultivars. Narrower gaps in high whole kernel cultivars may physically limit wax
deposition. Further study of the adaxial cuticle of more high and low whole kernel cultivars is needed to clarify if there is a link between epicuticular wax width and whole kernel.

Numerous electron dense objects were found in the adaxial cuticle of macadamia kernels by Walton and Wallace (2005), but were not found in this study. Further TEM study of the macadamia cuticle using KmnO₄ and ruthenium red in addition to OsO₄ may provide additional information about the attachment of the cuticle to the cell wall and other details (Holloway, 1982).

### 2.4.3. Abaxial cuticle structure of dropped and undropped kernels

This study showed that abaxial epidermal cells are clearly radial and columnar in shape, compared with the tangential, rectangular adaxial epidermal cells reported by Walton and Wallace (2005). The abundance of oil bodies in epidermal cells corresponds with the oil content of macadamia, as high as 75 to 80% (Saleeb et al., 1973; Trueman et al., 2000). Numerous protein storage vacuoles occur in epidermal cells, related to a protein content of around 9% (Saleeb et al., 1973). The large wax deposits on the cuticle may be elevated regions of the crust profile (Barthlott et al., 1998, Fig. 2.13). However, there may be some doubt regarding the integrity of the surface as the epicuticular wax of plant cuticles is very difficult to preserve intact and view by TEM (Holloway, 1982).
The osmophilic objects on the surface of the cuticle of TEM samples are clearly regular and spherical in shape, which is typical of fixed lipids, no doubt fixed by osmium before dehydration with acetone. This fixed lipid is very likely an artifact of sample preparation as it appeared in both dropped and undropped samples. Caution should normally be exercised in interpreting the nature of the external cuticle of TEM samples because the methods used to prepare the samples for TEM usually result in serious alteration of the wax surfaces (Reed, 1982). The use of high concentrations of acetone and polymerisation of resin at the standard 60°C can result in smoothing of the wax surface and in the worst case removal of all wax (Reed, 1982). However, this degrading process may be alleviated to some degree by the addition of osmophilic material to the wax surface (Reed, 1982). This appears to be the case with the macadamia samples where a continuous layer of osmophilic material overlays the epicuticular wax (Fig. 2.7, 2.8). An osmophilic surface layer such as this is reported by Holloway (1982) on the cuticle of Clivia miniata and Vicia fabiata. This fixed

**Fig. 2.13.** Schematic drawing of one of the main types of epicuticular wax deposits, a crust. Crusts are of considerable thickness (0.5-10μM) and have definite surface sculpturing. Source: Barthlott et al. (1998).
lipid layer on the macadamia surface appears to have protected the cuticle and enabled viewing of an intact surface.

2.4.4. Adaxial cuticle differences in surface morphology for high and low whole kernel cultivars

For whole kernels, SEM suggested some differences in the wax between the heat-separated cotyledons of cultivars HV A38 and HAES 741. In general, heat-separated wholes of both cultivars appeared to have less wax than halves, as shown by visibility of epidermal cells. There may be a feedback mechanism which reduces deposition of wax when surfaces are in contact compared with when there is a gap between cotyledons. The converse of this is that when there is a gap there is a stimulus to produce more wax as a protective measure for the embryo.

All half kernels of HAES 741 and some half kernels of HV A38 exhibited a generous covering of adaxial wax, while some half kernels of HV A38 displayed good cell detail, suggesting a light wax covering. The reduced wax on some HV A38 halves is another indication that HAES 741 produces more wax than HV A38. The characteristic sculptured appearance of the half kernels may be due to the chemical properties of the epicuticular wax. In the simplest form, cuticles are covered by an obligate film of wax over the cuticle proper (Holloway, 1982; Barthlott et al., 1998). In many species wax crystalloids form when sufficient wax is produced, with great variation in wax structures occurring between species and some variation within species (Holloway, 1982; Barthlott et al., 1998). The term crystalloid is used instead of crystalline to acknowledge that molecular organization of most epicuticular waxes has not been determined (Barthlott et al., 1998). Different morphology of crystalloids is related to differences in chemical composition (Jeffree et al., 1975; Gulz, 1984). A classification system and terminology has been suggested for epicuticular wax
crystalloids based on their micro-morphological features, not on chemical composition (Barthlott \textit{et al.}, 1998). According to this system, macadamia has wax of the crust type with simple crystalloids (Fig. 2.9.B, 2.10.B, 2.13). Where there is a gap between cotyledons there is room for the wax structure to develop unhindered resulting in a characteristic simple crystalloid crust surface. Structure of epicuticular wax is mainly dictated by inherent chemical and physical properties (Jeffree \textit{et al.}, 1975).

Epicuticular wax composition may play a part in the cotyledons remaining attached to maintain a whole kernel. The cotyledons are attached predominantly at the interface of the adaxial wax surfaces and the characteristics of the wax may be involved in the tendency of kernels to remain whole. There are several features of epicuticular wax which could affect kernel breakage: 1) the quantity of wax present on each cotyledon; 2) wax morphology; 3) the chemical composition of the wax.

\textit{Quantity of wax}

The quantity of epicuticular wax produced is variable. It is dependent on environmental conditions, such as radiant energy flux, humidity and soil moisture content (Walton, 1990). The rate of radiant energy regulates the quantity of wax formed in a direct relationship and low relative humidity and low soil moisture increase wax deposition (Baker, 1974; 1982). The gap between cotyledons may affect the quantity of wax produced, predisposing more adaxial wax deposition. Half kernels appear to have thicker wax layer on the adaxial cuticle compared with whole kernels, perhaps enabled by a large gap between kernels. Genetic factors may also affect the quantity of wax, for example, variations in gaps between cotyledons for different cultivars may affect the quantity of wax. The increased wax may in some as yet unknown way contribute to kernel breakage. However, most of the literature on plant
cuticles is related to leaves exposed to light, although there is information that jojoba leaves and seed coat have similar quantities of wax (Gulz, 1984). However, little is known about the effect of environmental conditions on the cuticle of embryos, a subject that merits further study.

Wax morphology

While wax morphology is under genetic control (Lundqvist and Wettstein, 1962), configuration, size and distribution of crystalloid waxes can be strongly influenced by environmental conditions (Baker, 1974; 1982). Morphological structure is determined by chemical composition (Baker, 1982; Gulz, 1984). Wax morphology being under genetic control raises the possibility that there may be subtle differences between the crystalloid structure of the epicuticular wax of different cultivars. Such differences may influence kernel separation at the wax interface between halves.

Composition of wax

Wax composition is less influenced by environmental factors (Walton, 1990) and some studies indicate there may not be much variation in wax composition from year to year. In a study of variation in the composition of epicuticular wax from Quercus robur years, Gülz and Miller (1992) found little variation in waxes in the years 1990-1991. This indicates that wax composition is strongly genetically determined (Gülz and Miller, 1992). Genetic control of composition is important with cuticular wax composition varying both among species and within a species (Post-Beittenmiller, 1996). It is possible that different cultivars of macadamia may have wax of different chemical composition. This in turn may affect the strength of the bond between cotyledon wax surface. Differences in epicuticular wax composition of high and low whole kernel cultivars could be investigated by HPLC.
2.4.5. Abaxial cuticle surface morphology of dropped and undropped kernels

The surface morphology of the abaxial cuticle of the dusty kernel was visibly different from the control. This contrast between the dropped nut and the undropped control provided a clear visual example of the damage that dropping nut-in-shell can cause. The control images were in appearance very similar to that described for *Pistacea vera* having an amorphous surface with a thick, granular, semicrystalloid crust superimposed (Baker, 1982). The surface of the adaxial cuticle was much more clearly defined than that of the abaxial cuticle, which has a more irregular, amorphous surface. The different surface may be a response to its exterior location on the embryo and the need for greater protection.

2.4.6. General features of macadamia cuticle

While there were differences in the cuticle structure of high and low whole kernel cultivars there were also similarities. All cultivars exhibited similar features of cuticle, such as a reticulate cuticular layer and more amorphous cuticle proper, overlying laminate cell walls (Osborn and Taylor, 1990). A cuticular peg formed from an excessive outer reticulate regions extends between the middle lamellae of epidermal cell junctions (Osborn and Taylor, 1990). This peg appears to be pectic in nature, rather than an extension of the cuticular layer, as indicated by its more electron-dense appearance (Holloway, 1982).

Macadamia cuticle is a Type 4 cuticle as classified by Holloway (1982), the main feature of this classification being that all regions are reticulate, that is, contain fibrillae. Fibrillae, which are stained by lead citrate, form an incrustation into the cell wall, and the pectin layer at the junction of the cuticular membrane (cuticle) with the cell wall is the origin of the fibrillae which permeate the reticulate region and the
cuticular layer (Holloway, 1982). In macadamia their more electron-dense appearance indicates that the pegs are pectic in nature (Holloway, 1982).

2.5. Summary

This study provided information on some factors involved in whole kernel and visible evidence of damage from dropping. Kernels that separate into halves have larger gaps between cotyledons than kernels that remain whole. The nature of gaps may be related to cultivars. Wax is thicker between the cotyledons of low whole kernel cultivars than high whole kernel cultivars. In addition, the cotyledons of high whole kernel cultivars are more strongly joined by this thinner layer of wax. Amount and composition of wax are most likely under genetic control.

Clear differences were found in the surface wax of kernel from dropped nuts compared with undropped controls. The cuticle was damaged, partially exposing epidermal cells. The damaged cuticle is less effective at protecting the kernel from further damage and microbial attack. Further SEM studies of this subject would be inexpensive and useful.

Directions for future research could be: 1), further study of the relationship of the gap between cotyledons to whole kernel for different cultivars; 2) Further study by SEM of kernels subjected to dropping.
CHAPTER 3

Chemical testing of dropped and undropped macadamia kernels for rancidity

3.1. Introduction

Macadamia nuts (NIS) are subjected to as many as 22 drops before nuts are cracked (McConachie, pers. comm., 2002). The effect on kernel quality of dropping macadamias as NIS will be examined in Chapter 6. Macadamia kernels contain as much as 80% oil (McConachie, 1997; Trueman et al., 2000) and macadamia contains 88% unsaturated fatty acids (McConachie, 1997). Macadamia oil may be subject to oxidative rancidity because of the high degree of unsaturation of oils (Robards et al., 1988a). In addition, hydrolytic rancidity of macadamias can result from the action of endogenous enzymes (Cavaletto, 1983). Volatile by-products of oxidation and short-chain fatty acids from hydrolysis produce rancid flavours in oily food products (Robards et al., 1988a; Nawar, 1996; Dela Cruz, 1966). It is not known whether kernels from dropped nuts are more prone to rancidity. The aim of this study is to determine by chemical analysis whether kernels from dropped nuts have detectable chemical differences to those from undropped nuts.

3.2. Materials and methods

3.2.1. Peroxide values

Oil samples were extracted from the first five of ten replicates of treatments of NIS dropped at 20% and 3% NIS MC in dropping Experiment 6.1 (Chapter 6). In this experiment nuts were dropped 4 times from a height of 2 metres onto a bed of NIS at 20% and 3% NIS MC. The nuts were dropped in June, cracked in July and tested for
Peroxide Values (PV) in December, 6 months after cracking. Kernels were stored in a laboratory at 22°C until mid-November, when it was moved to a cold-room at 4°C. Samples were obtained from both dropped nuts and undropped controls, for cultivar HAES 344 only. Between 5 and 7 whole kernels per replicate were randomly selected for oil extraction, depending on the number of whole kernels available in the replicate. The kernels were then crushed twice with a garlic press, the crushed kernel mixed to a slurry with pentane, and allowed to stand for 5 minutes. The slurry was then filtered, assisted by vacuum. The pentane was then stripped from the oil in a Buchi Rotavapor R-205. The resultant oil was divided for Peroxide Value and Free Fatty Acid determination and stored at 4°C ready for analysis. Samples were analysed within one week.

Peroxide Values were determined using AOAC method 965.33 modified as follows: smaller samples of oil were used (1g instead of 5g); 0.01N Na$_2$S$_2$O$_3$ was used instead of 0.1N Na$_2$S$_2$O$_3$; and, Na$_2$S$_2$O$_3$ titration was accomplished with a 100µL HPLC syringe instead of a burette. Peroxide Value (expressed as milliequivalents of peroxide per kilogram of sample) was calculated according to the formula:

$$PV = \frac{(S - B) \times N \times 1000}{\text{Sample wt (g)} \times 1000}$$

where:

$S = \text{sample titration (µL)}$

$B = \text{blank titration (µL)}$

$N = \text{normality of Na$_2$S$_2$O$_3$}$

3.2.2. Free fatty acids

Free Fatty Acid (FFA) values were determined using AOAC method 940.28, modified as follows: smaller samples of oil were used (1mL instead of 7.05mL); 0.1N
NaOH was used instead of 0.25N; and NaOH titration was accomplished with a micro-syringe instead of a burette. Free Fatty Acids were calculated as follows:

\[
\text{% FFA (as oleic) = } \left( \frac{\mu L \text{ alkali} \times N \text{ of alkali} \times 28.2 \text{mg}}{\text{sample wt} \times 1000} \right)
\]

3.2.3. Headspace analysis of artificially aged macadamia kernels

Nuts at 3% NIS MC were dropped four times onto a bed of NIS from a height of two metres. Kernels were then artificially aged for 22 weeks at two MC and compared with their respective undropped controls for volatile compounds. All moisture contents in the experiments in this thesis are calculated on a wet basis (wb). The moisture contents were: 1) < 1.5%, the industry recommended MC for kernel storage (Cavaletto et al., 1966); and 2) 2.4%, which is considered too moist for safe storage.

There were four treatments, one for each MC from the 3% dropped treatment and one undropped control for each MC. From each of ten replicates of each treatment nine half kernels were randomly selected and placed in 50mL screw top glass vials fitted with teflon septa. Vials were stored for 22 weeks in an incubator at 37°C followed by 6 weeks in a laboratory at approximately 21°C.

Treatments were tested for volatile byproducts to indicate oxidative deterioration using a Varian 3900 series (GC-MS) (Hansen Way Palo Alto, USA). A sample of 0.4mL headspace gases from each vial was injected manually into the GC-MS using a 1.0 mL gas-tight syringe. The injector split was closed in the first 18 seconds of the run, then opened to a split ratio of 50:1. A Zebron ZB-5ms 15m x 0.255mm x 0.25μm column was used with an initial column temperature of 30°C for 5 min then ramped at 10°C min⁻¹ to a final temperature of 200°C for 2 min, while the total run time was 24 min. The column flow rate was 1.2mL/min. Compound ionisation was by electron impact at 70eV and identification was performed using a mass range of 26 m/z to 300
m/z. Data was analysed using Varian MS Workstation software (Varian, Hansen Way, Palo Alto, USA). Because the peak areas of volatiles were too small for reliable measurement, peak heights were compared.

### 3.2.4. Statistical methods

Non parametric data for PV were analysed for significance by Kruskall-Wallis and Mann Whitney tests. FFA were analysed for significance by analysis of variance with 3 degrees of freedom, and Tukeys test for comparison of means ($P<0.05$).

### 3.3. Results

#### 3.3.1. Peroxide Value

There were no significant differences between treatments for Peroxide Value. All means were very low (Table 3.1).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Drop</th>
<th>Control</th>
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<tbody>
<tr>
<td>3% MC</td>
<td>0.10 (0.04)</td>
<td>0.04 (0.04)</td>
</tr>
<tr>
<td>20% MC</td>
<td>0.09 (0.04)</td>
<td>0.143 (0.03)</td>
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#### 3.3.2. Free Fatty Acids

Values for FFA were not significantly different ($P>0.05$, Fig. 3.2). Values ranged from a high of 0.60% (as oleic acid) for the 3% dropped nuts to 0.47% for the 3% control (Fig. 3.1).

#### 3.3.3. Headspace analysis

Few volatile compounds were detected by headspace GC-MS analysis and there were no significant differences between treatments ($P>0.05$). However, there was a difference in peak heights for moist kernels between the dropped treatments for a compound eluded at 10.07 min, and identified against a standard as nonanal (Table 3.2). Dropped treatments and controls for dry kernels showed negligible difference.
**Fig. 3.1** Free fatty acid values as % oleic acid for kernels from nuts dropped as nut-in-shell at 3% and 20% moisture content. Means and standard errors are presented.
Table 3.2. Height of peaks (ion count) of volatiles detected by GC-MS of artificially aged macadamia kernels

<table>
<thead>
<tr>
<th>MC</th>
<th>Sample</th>
<th>DROP</th>
<th>CONTROL</th>
<th>DROP</th>
<th>CONTROL</th>
<th>MC</th>
<th>Sample</th>
<th>DROP</th>
<th>CONTROL</th>
<th>DROP</th>
<th>CONTROL</th>
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<tbody>
<tr>
<td>Moist</td>
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<td>0</td>
<td>0</td>
<td>2.2</td>
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<td></td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
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<tr>
<td></td>
<td>3</td>
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<td>0</td>
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<td>26</td>
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<td>Mean</td>
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<td>10.9</td>
<td>0.7</td>
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<tr>
<td>Standard Deviation</td>
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<td>2.04</td>
<td>0.6</td>
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3.4 Discussion

Peroxide values were very low when judged against accepted standards. A PV of less than one is considered acceptable for a freshly refined fat (Robards et al., 1988a). An acceptable standard for macadamia kernels is considered less than 6, while greater than 6 indicates moderate to complete rancidity (McConachie, 1996). In view of the value set by Robards et al. (1998a), a Fig. of 6.0 appears high. As the highest value recorded in this experiment was 0.22, this oil could be considered of a very high quality in oxidative terms. The history of the tested kernel could be considered here. Kernels were stored for 16 weeks at ambient temperatures without vacuum, yet experienced little loss of oil oxidative quality. Although many kernels were visually oily this did not lead to detectable oxidative activity. This agrees with the finding of other workers that in oxidative terms, macadamia is a relatively stable oil (Winterton, 1966; Rosenthal et al., 1984; Kaijser et al., 2000).

The reliability of peroxide value as an indicator of rancidity of macadamias has been questioned (Mason et al., 1998). While a distinct relationship existed between PV and some results from the sensory evaluation of kernel for rancidity, in other results panellists rated kernel rancid when PV fell within acceptable limits (Mason et al., 1998). In a similar manner, PV of macadamia kernels aged for 14 weeks was acceptable, but taste panellists detected a stale/rancid flavour (O’Riordan et al., 2005). The Peroxide Value test measures levels of peroxides that are generally flavourless (Robards et al., 1988a) but provides no indication of volatile compounds responsible for some rancid flavours. Headspace analysis may be able to detect volatile by-products of peroxidation responsible for off-flavours (Pike, 1998). At present sensory evaluation remains the only reliable test of rancidity in macadamias (Mason et al., 1998).
While 75% of FFA values were within industry guidelines, there is still ground for concern. Three FFA values found were within the range considered acceptable by industry for high quality macadamia oil, *i.e.*, up to 0.6% (McConachie, 1996) with only one, the 3% dropped treatment, reaching this level. However, there is disagreement on what is an acceptable FFA level. McConachie (1996) considers high quality oil should have FFA of only 0.1-0.3%. In contrast, Arnett (1995) considered a value as high as 0.9 acceptable. None of the treatments, including controls, achieved the 0.3% level desired by McConachie (1996), and for the 3% dropped treatment, 3 samples were above 0.5%, with the highest value 0.76%. The samples used in the analysis were not redried after kernel assessment before the storage period.

Macadamias will rehydrate readily from 1.5% MC in ambient conditions (Kowitz and Mason, 1998; Palipane and Driscoll, 1992), so that the test kernels very likely would have re-hydrated slightly beyond the moisture level recommended for storage of 1.5% MC (Cavaletto *et al.*, 1966). There was no significant difference in treatments, which may indicate that rough handling is not a concern for development of hydrolytic rancidity.

There is some doubt concerning the reliability of FFA tests for determination of hydrolytic rancidity for macadamias. Sensory panels have found product which had an acceptable acid value by the above standards rancid and unacceptable (Mason *et al.*, 1998). Maximum FFA levels of 0.5 may be unacceptably high (McConachie, 1996). The ultimate test for rancidity is sensory evaluation by tasting panels; however, as this is the most costly method, the search continues for acceptable indicators of rancidity (Robards *et al.*, 1988a).

While GC-MS analysis could detect no significant difference between dropped treatments and controls for volatile compounds, there was an interesting difference
between dry kernels and moist kernels. Only moist kernels generated measurable volatiles, and there was a clear difference between dropped samples and controls. The volatile concerned, nonanal is used as a food additive and is described as having a strong fatty odour which develops an orange and rose character on being diluted (Anon., 1967). The presence of nonanal in the moist dropped samples indicates that oxidation may be occurring (Vichi et al., 2003). Oleic acid is the predominant unsaturated fatty acid in macadamia oil. Oxidative cleavage at the double bond of oleic acid, between C9 – C10, would produce nonanal. Nonanal has been suggested as a suitable marker of oxidation for virgin olive oil, similarly high in oleic acid (Vichi et al., 2003). Nonanal may be a suitable marker for objective instrumental assessment of rancidity in macadamias. Himstedt (2002) identified hexanal as an important volatile indicator of rancidity, but this was not detected in our study. Hexanal results from further peroxidation so is produced at a later stage of rancidity. Nonanal could be an earlier indicator of oxidative rancidity and further study may be warranted to determine if this volatile is useful as an early indicator of rancidity.

The difference between moist and dry samples also emphasises that storing kernel below 1.5% MC is critical to maintaining shelf life (Cavaletto et al., 1966). Sensory evaluation remains the most reliable test for rancidity and could be used to test for differences between dropped and undropped kernels in future studies.

The results of this study indicate that FFA, probably from lipolysis, may be a greater concern in macadamia rancidity than peroxidation. While little evidence could be found of oxidation, FFA values were high enough to raise concerns, considering that differences in opinion on safe levels exist. The FFA results emphasise the importance of storing kernels below 1.5% MC to minimise the risk of elevated FFA. The results of this study could suggest that macadamia kernels are relatively stable
oxidatively and rancidity is not easily produced. These results may have had more to
do with the ideal procedures used in the experiments (except for dropping) than
chemical factors. These results support the desirability of further studies on rancidity.
Tasting panels could be used to test dropped kernels and controls for differences in
eating quality. Whole kernel could be used, with one half used for tasting, and the
other kept for GCMS analysis for volatile by-products of oxidation. This process may
also identify compounds causing off-flavours that are not associated with rancidity.

3.5. Summary and recommendations to industry

Peroxide values were low and well within industry guidelines. Free fatty acid
values were also within industry guidelines, but were high enough to raise concerns.
Further chemistry studies are suggested: 1) sensory evaluation of dropped and
undropped kernels for taste differences after cracking; 2) testing dropped and
undropped kernels by sensory evaluation after a period of artificial ageing (whole
kernels are tested, half is tasted, the other half is used for GCMS).
CHAPTER 4

How cultivar, site and season influence macadamia whole kernel, shoulder damage and pieces

4.1. Introduction

The macadamia industry is located in several regions spread over 1500 km. The main locations are: 1) Atherton Tableland (17ºS), Bundaberg region (25ºS), South East Queensland (27ºS) and Northern New South Wales (28ºS). Environmental factors such as variations in geographical location and seasonal differences may affect quality parameters.

There is some information on the effect of site and season on the composition of macadamias and other nuts. Different cultivars of macadamias at different sites have been shown to vary in percent kernel and Grade One kernel (Radspinner, 1971) and in fatty acid profile and percentage content of oil (Himstedt, 2002). By contrast, hazelnuts varied in oil composition in different regions, but not between cultivars (Parcerisa et al., 1994). Pecans also varied substantially in lipid composition from year to year with differences being cultivar dependent (Rudolph et al., 1992).

Temperature and rainfall variations can also significantly affect yield of macadamias (Stephenson et al., 2000).

Macadamia whole kernel percentage at cracking is an important quality issue. Whole kernels attract a premium of $2.50 per kg over halves in 2005 (Twentyman, pers. comm., 2005). There is some evidence that the tendency for macadamia kernels to break into halves is related to cultivar (Stephenson and Gallagher, 2000; Walton and Wallace, 2005). There is limited information for macadamia on how whole kernel differs between some cultivars and regions (Stephenson and Gallagher, 2000),
however, nothing is known about variations in shoulder damage and pieces for kernels produced in different regions and seasons.

Choice of cultivar and site are important management decisions affecting future production for many years and decision-making could be enhanced by research into cultivar and site effects on quality. This study was designed to examine the yield of whole kernel, the amount of shoulder damage and loss as pieces for three cultivars in three macadamia growing regions of eastern Australia over three consecutive seasons. The aim was to determine the influence of cultivar on quality parameters such as whole kernel, shoulder damage and weight of pieces in relation to site and seasonal variations.

4.2 Materials and methods

Three locations in eastern Australia were selected to examine the variation in quality between sites, Bundaberg (24°49.79’S, 152°17.23’E), Wolvi (26°9.63’S, 152°48.65’E), and Clunes (28°45.76’S, 153°30.77’E). Nuts were sampled in April in each of three seasons, 2002, 2003 and 2004. Three cultivars were sampled at each site, one high whole kernel cultivar, HV A38 (Wallace et al., 2001), and two widely planted low whole kernel cultivars, HAES 344 and HAES 741 (Stephenson and Gallagher, 2000; Walton and Wallace, 2005). At Bundaberg, Wolvi and Clunes, two replicate samples, each consisting of 50 nuts, were collected from each of 5 trees per cultivar, giving a total of 10 replicates per cultivar. Trees were regarded as blocks with 2 replicates per tree. All nuts were hand-harvested from the ground to avoid possible damage from machinery. The trees experienced a period of drought in 2002 which was most marked at the Wolvi site, where water for irrigation was exhausted early in the maturation stage of nuts. In 2003, nuts were sampled from all sites in April. Sampling methods were similar to those above, except that due to insufficient
nuts per tree for HAES 741 at Wolvi, a variation was necessary. For this cultivar a bulk sample was obtained from approximately 30 trees and this sample was sub-sampled for 10 replicates. In 2004 sampling methods were the same as for 2002.

All nuts were dehusked within 24 hours of harvest using a ‘Shaw’ type mechanical dehusker (O’Hare et al., 1996). As soon as possible following dehusking, nuts were dried in laboratory fan-forced ovens. The drying regime was 2 days at 38°C, 2 days at 45°C, followed by the required time at 58°C to dry nuts to 3% MC NIS wet basis (wb), to achieve approximate kernel moisture content of 1.5% (Anon, 1995). All nuts were cracked by hand using a “T J’s” TM nutcracker to minimise damage to nuts. All possible care was taken to minimise stresses on nuts during cracking, for example, care was taken to align the axis of the hilum and micropyle with the jaws of the cracker (Braga et al., 1999). These drying and cracking methods apply to all experiments in this thesis. Nuts which had to be stored until further processing were placed in plastic clip-lock bags at ambient temp (range of 11-21°C). If the maximum temperature exceeded this range, nuts were stored at 4°C.

Whole kernel was recorded as number of wholes and weight of wholes. Shoulder damage refers to the removal of pieces of tissue from the hemisphere of the kernel at the micropyle end. Unsound kernels were discoloured, immature, insect-damaged or mouldy. Shoulder damage, dustiness and oiliness were assessed and recorded only for whole kernel. A kernel was considered to have shoulder damage if an area of tissue greater than 3mm diameter was removed. Wholes with greater than one eighth missing were included in the halves count. Large pieces were those smaller than halves, but with a diameter greater than 9mm. Small pieces were less than 9mm, but greater than 5mm in diameter. Pieces <5mm and dust were not recorded because of the small weights involved. Adhered kernel was not recorded. Dustiness refers to a
dusty coating on the surface of the kernel determined first visually, then confirmed by touch. Feeling dusty to touch only was not sufficient to be classified as dusty. Oiliness refers to a darker, ‘oily’ appearance of the nut than is normal. This was confirmed by rubbing the apparently oily surface on white paper; if the kernel left a mark on the paper the kernel was deemed oily. Kernel adhering to the shell, dust and unsound kernels were not included in total kernel. Unsound kernel refers to insect damage, microbial damage or immaturity.

4.2.1. Statistical analysis

Weight of whole kernel as a percentage of total sound kernel weight was considered a more suitable variable to compare whole kernel as it revealed yield, not just number, and enabled more meaningful comparisons. All results for whole kernel in following chapters refer to this variable, calculated according to the formulae:

\[
\text{Whole kernel weight (%) = } \frac{\text{wt whole kernel}}{\text{Total wt of sound kernel}} \times 100
\]

\[
\text{Total wt of sound kernel = wt wholes + wt halves + total wt pieces}
\]

Weight of pieces was calculated as a percentage of total sound kernel weight. Shoulder damage, oily kernels and dusty kernels were calculated as percentages of whole kernel number. Because of missing data, HV A38 was not included in analysis for weight of pieces in 2002. Means and standard errors for each variable were calculated. All data were normally distributed and were initially analysed with a factorial ANOVA with year, site and cultivar as factors (Tables 4.1, 4.2, 4.3). In all cases there were significant interactions between year and cultivar, year and site, site and cultivar, and year, site and cultivar \((P < 0.001)\) (Tables 4.1, 4.2, 4.3). Therefore, for each year, means were compared for each combination of cultivar and site (nine combinations for each year), using a series of one-way ANOVAs with eight degrees
of freedom. Where significant differences were found, Duncan’s multiple range test was applied for comparison of means.

4.3 Results

4.3.1. Whole kernel weight

In 2002, cultivar HV A38 produced significantly more whole kernel than both HAES 344 and HAES 741 at all three sites \( (P<0.05) \) (Fig. 4.1). Cultivar HAES 741 produced significantly more whole kernel weight at Wolvi than at Bundaberg or Clunes.

Table 4.1. Factorial ANOVA for weight of whole kernel (%) for 3 cultivars at 3 sites over 3 years.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>YEAR</td>
<td>10115.828</td>
<td>2</td>
<td>5057.914</td>
<td>66.834</td>
<td>.000</td>
</tr>
<tr>
<td>SITE</td>
<td>578.304</td>
<td>2</td>
<td>289.152</td>
<td>3.821</td>
<td>.023</td>
</tr>
<tr>
<td>CULTIVAR</td>
<td>22587.383</td>
<td>2</td>
<td>11293.691</td>
<td>149.233</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * SITE</td>
<td>3541.765</td>
<td>4</td>
<td>885.441</td>
<td>11.700</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * CULTIVAR</td>
<td>7099.768</td>
<td>4</td>
<td>1774.942</td>
<td>23.454</td>
<td>.000</td>
</tr>
<tr>
<td>SITE * CULTIVAR</td>
<td>4299.996</td>
<td>4</td>
<td>1074.999</td>
<td>14.205</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * SITE * CULTIVAR</td>
<td>3494.467</td>
<td>8</td>
<td>436.808</td>
<td>5.772</td>
<td>.000</td>
</tr>
<tr>
<td>Error</td>
<td>18314.176</td>
<td>242</td>
<td>75.678</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1049040.368</td>
<td>269</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In 2003, HV A38 produced significantly more whole kernel at Bundaberg and Clunes than HV A38 at Wolvi, and both HAES cultivars at all sites, (Fig. 4.1). Whole kernel was variable from year to year (Fig. 4.1). In 2004, HAES 344 at Wolvi produced the highest whole kernel (Fig. 4.1). Cultivar HAES 741 had low whole kernel for this season at Bundaberg (48%) and Wolvi (51%), but was significantly higher at Clunes (70%). Another ‘low’ mean for 2004 (54%) was for HAES 344 at Clunes.
Fig. 4.1. Whole kernel weight (%) for 3 macadamia cultivars at 3 sites during 3 seasons. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, $P<0.05$).
4.3.2. Shoulder damage

Shoulder damage was more variable than whole kernel, and not consistently related to cultivar. In 2002, shoulder damage varied with site and cultivar and significant differences resulted. The highest shoulder damage was for HV A38 at Wolvi (28%) and the lowest from HAES 741 at Clunes (3%) (Fig. 4.2). The result for HV A38 at Wolvi was over twice that of the highest of the two other cultivars. In 2003 there was very little difference between sites (Fig. 4.2), except that HAES 344 at Bundaberg produced significantly more damage than all other cultivars at all sites ($P<0.05$). The only other difference was that HV A38 at Clunes incurred significantly less shoulder damage than at the other two sites ($P<0.05$) (Fig. 4.2). Cultivar HAES 741 suffered a high degree of shoulder damage (21% of kernels) at Clunes in 2004 (Fig. 4.2). This was significantly higher ($P<0.05$) than for HAES 741 and HV A38 at Wolvi and Bundaberg. HV A38 had the lowest damage (8%).

**Table 4.2.** Factorial ANOVA for shoulder damage (%) for 3 cultivars at 3 sites over 3 years.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>YEAR</td>
<td>887.840</td>
<td>2</td>
<td>443.920</td>
<td>21.516</td>
<td>.000</td>
</tr>
<tr>
<td>SITE</td>
<td>154.685</td>
<td>2</td>
<td>77.343</td>
<td>3.749</td>
<td>.025</td>
</tr>
<tr>
<td>CULTIVAR</td>
<td>189.381</td>
<td>2</td>
<td>94.691</td>
<td>4.589</td>
<td>.011</td>
</tr>
<tr>
<td>YEAR * SITE</td>
<td>2077.357</td>
<td>4</td>
<td>519.339</td>
<td>25.171</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * CULTIVAR</td>
<td>2101.660</td>
<td>4</td>
<td>525.415</td>
<td>25.465</td>
<td>.000</td>
</tr>
<tr>
<td>SITE * CULTIVAR</td>
<td>1190.663</td>
<td>4</td>
<td>297.666</td>
<td>14.427</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * SITE * CULTIVAR</td>
<td>806.550</td>
<td>8</td>
<td>100.819</td>
<td>4.886</td>
<td>.000</td>
</tr>
<tr>
<td>Error</td>
<td>4993.059</td>
<td>242</td>
<td>20.632</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>57402.759</td>
<td>269</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4.2. Shoulder damage (%) for 3 cultivars at 3 sites, 2002 to 2004. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P<0.05$).
4.3.3. Weight of pieces

Results for weight of pieces were variable. In 2002, cultivar HAES 344 produced significantly more pieces at Clunes (22%) than Bundaberg (15.2%) (Fig. 4.3), but the reverse occurred for HAES 741, which produced more pieces at Bundaberg (16%) than at Wolvi (10%) and Clunes (6%). In 2003 there were significant differences between sites only for HV A38 for weight of pieces, but not between cultivars at each site (Table 4.4). Values for pieces for 2003 were greatly reduced compared to 2002. The highest loss of kernel to pieces was for HAES 344 at Wolvi with a weight of pieces of only 2.5% of total kernel.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>d f</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>YEAR</td>
<td>4460.444</td>
<td>2</td>
<td>2230.222</td>
<td>231.834</td>
<td>.000</td>
</tr>
<tr>
<td>SITE</td>
<td>6.635</td>
<td>2</td>
<td>3.317</td>
<td>.345</td>
<td>.709</td>
</tr>
<tr>
<td>CULTIVAR</td>
<td>1474.359</td>
<td>2</td>
<td>737.180</td>
<td>76.631</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * SITE</td>
<td>17.084</td>
<td>4</td>
<td>4.271</td>
<td>.444</td>
<td>.777</td>
</tr>
<tr>
<td>YEAR * CULTIVAR</td>
<td>2243.452</td>
<td>4</td>
<td>560.863</td>
<td>58.302</td>
<td>.000</td>
</tr>
<tr>
<td>SITE * CULTIVAR</td>
<td>294.765</td>
<td>4</td>
<td>73.691</td>
<td>7.660</td>
<td>.000</td>
</tr>
<tr>
<td>YEAR * SITE * CULTIVAR</td>
<td>544.517</td>
<td>8</td>
<td>68.065</td>
<td>7.075</td>
<td>.000</td>
</tr>
<tr>
<td>Error</td>
<td>2328.015</td>
<td>242</td>
<td>9.620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17470.365</td>
<td>269</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.4. Weight of pieces (%) for 3 cultivars at 3 sites, season 2003. Means and (standard errors) are presented, means with different letters are significantly different for both cultivar and site (Duncan’s, $P<0.05$).

<table>
<thead>
<tr>
<th></th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundaberg</td>
<td>1.26±0.58</td>
<td>2.40±0.30</td>
<td>2.24±0.33</td>
</tr>
<tr>
<td>Wolvi</td>
<td>2.30±0.39</td>
<td>2.55±0.37</td>
<td>2.04±0.44</td>
</tr>
<tr>
<td>Clunes</td>
<td>0.76±0.26</td>
<td>1.48±0.32</td>
<td>1.38±0.34</td>
</tr>
</tbody>
</table>

Values for weight of pieces were very low in 2004, as in 2003, ranging from 1.1% of kernel at Clunes for HV A38 to a high of 2.6% for HAES 741 at Clunes. There was a significant difference ($P<0.05$) between cultivars only at Wolvi and values were not significantly different between sites for each cultivar (Table 4.5).

Table 4.5. Total pieces weight (%) for three cultivars at three sites, season 2004. Means and (standard errors) are presented, means with different letters are significantly different for both cultivar and site (Duncan’s, $P<0.05$).

<table>
<thead>
<tr>
<th></th>
<th>HV A 38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundaberg</td>
<td>1.75 (0.18)$^{ab}$</td>
<td>2.47 (0.30)$^{b}$</td>
<td>2.08 (0.40)$^{ab}$</td>
</tr>
<tr>
<td>Wolvi</td>
<td>1.12 (0.11)$^{a}$</td>
<td>1.51 (0.45)$^{ab}$</td>
<td>2.37 (0.37)$^{b}$</td>
</tr>
<tr>
<td>Clunes</td>
<td>1.50 (0.40)$^{ab}$</td>
<td>2.63 (0.38)$^{b}$</td>
<td>1.83 (0.48)$^{ab}$</td>
</tr>
</tbody>
</table>

Fig. 4.3 Total pieces weight (%) for 2 cultivars at 3 sites, 2002. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P<0.05$).
4.4. Discussion

4.4.1. Whole kernel

In the current study the principal influence on whole kernel was cultivar. The most consistent producer of high whole kernel at each site was cultivar HV A38. However, there was some variation for each cultivar from site to site and season to season, HAES 344 and HAES 741 being more variable. However, while both HAES 344 and HAES 741 are able to produce high whole kernel in some seasons they can also return very low percentages, being less reliable than cultivars such as HV A38 (current study) and HV A16 (Stephenson and Gallagher, 2000). The strong genetic control on whole kernel concurs with previous work by Stephenson and Gallagher (2000) and Walton and Wallace (2005).

Seasonal effects may help to explain the low whole kernel for HAES 344 and HAES 741 in the drought year, 2002. In 2002 HV A38 produced significantly more whole kernel than the other cultivars at every site, more than double that from HAES 741 at Bundaberg and Clunes. This may indicate that HV A38 has a capacity to tolerate dry weather conditions.

Site and environment affect many quality parameters of nut crops. Pecan total nut weight and percent kernel were significantly affected by location (Thompson et al., 1989). Macadamia and hazelnut oil composition can be affected by location (Himstedt, 2002; Parcerisa et al., 1994). Seasonal variations may also influence quality. Daily mean temperatures during pecan nut expansion may have been a major factor determining nut weight response (Thompson et al., 1989). Pecan oil concentration and fatty acid composition differed substantially between years, and
was influenced by environmental factors (Rudolph et al., 1992). In macadamia the optimum temperature for growth and photosynthesis is 25°C (Trouchoulias and Lahav, 1983). A high temperature of 35°C decreased macadamia kernel growth and weight, and oil content during the maturation stage (Stephenson and Gallagher, 1986a). Percentage of first grade kernels was affected more by season than by differing nitrogen applications (Stephenson et al., 2000).

The whole kernel recovery from HAES 344 and HAES 741 in this study in 2003 and 2004 is higher than recorded by Stephenson and Gallagher (2000). While the results are not directly comparable because Stephenson and Gallagher reported whole kernel %, not weight, nevertheless, there is a clear difference. For HAES 344, Stephenson and Gallagher (2000) reported 35% whole kernel for HAES 344 at Wolvi. This compares with a mean of 58% for the 3 seasons in this study and with 64% reported by Walton and Wallace (2005). For HAES 741, Stephenson and Gallagher (2000) recorded whole kernel of 36% at Wolvi, compared with 50% for this study and 50% for Walton and Wallace (2005). There are two possible reasons for this difference. First, Stephenson and Gallagher (2000) used mechanical cracking and this can be expected to reduce whole kernel compared with hand cracking, the method in the current study (Wallace et al., 2001). Second, their results are 14-year means compared with only 3 years for this study. Experience in this laboratory handling macadamia kernel after cracking indicates that many of the HAES 344 and HAES 741 cotyledons are not strongly attached and can be separated with very little force. This may help explain the discrepancy between the whole kernel figure reported by Stephenson and Gallagher (2000) and the higher figures in the current study where minimal stresses were applied.
4.4.2. Shoulder damage and weight of pieces

Shoulder damage is very common on commercial macadamia kernels but has not previously been investigated thoroughly. Although results are variable the differences for shoulder damage in this study appear to be more related to season than site or cultivar. For each year and cultivar, some differences between sites for shoulder damage are evident, for example, HV A38 had high shoulder damage in 2002. Apart from this shoulder damage levels were low in the drought year. However, there is no consistent pattern and site does not appear to be a major factor in shoulder damage.

The dry 2002 season produced a much greater weight of pieces, up to 8 times the following two seasons. Weight of pieces for HAES 344 and HAES 741 was up to 8 times that for the other seasons, being as high as 15% to 20% of total kernel weight. In contrast there was more shoulder damage in 2003 and 2004, suggesting that the kernel tissue was more likely to break in the drought year, but also less likely to adhere to the enamelled shell area and cause shoulder damage. This drought year was the only season there were significant differences in pieces. Pieces are important because they represent economic loss. This may be as total loss in very small pieces, or loss in value because pieces command lower prices. On average, pieces are worth 18% less than whole kernel and 7% less than halves. In addition, as with shoulder damage, pieces represent damaged tissue and possible further deterioration of product.

4.5. Summary

Whole kernel was mainly determined by cultivar, with HV A38 producing higher whole kernel than HAES 344 and HAES 741 at each site. This indicates that HAES 344 and HAES 741 may be more susceptible to environmental fluctuations. However, whole kernel in this study for HAES 344 and HAES 741 was higher than reported by
Stephenson and Gallagher (2000), possibly due to more careful handling. Under commercial conditions these cultivars do not produce acceptable levels of whole kernel.

These results for whole kernel emphasize the key role of macadamia plant breeding programmes and careful cultivar selection in improving kernel quality. Whole kernel is an important quality issue and likely to increase in importance as world macadamia production increases. Long-term planning is essential for tree crops and prudent selection of cultivars now is critical to increasing whole kernel production in the future.

4.6. **Recommendations to industry**

The macadamia industry should:

- prioritize the important cultivar selection criteria, with a long-term view, for example, the importance of whole kernel. Planning should not be unduly influenced by a period of buoyant prices;
- exercise caution in matching cultivars to sites, as cultivars perform differently at different sites;
- irrigate at some locations to even out seasonal effects.

Further studies could:

- investigate the performance of other high whole kernel cultivars over different sites and seasons;
- further examine the effect of site and season on whole kernel, shoulder damage and pieces;
- investigate further how the gap between cotyledons relates to whole kernel in different cultivars.
CHAPTER 5

How delayed harvest and dehuskers affect macadamia quality

5.1. Introduction

Macadamia nuts in Australia are harvested from the ground following abscission. During the harvesting season, harvesting rounds may be delayed for a number of reasons: the rapidity of nut abscission; access to harvesting equipment; availability of storage on farm; the ability of processors to receive product; and weather conditions (Hamilton and Storey, 1956; Grimwood, 1971). The timing of harvest rounds is often a function of nut density on the ground for economic reasons (Liang et al., 1996). Spoilage of nuts on the ground is affected by both soil moisture content and time on the ground (Liang et al., 1996). Quality may be adversely affected by delays in harvesting rounds because of chemical and physiological changes occurring in nuts while they are on the ground at high moisture (MC) (Cavaletto, 1983). Leaving nuts on the ground for four weeks did not affect recovery of processable kernel or eating quality, however, longer periods reduced quality mainly with respect to the processed recovery from nuts exposed to sunlight (Mason and Wells, 1984). The effect of delays in harvest on aspects of quality such as whole kernel recovery, shoulder damage, pieces and roasting quality have not been investigated.

The fibrous husk of freshly harvested macadamia fruit constitutes 40-45% weight of the fruit (Cavaletto, 1983). The first step in processing is the removal of husk, which is normally accomplished on-farm by mechanical dehuskers, preferably within one day of harvesting. A variety of machines have been developed for this task.
Physical damage to kernel may result from postharvest handling of nuts (O’Hare et al., 1996). The number of cracked nuts produced by a new dehusker has been evaluated by Luan and Ling (1983) but there is limited information available on the effects of different dehuskers on other quality descriptors such as percentage of whole kernel recovered, degree of shoulder damage, production of pieces and effect on roasting quality. This study examines the effect on quality of two mechanical dehuskers and compares them with hand dehusking.

An important issue is the appearance of kernels when they are roasted. Any processes causing chemical changes in kernels may affect the quality of roasted kernels due to chemical reactions such as the Maillard reaction during roasting (Belitz et al., 2004). Practices such as delaying harvest and mechanical dehusking may influence the roasting quality of macadamia kernels. This chapter will investigate the effects of delayed harvest and different dehuskers on roasting quality.

### 5.2. Materials and methods

#### 5.2.1. Delayed harvest experiments

Three experiments were conducted to examine the effects of delayed harvest on macadamia quality, as indicated by whole kernel %, shoulder damage, weight of pieces and roasting properties of macadamia kernels. Nuts for the first two experiments were harvested from Sahara Farms at Glasshouse Mountains (26°53.44’S, 152°56.16’E), and for the final experiment from Warawee Plantation at Wolvi (26°9.63’S, 152°48.65’E). All experiments used nuts of cultivar HAES 344, and nuts were mechanically dehusked by a metal scroll ‘Shaw’ type dehusker.

In 2003, a delayed harvest experiment (Experiment 5.1) was conducted with two treatments: 1) control, where nuts were dehusked and dried fully immediately following harvest; and 2) delayed harvest, where nuts were dried slowly outdoors in
shade for three weeks after abscission, then dehusked at 10.3% MC. Nuts were harvested in August and a bulk sample from ca. 80 trees was sub-sampled to obtain 20 replicates of 50 nuts each. Ten replicates were assigned to each treatment.

Experiment 5.2 was conducted using nuts harvested directly from the trees at Glasshouse Mountains. This was a measure to minimize the variability in MC of nuts harvested from the ground and different times on the ground, as experienced in normal harvest practice.

There were five treatments:
1) control, dehusked, dried and cracked immediately following harvest;
2) nuts placed in partial shade for 3 weeks prior to dehusking;
3) nuts placed in full shade for 3 weeks prior to dehusking;
4) nuts placed in partial shade for 5 weeks prior to dehusking;
5) nuts placed in full shade for 5 weeks prior to dehusking.

Nuts from treatments 2 to 5 were placed on the ground in a small patch of rainforest to simulate shaded macadamia orchard conditions. One replicate for each treatment and control was harvested from each of ten trees directly from the trees.

Experiment 5.3 used nuts harvested from the ground at Wolvi. One aim of this experiment was to expose nuts to conditions closely resembling orchard conditions. The treatments were the same as for delayed harvest experiment 5.2. One replicate for each treatment and control was harvested from each of ten trees.

5.2.1.1. Statistical analysis

Means were calculated for whole kernel weight %, shoulder damage %, pieces weight %, dustiness (%) and oiliness (%). Parametric data were analysed by t-test for experiment 5.1, and by ANOVA with 4 degrees of freedom for experiments 5.2 and
5.3. Where significant differences were detected, means were compared using Duncan’s multiple range test.

5.2.2. Dehusking experiments

Two experiments were conducted on dehuskers in 2002. Nuts of cultivars HAES 344 and HAES 741 for Experiment 5.4. were harvested at Wolvi in April 2002, and for Experiment 5.5 in May. For Experiment 5.4, all nuts were dehusked at a high (field) NIS MC. In experiment 5.5, nuts were dehusked at a lower MC after a period of drying on the ground at ambient temperature. There were three treatments for both experiments:

1) hand dehusking, the control, was accomplished with aviation snips;
2) a “Shaw” type mechanical dehusker, a type widely used in the industry; which employs rollers with metal scrolls working against spring loaded fingers;
3) an “Admac” dehusker, which squeezes nuts between an auger fitted with strips of rubber and an outer longitudinally barred metal cage.

For Experiment 5.4 and 5.5 a bulk sample was obtained from approximately 10 trees and this was sub-sampled for 10 replicates of 50 nuts for each treatment of each experiment. All nuts for experiment 5.4 were dehusked at approximately 22% MC.

The nuts for experiment 5.5 were allowed to partially dry before dehusking. This was achieved by spreading nut-in-husk (NIH) in a thin layer on a concrete slab which received mild winter sunlight in the afternoon but was protected from rain. At approximately 10% MC (after approximately three weeks drying) the nuts were dehusked as for Experiment 5.4, then dried down to 3% MC NIS for cracking.

Dehusker Experiment 5.6 was conducted in 2003. The purpose of this experiment was to further examine the effect of two different dehuskers on macadamia kernel quality at high and intermediate moisture contents, and to also investigate the effect of
dehusking on roasting quality. The three dehusker treatments for both moisture contents of Experiment 5.6 were the same as for Experiments 5.4 and 5.5.

Four replicate samples from cultivar HAES 344, each consisting of 50 nuts, were harvested in June 2003 from each of 15 trees at Glasshouse Mountains. This provided a total of 10 replicates each of 50 nuts per treatment per MC.

Nuts for the field MC treatments were dehusked immediately following harvesting when the mean NIS MC was 22.7%. Nuts for the lower MC treatments were dried at ambient temperatures. These nuts were dehusked four weeks after harvest at 11.8% MC. Whole kernel weight (%), shoulder damage (%), weight of pieces (%), dustiness (%) and oiliness (%) were calculated for all experiments. All treatments were dried to approximately 3% NIS MC for cracking.

5.2.2.1. Statistical analysis

Parametric data were initially analysed using a factorial ANOVA with dehusker, cultivar and dehusker*cultivar as terms for Experiments 5.4 and 5.5, or dehusker, time delay, and dehusker* time delay as terms for Experiment 5.6. However, due to a significant interaction between dehusker and cultivar, means were compared for each combination of cultivar and dehusker, using a series of one-way ANOVAs with eight degrees of freedom. Data for shoulder damage for dehusker Experiment 5.4 were square-root transformed to meet the assumptions of ANOVA. Where significant differences were detected, means were compared using Duncan’s multiple range test.

5.2.3. Dehusker effects prior to cracking

This compared the effects of the three dehusking methods before the stresses caused by cracking. Cracking imposes additional stress on kernels to those experienced during dehusking. To eliminate the effect of cracking stresses some nuts were sawn apart through the nut-shells around the circumference in the equatorial
region. In this way any mechanical damage to kernels could be attributed to
dehusking method alone as this was the only stress nuts had been subject to. For
cultivar HAES 344, 20 nuts were opened for each of the two dehuskers and 40 nuts
for hand dehusking (control). For HAES 741, 20 nuts were opened for each of the two
dehuskers only due to scarcity of nuts. Whole kernel (% by number) and shoulder
damage (%) were calculated.

5.2.4. Roasting experiments

In all the delayed harvest experiments, ten whole kernels were selected at random
from each replicate. For dehusking, only replicates from Experiment 5.6 were
sampled for roasting. Samples for roasting were dried to 1.5% MC (De La Cruz et al.,
1966). Samples were then air roasted in a Memmert fan-forced laboratory oven for 20
min at 130°C. Roasted samples were examined for colour, patchiness of colour and
surface damage. Where possible, assessment was carried out “blind” to eliminate the
possibility of bias entering assessment. The darker portion of the kernel which is in
contact with the tannin layer of the shell before cracking was not used to determine
colour and patchiness as the naturally darker surface tends to mask colour changes
due to roasting. However, for surface damage the whole of the kernel was assessed.
As a standard for colour evaluation, a Taubmans Colour Concepts colour swatch
No.44 was used to grade kernels. The colours were assigned categories as follows:
Abbot White=1, Annabelle=2, Pixie=3, Momento=4, Paxton=5, progressing from
lightest to darkest colour. For patchiness of colour, kernels were placed into
categories from 1-3, 1 representing minimal patchiness, 2 moderate patchiness and 3
severe patchiness. For surface damage kernels were placed into categories from 1-3, 1
representing minimal surface damage, 2 moderate surface damage and 3 severe
surface damage. This roasting regime is used consistently throughout this thesis in all chapters where roasting is employed.

5.2.4. Statistical analysis

Because parametric statistics are much more powerful than non-parametric tests, rank data where possible were converted to percentages in each category, and parametric statistics were used to test for significant difference. For colour, category 5 (very dark, equivalent to reject kernels) and category 4 (dark) colours only were chosen for analysis. This was because these two categories are dark enough to be either rejected or graded out, and so are more important for quality assessment. For Experiment 5.1 data for roasting colour in categories 4 and 5 were transformed by square root before analysis by t-test. Only data for category 3 for severe patchiness of colour and severe surface damage were analysed for significant difference as these were the only categories with obvious loss of visual quality. Parametric data for category 4 (dark colour) for Experiments 5.2 and Experiment 5.3 and the dehusker Experiment 5.6 were analysed by one way ANOVA and where significant differences were detected means were compared using Duncan’s multiple-range test. Non-parametric data for severe patchiness of colour for Experiment 5.2, and severe patchiness of colour and severe surface damage for Experiment 5.3 were analysed by Kruskall-Wallis and Mann-Whitney U tests. Data for colour of roasted kernels in category 4 in Experiment 5.6 were transformed \(\log_{10} +1\) before analysis.
5.3. Results

5.3.1 Delayed harvest

Delayed harvesting for Experiment 5.1 in 2002 significantly decreased whole kernel and increased shoulder damage and weight of pieces in nuts which were dehusked after a delay (Fig. 5.1). In the delayed harvest treatment whole kernel weight decreased by approximately 14% ($P=0.009$), shoulder damage increased by 30% in the same treatment ($P<0.001$) and weight of pieces also increased by 3% ($P=0.007$).

Delaying harvest of nuts (Experiment 5.2) in a simulated delayed harvest of tree-harvested nuts resulted in a significant decrease in whole kernel weight ($P<0.05$), dropping from 55.0% in the control to a low of 33.8% for nuts suffering a delay of 5 weeks in full shade (Fig. 5.2). Shoulder damage was significantly increased ($P<0.05$) in both the 5 week treatments, at approximately double the control of 12.1% (Fig. 5.2). There was also a doubling in weight of pieces in the 5 week treatments compared with 3.4% for the control (Fig. 5.2).

In Experiment 5.3, in a simulated delayed harvest of ground-harvested nuts under commercial orchard conditions, there were no significant differences for whole kernel weight (Table 5.1). Shoulder damage was significantly greater ($P<0.05$) in the 3 week partial shade treatment than in the 5 week partial shade treatment (Table 5.1), but there were no differences between treatments and the control. The results for total pieces weight show a similar trend to shoulder damage, with the 5 week treatments producing lower weight of pieces (Table 5.1). However, the only significant difference was between the 5 week full shade treatment (1.6%) and the 3 week partial shade treatment (3.3%).
Fig. 5.1. How delay in harvest after abscission affected quality of macadamia kernels for cultivar HAES 344 in 2003, Experiment 5.1. A) whole kernel weight ($P=0.009$), B) shoulder damage ($P<0.001$) and C) weight of pieces ($P=0.007$). Means and standard errors are presented; means with different letters are significantly different.
Fig. 5.2. A) Whole kernel weight (%), B) shoulder damage (%) and C) weight of pieces (%) for kernels of cultivar HAES 344 from nuts which have suffered delays in harvest in part shade and full shade, Experiment 5.2. Nuts were harvested directly from the trees. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, \( P < 0.05 \)).
Table 5.1. Weight of whole kernel (%), shoulder damage (%) and weight of pieces (%) for nuts of cultivar HAES 344, Experiment 5.3. Nuts were harvested from the ground. Means (and standard errors) are presented. Means with different letters in the same row are significantly different ($P<0.05$).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>3 wks delay</th>
<th>3 wks delay</th>
<th>5 wks delay</th>
<th>5 wks delay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Part Shade</td>
<td>Full Shade</td>
<td>Part Shade</td>
<td>Full Shade</td>
</tr>
<tr>
<td>Whole kernel</td>
<td>70.97 (1.82)</td>
<td>62.18 (3.01)</td>
<td>64.84 (2.30)</td>
<td>66.90 (3.55)</td>
<td>65.96 (2.50)</td>
</tr>
<tr>
<td>weight %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td>17.1 (1.5)$^{bc}$</td>
<td>20.1 (2.4)$^{c}$</td>
<td>17.5 (0.8$^{bc}$</td>
<td>7.9 (1.3)$^a$</td>
<td>11.6 (0.8)$^{ab}$</td>
</tr>
<tr>
<td>damage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total pieces</td>
<td>1.89 (0.30)$^{ab}$</td>
<td>3.30 (0.36)$^b$</td>
<td>2.83 (0.55)$^{ab}$</td>
<td>1.86 (0.32)$^{ab}$</td>
<td>1.61 (0.30)$^a$</td>
</tr>
<tr>
<td>weight %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.3.2. How delayed harvest affected roasting quality

In all three delayed harvest experiments there was a significant colour difference between the controls and the delayed harvest treatments for dark colour (rank 4).

While there were few very dark kernels they all came from the delayed treatments (Fig. 5.3, 5.4 and 5.5). In Experiment 5.1 in 2003, numbers in rank 4 colour ($P<0.001$) (Fig. 5.3), severe patchiness of colour ($P<0.001$) and severe surface damage ($P=0.004$) (Table 5.2) were all significantly greater for the delayed harvest nuts compared with the control. The control had only 6.0% dark (rank 4) kernels, but delayed harvest nuts produced almost eight times that amount (Fig. 5.3). There were very few very dark (reject) kernels. The control had only 2.0% severe patchiness of colour, but this rose to 19.0% for the delayed harvest nuts. Severe surface damage for the delayed harvest nuts was significantly greater than the control ($P=0.004$) (Table 5.2).
Table 5.2. Severe patchiness of colour and severe surface damage for roasted kernels from nuts of delayed harvest Experiment 5.1, 2003. Mean ranks are presented.

<table>
<thead>
<tr>
<th></th>
<th>3 wk Delayed Harvest</th>
<th>Control</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe patchiness of colour</td>
<td>15.20</td>
<td>5.80</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Severe surface damage</td>
<td>14.15</td>
<td>6.85</td>
<td>0.004</td>
</tr>
</tbody>
</table>

In Experiment 5.2 in 2004 a delayed harvest produced few very dark (reject) kernels (Table 5.3), however, all came from delayed treatments. There were significantly less dark (category 4) kernels in the control than the treatments (P<0.05). Severe surface damage ranks for the 5 week part shade treatment were significantly higher (P<0.05) than the control (Fig. 5.4) but severe patchiness of colour was not different (Table 5.4).

Fig. 5.3. Dark (category 4) kernels produced by roasting macadamia kernels following a three week simulated delayed harvest, Experiment 5.1, 2003. Means and standard errors are presented; means with different letters are significantly different (P<0.001).
Table 5.3. Very dark kernels (%) from nuts from a simulated delayed harvest, Experiment 5.2, 2004, for tree-harvested nuts. Means (and standard errors) are presented.

<table>
<thead>
<tr>
<th>Time delay</th>
<th>Treatment</th>
<th>Very dark kernels</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Control</td>
<td>0.00</td>
</tr>
<tr>
<td>3 weeks</td>
<td>Part shade</td>
<td>1.3 (1.3)</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td>5 weeks</td>
<td>Part shade</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Fig. 5.4. Roasting quality for kernels from nuts of Experiment 5.2, 2004, subjected to a simulated delayed harvest. A) Dark kernels (category 4), means and standard errors are presented, means with different letters are significantly different, Duncan’s, $P < 0.05$; B, Severe surface damage mean ranks, $P < 0.005$. 
When nuts were harvested from the ground and subjected to a delayed harvest all four delayed treatments had significantly more dark kernels than the control, ranging from three times for the 3 week full shade treatment to four times for the 5 week part shade treatment (Fig. 5.5). Severe patchiness of colour and severe surface damage were not significantly different (Table 5.5).

![Bar chart showing dark kernels (%) for different treatments](image)

**Fig. 5.5.** Dark (Rank 4) roasted kernels(%) for kernels from nuts of Experiment 5.3, 2004, subjected to a simulated delayed harvest. Means and standard errors are presented. Means with different letters are significantly different (Duncan’s, $P < 0.05$). PS = part shade; FS = full shade.

**Table 5.4.** Severe patchiness of colour for kernels from delayed harvest nuts from Experiment 5.2, 2004. Means ranks are presented.

<table>
<thead>
<tr>
<th>Time delay</th>
<th>Treatment</th>
<th>Mean ranks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Control</td>
<td>19.10</td>
</tr>
<tr>
<td>3 weeks</td>
<td>Part shade</td>
<td>24.69</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>22.60</td>
</tr>
<tr>
<td>5 weeks</td>
<td>Part shade</td>
<td>30.05</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>26.10</td>
</tr>
</tbody>
</table>
Table 5.5. Severe patchiness of colour and severe surface damage for kernels from delayed harvest nuts, Experiment 5.3, 2004. Mean ranks are presented.

<table>
<thead>
<tr>
<th>Time delay</th>
<th>Treatment</th>
<th>Severe patchiness of colour</th>
<th>Severe surface damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Control</td>
<td>13.50</td>
<td>16.90</td>
</tr>
<tr>
<td>3 weeks</td>
<td>Part shade</td>
<td>29.90</td>
<td>31.90</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>30.65</td>
<td>25.60</td>
</tr>
<tr>
<td>5 weeks</td>
<td>Part shade</td>
<td>29.65</td>
<td>25.60</td>
</tr>
<tr>
<td></td>
<td>Full shade</td>
<td>23.80</td>
<td>27.50</td>
</tr>
</tbody>
</table>

Images of differences in colour typical of both delayed harvest experiments in 2004 are presented in Fig. 5.6.

Fig. 5.6. A: Examples of roasted kernels from Delayed Harvest Experiment, 2004, when nuts were harvested directly from the trees. B: The Taubmans ‘Colour Concepts’ colour swatch No.44 colour swatch used as a standard for colour determination.
5.3.3. Dehusker results

Mechanical dehusking did not significantly decrease whole kernel percent weight for nuts from cultivars HAES 344 and HAES 741 and there were no differences between dehuskers in Experiment 5.4, 2002 (Table 5.6).

Table 5.6 Whole kernel weight (%) and weight of pieces (%) for three dehuskers for two cultivars, 2002. Means (and standard errors) are presented.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Hand</th>
<th>Shaw</th>
<th>Admac</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAES 344</td>
<td>Whole wt (%)</td>
<td>37.8 (3.5)</td>
<td>43.2 (3.0)</td>
</tr>
<tr>
<td></td>
<td>Wt of pieces (%)</td>
<td>15.8 (1.6)</td>
<td>13.6 (1.6)</td>
</tr>
<tr>
<td>HAES 741</td>
<td>Whole wt (%)</td>
<td>38.5 (3.4)</td>
<td>47.0 (2.2)</td>
</tr>
<tr>
<td></td>
<td>Wt of pieces (%)</td>
<td>12.1 (2.3)</td>
<td>6.1 (1.4)</td>
</tr>
</tbody>
</table>

Fig. 5.7 Shoulder damage (%) for two cultivars dehusked at field MC (22%). Two mechanical dehuskers are compared with hand dehusking as a control. Means and standard errors are presented. Means with different letters are significantly different (Duncan’s, $P <0.05$).
The Admac dehusker caused significantly more shoulder damage than the other dehusking treatments (Fig. 5.7). For cultivar HAES 741 shoulder damage from the Shaw dehusker was twice that of the control and for the Admac dehusker was three times that of the control. For cultivar HAES 344, the Admac dehusker produced over twice the shoulder damage from the control (Fig. 5.7). There were no differences between hand dehusking and mechanical dehuskers for weight of total pieces.

In dehusker Experiment 5.5 in 2002, when drier nuts (10% moisture content) were dehusked after three weeks slow drying on the ground there was significant shoulder damage ($P < 0.05$) from both dehuskers for both cultivars (Fig. 5.8). For HAES 741 mechanical dehusking increased shoulder damage by approximately 12% to 14% over hand dehusking (Fig. 5.8). Whole kernel weight and weight of pieces were not affected by dehuskers.

![Graph showing shoulder damage for two cultivars dehusked at intermediate MC (10%). Two mechanical dehuskers are compared with hand dehusking as a control. Means and standard errors are presented. Means with different letters are significantly different (Duncan’s, $P < 0.05$).](image)

**Fig. 5.8** Shoulder damage (%) for two cultivars dehusked at intermediate MC (10%). Two mechanical dehuskers are compared with hand dehusking as a control. Means and standard errors are presented. Means with different letters are significantly different (Duncan’s, $P < 0.05$).
In dehusker Experiment 5.6 in 2003, there was a significant reduction in whole kernel for the delayed Shaw dehusker treatment only \((P<0.05)\) when nuts were dehusked at a lower MC. (Fig. 5.9). However, there was no difference between mechanical dehuskers at the same MC (Fig. 5.9). There was a significant increase in weight of pieces \((P<0.05)\) for all treatments dehusked at the lower MC (Table 5.7).

![Whole kernel weight for 3 dehusking methods used in Experiment 5.6 on nuts dehusked immediately after harvest and nuts dehusked after a delay at 12% MC. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, \(P<0.05\)).](image)

**Fig. 5.9.** Whole kernel weight for 3 dehusking methods used in Experiment 5.6 on nuts dehusked immediately after harvest and nuts dehusked after a delay at 12% MC. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, \(P<0.05\)).

There were no differences between dehuskers for shoulder damage in Experiment 5.6. However, weight of pieces increased significantly in all treatments of nuts dehusked after a delay (Table 5.7). The Admac dehusker generated significantly more pieces than all other treatments.
Table 5.7. Weight of pieces for nuts dehusked at field MC and a lower MC (11.8%), Experiment 5.6. Means (and standard errors) are presented; numbers with different letters are significantly different between MC (Duncan’s, $P < 0.05$).

<table>
<thead>
<tr>
<th>Dehusker</th>
<th>Dehusk Immediately (22% MC)</th>
<th>Delay dehusking (11% MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand</td>
<td>4.28 (0.45)$^{ab}$</td>
<td>6.29 (0.97)$^c$</td>
</tr>
<tr>
<td>Shaw</td>
<td>4.24 (0.90)$^{ab}$</td>
<td>6.06 (0.82)$^c$</td>
</tr>
<tr>
<td>Admac</td>
<td>3.63 (0.56)$^a$</td>
<td>8.60 (0.87)$^d$</td>
</tr>
</tbody>
</table>

When nuts were sawn open following dehusking by the above three methods whole kernel numbers were not affected by dehusking method. However, shoulder damage for the Admac dehusker was twice that for hand dehusking and the Shaw dehusker (Table 5.8). Results for the Shaw dehusker were comparable with hand dehusking at this moisture content. Shoulder damage results are similar to those for the first dehusker experiment.

Table 5.8. Shoulder damage (%) for nuts of two cultivars opened by sawing apart following dehusking by hand and by two mechanical dehuskers.

<table>
<thead>
<tr>
<th>Dehusker</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand</td>
<td>22.5</td>
<td>----</td>
</tr>
<tr>
<td>Shaw</td>
<td>20.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Admac</td>
<td>53.3</td>
<td>50.0</td>
</tr>
</tbody>
</table>

There was significant After Roast Darkening of kernels from nuts dehusked after a delay in Experiment 5.6. The Admac treatment had 8.2% very dark (reject) kernels and the Shaw treatment had 5.2%, compared with zero for all other treatments (Table 5.9). All treatments dehusked at 12% MC, including the hand dehusked control had significantly more dark kernels (rank 4) than those dehusked at high MC (Fig. 5.10). The Admac treatment showed the strongest effect (52.1%) compared with only 8.5%
for the high MC treatment. The Admac machine produced significantly more dark kernels than the Shaw machine ($P < 0.05$).

For severe patchiness of colour and severe surface damage there were no significant differences.

**Table 5.9.** Very dark kernels (%) produced by 3 dehusking methods at field moisture content and after a delay before dehusking, Experiment 5.6.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Moisture content</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand</td>
<td>Field MC</td>
<td>0.00</td>
</tr>
<tr>
<td>Shaw</td>
<td>Field MC</td>
<td>0.00</td>
</tr>
<tr>
<td>Admac</td>
<td>Field MC</td>
<td>0.00</td>
</tr>
<tr>
<td>Hand</td>
<td>Low MC</td>
<td>0.00</td>
</tr>
<tr>
<td>Shaw</td>
<td>Low MC</td>
<td>5.22</td>
</tr>
<tr>
<td>Admac</td>
<td>Low MC</td>
<td>8.22</td>
</tr>
</tbody>
</table>

**Fig. 5.10.** Dark kernel (%) of roasted macadamia kernels dehusked at high MC after harvest and at lower MC after 3 weeks delay, Experiment 5.6. Means and standard errors are presented; different letters indicate significant difference (Duncan’s, $P<0.05$).
5.4. Discussion

5.4.1. Delayed harvest

The results for the delayed harvest experiments show clearly that macadamia nuts left on the ground for three to five weeks suffered loss in quality in terms of whole kernel, shoulder damage and weight of pieces for raw, unroasted kernel. In addition, when kernels from delayed harvest were roasted, quality was significantly affected as measured by dark kernels, severe patchiness of colour and severe surface damage. A previous study of delayed harvest did not find any loss in quality of macadamia subjected to delayed harvest with regard to processing recovery or eating quality up to four weeks delay (Mason and Wells, 1984). However, there was some loss in quality after four weeks, mainly in processing recovery (Mason and Wells, 1984). By contrast, the significant roasting quality changes in the current study after 3 to 5 weeks may reflect different assessment methodology, seasonal variation, or cultivar differences.

5.4.1.1. Whole kernel

Delaying harvest reduced whole kernel in both 2003 and 2004. All treatments delayed for three weeks or more had reduced whole kernel compared to controls. Therefore, time of nuts on the ground is a factor in reducing whole kernel, and leaving nuts on the ground for 3 weeks or longer is likely to cause reduced whole kernel. This reduction in whole kernel may be related to factors such as drying and repeated heating and cooling.

Lower MC of the fruit at dehusking may influence whole kernel percentage due to the greater force required to remove the tougher, drier husk. At the conclusion of delayed harvest experiments MC had decreased to about half that of control nuts at dehusking. This may have made the kernels more susceptible to the stresses of
dehusking. Some other seeds are more prone to splitting (separating) at lower MC, such as pea-beans (Perry and Hall 1966). Another condition leading to lower whole kernel could be a space developing between the macadamia cotyledons during drying on the ground. The space between the cotyledons of navy beans increased at lower MC, a factor that may have resulted in splitting of that seed (Hoki and Picket, 1973). This may also happen in macadamia during harvest delay, reducing the bond between half kernels. A further factor may be diurnal heating and cooling of nuts, particularly those in part shade (part sunlight). This heating and cooling may subject the junction between half kernels to additional stresses causing separation of cotyledons.

Another factor affecting whole kernel could be the extended period of drying experienced by the delayed harvest treatments compared with controls. The control was dried immediately and rapidly, beginning at 38°C for two days, then 45°C for two days, and finally at 58°C until NIS MC of 3% was reached. Nuts on the ground experienced slow drying over a 3-5 week period to reach 10-16% MC (depending on the experiment) before drying to 3% MC was completed as described above. This difference in the drying process may have an influence on the bonding of the embryo (kernel) at the interface of the cuticles of the cotyledons.

5.4.1.2. Shoulder damage and pieces

Shoulder damage increased in all the delayed harvest experiments, but the clearest difference was after 3 weeks in Experiment 5.1 in 2003 and after 5 weeks in Experiment 5.2 in 2004. There are no obvious physical causes suggested for increase of shoulder damage in delayed harvest nuts, in contrast to when nuts are dropped (Chapter 6). However, a possible cause is kernels adhering to the inside of the shell, particularly the white enamel area, a problem with c (Hartung and Storey, 1939; Cavaletto, 1986). While this characteristic appears to be related to cultivar it seems to
occur to some degree with most cultivars (Cavaletto, 1983). While the reason for this adhesion is not entirely clear, it may be due in part to the presence on the enamel area of a vestigial inner seed coat (Hartung and Storey, 1939). As nuts dry slowly, the surface of the kernel may not separate from the shell as easily at lower MC as when nuts are fresh, causing tearing of tissue when the kernel separates from the shell. Alternatively, the kernel tissue may be more brittle and shear more easily at lower MC. MC affects the resistance of some other seeds to damage. For example, damage to soybeans during handling increased as MC decreased (Bilanski, 1966; Bartsch et al., 1986). Similarly, the resistance of corn, winter wheat, barley and oats to damage increased with MC (Bilanski, 1966). A lower MC at dehusking may be involved in more shoulder damage. It is clear that delaying harvest even for as short a period as 3 weeks may result in increased shoulder damage.

Weight of pieces also increased significantly in delayed harvest treatments and production of pieces may have been influenced by the much lower MC at dehusking. As with shoulder damage, it was the five week treatments which produced the most damage. These results show that time on the ground is implicated in the amount of surface damage to nuts from a delayed harvest. If tissue becomes more brittle as suggested above for shoulder damage, it would also be more prone to damage in the form of pieces. It is interesting that slow-dried kernel in the drying experiment (Chapter 7) also showed an increase in pieces.

5.4.1.3. Roasting

Delaying harvest produced significant quantities of dark (Rank 4) roasted kernels. While these kernels were not dark enough to warrant rejection, they were sufficiently different from other kernels to require resorting. This phenomenon in macadamias is referred to as ARD, which refers to the darkening that appears after roasting at the
time of evaluation. It is the sum of any colour change during roasting and any change that occurs immediately following roasting prior to evaluation. In brief, there are two types of browning, 1) enzymatic browning (EB) and 2) nonenzymatic browning (NEB). NEB is caused either by the Maillard reaction (Belitz et al., 2004) or caramelisation (Coultate, 2002).

The classic enzymatic browning problem in foods involving phenylalanine ammonia-lyase (PAL) and polyphenol oxidase (PPO) are unlikely to be involved in roasted macadamias as the delayed harvest treatments are not subject to any different processes causing injury. During cracking and kernel assessment there was no evidence of any tissue browning prior to roasting. In addition, the temperature used for drying should have inactivated enzymes such as PAL and PPO (Saltveit, 2000).

The most likely cause of ARD of roasted macadamias is browning due to the Maillard reaction or caramelisation. Prichavudhi and Yamamoto (1965) reported that macadamias dried at higher temperatures were subject to excessive browning at roasting, probably related to higher levels of reducing sugars induced by the high temperature. For caramelisation there needs to be sufficient total sugars. For the Maillard reaction to proceed there must be an increase in the most limiting reactant in the browning reaction, most likely in reducing sugars, although amino acids or suitable proteins must also be available. Brown centres of roasted hazelnuts contained significantly more sugars than lighter surrounding layers (Ozdemir et al., 2001). It is possible that the chemical changes involved in preparations for germination may provide the extra sugar necessary. The macadamia is considered a recalcitrant type (nonorthodox) seed (Doijode, 2001). A recalcitrant seed is one that continues to progress toward germination and is viable for a relatively short period of time at ambient conditions (McDonald, 2004). This means that the complete (in-shell)
macadamia seed is prone to germinate at maturity and is likely to be subject to enzymatic activities associated with germination. This was suggested by Jones (1939) who noted a slight increase in reducing sugars in macadamia embryos at maturity just before harvest, and proposed that this may have been due to germination beginning. Hadorn et al. (1981) reported that in whole (in-shell) walnuts, sucrose levels dropped considerably (22%) at the beginning of storage while glucose increased by 70% and fructose by 62%. In a similar way, macadamia seeds may generate more hexoses while lying on the ground for extended periods.

Many seeds will show visible signs of germination if stored at the MC at which they are shed (Berjak and Pammenter, 2004). Such seeds are not only hydrated but also metabolically active (Berjak and Pammenter, 2004). At harvest, the macadamia nut typically has 20% MC, and this decreases slowly as nuts lie on the ground awaiting harvest. An example of this slow drying is reported above, when nuts at the conclusion of five weeks on the ground under trees were at 13% MC. It is common for nuts to experience a delay such as this during a harvest season in eastern Australia. This is a high MC when compared with 3% NIS MC (1.5% kernel MC) recommended for storage of macadamias (Cavaletto, 1983). Nuts at 13% MC may be sufficiently moist to sustain the biochemistry of germination, especially considering the fact that macadamias contain 75 to 80% oil (Saleeb et al., 1973; Trueman et al. 2000). In germinating seeds, storage lipids are converted into carbohydrates. The conversion of lipids to sugar is triggered by germination and the first step is hydrolysis of triacylglycerols stored in oil bodies to free fatty acids by lipase found on the half-membrane of the oil body (Taiz and Zeiger, 1991). This process takes place in a type of peroxisome called a glyoxysome that is found in oil rich storage tissue of seeds. Fatty acids are converted to glucose in the cytosol and finally into sucrose for
transport in the seed (Taiz and Zeiger, 1998). Mason and Wells (1984) stated that germination may be a problem for nuts left on the ground in shaded or wet conditions for more than four weeks. Thus it is possible for glucose levels to increase in macadamia seeds on the ground in a delayed harvest, providing hexoses for the Maillard reaction or caramelisation. Germination also causes an increase in amino acids as proteolytic mechanisms are activated in the protein storage vacuole and other compartments (Jiang and Rogers, 2001). In this way germination provides the reagents needed for the Maillard reaction.

When colour was assessed in these experiments, dark colour had to be evenly distributed over the kernel for it to be included in a colour rank. Colouring of the axis region alone was not enough for a colour rank. ‘Dark’ kernels had an overall brown colour. This indicates that the process enabling browning was distributed throughout the cotyledon, and not just confined to the axis region. This suggests that if oil was being converted to glucose this was occurring throughout the cotyledon. In cereals, lipases have little or no activity before germination, however, during germination lipase activity gradually spreads throughout the endosperm (Kruger, 1989). In a similar manner, lipase activity in germinating, delayed harvest macadamia seed may spread throughout the cotyledon.

It is also possible that some form of enzymatic browning is involved in the ARD of delayed harvest nuts. Recalcitrant type seeds such as macadamia are still biologically active at high MC as when lying on the ground after abscission (Berjak and Pammenter, 2004). McConachie (1992) reported on an investigation into ‘brown centres’ in macadamia kernels. This physiological disorder consists of nuts which may appear normal on the exterior but are coloured a shade of brown in the centre. This can occur when nuts are dried when the MC is too high (Prichavudhi and
Yamamoto, 1965), and also during roasting. Brown centres of unroasted kernel may suggest a process contributing reducing sugars to ARD during roasting. Kernels with brown centres were found to have reduced levels of sucrose and elevated levels of fructose and glucose (McConachie, 1992), a condition that is not normal in non-germinating seeds (Cochrane, 1999), indicating splitting of sucrose. It is unclear exactly how increased hexoses relate to the brown centres occurring without roasting, although the Maillard reaction does not necessarily require high temperature and can proceed even under refrigeration if other conditions are suitable (Whitfield, 1992).

Severe patchiness of colour was also significantly affected when delayed harvest kernels were roasted in two of the three experiments. This defect sometimes occurs in the form of mottling of the surface of the kernel. This patchiness may be associated with localized damage, such as from shoulder damage and the site of removal of pieces, as it often appears worse around such defects. Severe surface damage was also significant in roasted delayed harvest kernels in two of the three experiments. Areas of surface damage appear subject to further deterioration over time, manifesting as a dusty surface. Both patchiness of colour and surface damage are visually unattractive and may be the site of further deterioration such as oxidation of oil. It is unknown whether shoulder damage is related to patchiness of colour.

The practice of leaving nuts on the ground for extended periods between harvest rounds, e.g., 4 weeks in dry weather (Mason, 2000) is considered normal practice. The near-indestructible shell of the nut may be partly responsible for a false sense of security regarding the integrity of its contents. In other nut crops, it is readily accepted that nuts should be harvested from the ground as soon as possible after abscission. If almonds are exposed to wet and hot conditions on the ground they are subject to an internal disorder called concealed damage, resulting in dark discolouration of the
kernel, and sometimes an unpalatable off-flavour (Kader and Thompson, 1992). In a similar manner, walnuts on the ground are subject to dark kernels, especially at high temperatures (Kader and Thompson, 1992). These examples of nut deterioration on the ground support the proposal that macadamia nuts should be harvested from the ground as frequently as possible during the harvest season if optimal quality is to be achieved.

5.4.2. Dehusking

The dehusker experiments showed that mechanical dehuskers are capable of causing significant shoulder damage and both dehuskers used in these experiments caused shoulder damage. It is a widely held view that nut-in-shell at field moisture content is not readily damaged, and that dehusking at this moisture content presents no risks (Pearce, pers. comm., 2002). This appears true for whole kernel, as mechanical dehuskers did not affect whole kernel in dehusker Experiments 5.4 and 5.5 when nuts were dehusked at field MC, but is not true of shoulder damage. In both these experiments, dehuskers significantly increased shoulder damage, with the Admac dehusker causing slightly more damage. Considering that this is an essential operation it is surprising that the effect of dehuskers on kernel quality has not previously been more thoroughly investigated. Shoulder damage indicates the importance of optimal and regular adjustment of dehuskers. Further research on developing improved dehuskers may be warranted.

In the dehusker Experiment 5.6, a reduction in whole kernel was recorded when nuts were dehusked at a lower MC (12%). This reduction was recorded only for the Shaw dehusker. Weight of pieces increased significantly for all treatments compared with controls, with the Admac machine producing more pieces. It is interesting that pieces were increased even in the hand-dehusked low MC treatment. This indicates
that even without severe mechanical intervention, pieces were being generated during the slow drying on the ground. This may suggest some form of deterioration of tissue during this time. Pieces are an indicator of surface damage of the kernel. When harvesting is delayed and nuts dry on the ground they are then dehusked at a lower MC than when dehusked immediately after abscission. These results show that lower quality kernels in terms of whole kernel, shoulder damage and pieces can be expected when nuts are dehusked at lower MC.

Mechanical dehusking of nuts after a period of slow drying on the ground can lead to large numbers of dark kernels at roasting, with significant rejections. However, it is unclear if the cause is the dehusking or the time delay. Control (hand dehusked) kernels also had significant ARD, which may support a time effect as germination begins, as discussed above. Dehusking may exacerbate this effect, shown by the Admac dehusker treatment in dehusker Experiment 5.6 having significantly more ARD than the Shaw treatment. In addition, severe surface damage to kernel was apparent at roasting kernels from both dehuskers. This may have resulted from the lower MC. It is possible that ‘concealed’ damage occurs due to compression of kernels at high turgor pressure at dehusking, the damage only being manifest as ARD when nuts are roasted. While this type of damage is unavoidable at present because dehusking is essential, improvement of dehusking methods could lead to significantly improved quality of roasted macadamias. When these roasting effects on quality are added to the loss of whole kernel, shoulder damage and pieces, it is clear that dehusking macadamias after delaying harvest has many significant effects on quality and value.
5.5. Summary

Delaying harvest by three weeks or more decreased kernel quality significantly by

- decreasing whole kernel,
- increasing shoulder damage and weight of pieces,
- increasing dark kernels, severe patchiness of colour and severe surface damage.

Dehusking with mechanical dehuskers reduces kernel quality significantly by increasing shoulder damage. Dehusking after delayed harvest significantly reduces whole kernel and increases weight of pieces. This can apply to nuts left on the ground for extended periods in dry weather, or nuts from sun-exposed positions.

5.6. Recommendations to industry:

- harvest rounds during harvest season should be as frequent as possible, preferably with intervals of no more than two weeks,
- careful and frequent dehusker adjustment is essential to minimise damage,
- improved dehusker design should be investigated considering that this operation is unavoidable.
CHAPTER 6

How dropping macadamia nut-in-shell reduces kernel quality

6.1. Introduction

Macadamia kernels are enclosed in a rigid shell, the seed coat, which is formed from the outer integument of the ovule (Stroschen, 1986). The shell is extremely strong, considered to be stronger than reinforced concrete (Jennings and Macmillan, 1986) and provides protection in many ways. Macadamia nuts are subjected to numerous impacts while being processed, mainly due to dropping onto various surfaces during postharvest procedures. Nuts could be subjected to as many as 20 drops as NIS during the processing chain from harvest to cracking (McConachie, pers. comm., 2002). Moisture content may affect susceptibility to kernel damage when nuts are dropped and lower recovery of marketable kernel due to shattering of kernel at cracking (Liang, 1977; Tang et al., 1982). Weight of pieces after cracking increased as moisture content of macadamias was reduced (Sarig et al., 1980).

Between harvest and cracking, nuts are dropped at different moisture contents. The initial drops are at relatively high field moisture contents (e.g., 17-22% wb NIS MC), and subsequent drops are at lower NIS MC as nuts are progressively dried on-farm. The final MC desired for transport to the processor is approximately 8-10% (AMS, 2000). On the farm following dehusking, nuts are typically augered into a silo for storage and partial drying. This typically involves a drop of 3-4 metres or more in some cases. Nuts are dropped onto surfaces of varying composition and thickness. These surfaces may be a steel plate as in drying and storage silos and some truck
bodies, aluminium in the case of more recent vehicles, or a surface of NIS in silos and bins once receiving plate surfaces have been covered with nuts (McConachie, pers. comm), 2002. These different surfaces could be expected to have different impact effects on the dropped NIS. Apart from the drop into a silo following dehusking, there are usually one or more additional drops on the farm when nuts are resorted before shipment to processors.

Susceptibility to damage varies among different biological products due to inherent variability. When the effect of impacts on biological objects such as greenhouse tomatoes was compared with non-biological objects of rubber and plastic-like spheres, the non-biological objects produced consistent results while the biological products displayed variability and susceptibility to damage (Lichtensteiger et al., 1988). It is clear that the effect of impacts on biological objects is very difficult to predict. An exploratory study using only 30 nuts per treatment reported that dropping macadamia nuts at low MC (1% kernel MC) onto a steel plate from heights up to four metres increased pieces, and reduced whole kernel, though no statistical analysis was available (Cavaletto, 1986). Cavaletto (1990) suggested that repeated impacts to macadamia nuts cause an oily surface appearance of some kernels, consistent with bruising and browning on roasting. However, there is no information on the effects of dropping nuts of different cultivars at a variety of MC onto different surfaces on quality parameters such as whole kernel, shoulder damage, pieces, or roasting quality. The type and extent of damage caused by dropping has not been investigated. A large quantity of macadamia kernel is sold at the retail level as roasted product (Mason et al., 1995), therefore any lowering of the quality of roasted kernels is of some concern. Uneven colouring of product causes negative consumer reaction and hence the need for extra sorting to remove the high proportion of dark kernels.
This series of four studies reports the effect on kernel of repeated dropping of NIS from set heights. The aims of these experiments were to assess the effect on kernel quality of both raw and roasted kernel of dropping NIS from different cultivars at different MC onto different surfaces.

6.2. Materials and methods

6.2.1 Dropping nuts

There were four dropping experiments. In Experiment 6.1, cultivars HAES 344 and HAES 741 were harvested from Sahara Farms, Glasshouse Mountains (26°53.44’S, 152°56.16’E) and HV A38 from Hidden Valley Plantation, Beerwah (26°50.06’S, 152°55.01’E), in June 2002. A bulk sample of each cultivar was harvested and 10 replicates of 50 nuts were sub-sampled from each cultivar for each treatment and control. Treated nuts were dropped 4 times from a height of 2m onto a bed of macadamia nut-in-shell. One treatment was dropped at field moisture content (20%) and another at 3% MC. Nuts were then dried to 3% MC for cracking. There was a separate undropped control for nuts at each moisture content.

Whole kernel, shoulder damage, weight of pieces, dust and oiliness of kernels were recorded. In Experiment 6.2, harvesting was the same as for Experiment 6.1. Five replicates of fifty nuts each were dried to 7% MC NIS and dropped as above. Nuts were then dried to 3% NIS MC for cracking.

Dropping Experiment 6.3 was conducted in 2003. Nuts from cultivars HAES 344 and HAES 741 were harvested at Sahara Farms, Glasshouse Mountains in April, 2003. Eight replicate samples, each consisting of 50 nuts, were harvested from each of 10 trees per cultivar. One replicate per tree was assigned to each of the 4 treatments and 4 controls. The four treatments used were field moisture content (17%), 9% MC,
7% MC and 3% MC. There was a separate control for each treatment. Nuts from each treatment were dropped onto a bed of NIS as for Experiment 6.1.

In dropping Experiment 6.4, nuts of cultivar HAES 344 were harvested from Sahara Farms, Glasshouse Mountains in mid May 2004. One replicate per treatment and control was harvested from each of ten trees at a field MC of approximately 20%. Nuts were dropped at two moisture contents, field MC (20%), and 10%, and there were two dropping surfaces, NIS and a metal plate. Nuts were dropped once only from a height of four metres for each moisture content and/or each surface. This meant that some treatments were dropped twice, e.g., for two different MC’s or two different surfaces at the same MC or a combination of a surface and a MC. A bed of NIS and a high tensile aluminium plate of 5mm thickness were used for dropping surfaces. Details of the ten treatments are shown in Table 6.1. Two controls were used which were not dropped, one dried to 3% NIS MC for 20% dropped treatments, and one dried first to 10% MC, then dried to 1.5% MC for 10% dropped treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Type</th>
<th>NIS Surface</th>
<th>Metal Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control 20% MC</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>2</td>
<td>Drop 20% MC</td>
<td>----</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>Drop 20% MC</td>
<td>Y</td>
<td>----</td>
</tr>
<tr>
<td>4</td>
<td>Control 10% MC</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>5</td>
<td>Drop 10% MC</td>
<td>----</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>Drop 10% MC</td>
<td>Y</td>
<td>----</td>
</tr>
<tr>
<td>7</td>
<td>Drop 20% &amp; 10%MC</td>
<td>----</td>
<td>Y</td>
</tr>
<tr>
<td>8</td>
<td>Drop 20% &amp; 10%MC</td>
<td>Y</td>
<td>----</td>
</tr>
<tr>
<td>9</td>
<td>Drop first at 10%,</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>then 20%MC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Drop first at 20%,</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>then at 10%MC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1. Dropping treatments for Experiment 6.4 for macadamia kernels from cultivar HAES 344 dropped at 20% and/or 10% NIS MC onto NIS and/or metal plate
6.2.1.1. Assessing oiliness and dust

Oiliness was assessed by examining the hemisphere of the nut at the micropylar end. The hilum end normally has a characteristic darker appearance which may mask an oily appearance. A kernel was deemed to be ‘oily’ if the surface at the micropyle end appeared oily and darker than surrounding tissue. An oily condition was confirmed by rubbing the ‘oily’ surface lightly on white paper. If rubbing left an oily mark, the sample was deemed oily. Oiliness was recorded only for whole kernel. Whole kernels were assessed visually for dusty appearance. This excluded many kernels that felt dusty although they did not show much visible dust, resulting in a conservative count of dusty nuts. Wholes were examined for oiliness at cracking, 2 weeks after cracking, at 6 weeks, and 18 weeks after cracking for Experiments 6.1 and 6.2, 10 weeks for Experiment 6.3, and 8 weeks for Experiment 6.4.

6.2.1.2. Statistical analysis

Means were calculated for whole kernel weight (%), shoulder damage (%), weight of pieces (%), dusty nuts (%) and oily nuts (%) in all experiments. For Experiment 6.1, parametric data were analysed for all cultivars together with cultivar and treatment as factors using a one-way ANOVA with 11 degrees of freedom and Duncan’s multiple range test for comparison of means. A non-parametric Kruskall-Wallis test and Mann-Whitney U-tests were used to test for differences in dusty kernels because data were non-parametric. Cultivars were analysed separately and a Bonferroni correction factor was used to determine the appropriate level of significance.
For Experiment 6.2, parametric data were analysed for all cultivars together using a 2-way ANOVA with 5 degrees of freedom, with cultivar and treatment as factors, and Duncan’s multiple range test for comparison of means. Non-parametric data for oiliness at 18 weeks were tested using Mann-Whitney U-test to compare treatments with controls for oily and dusty kernels. A Bonferroni correction factor was used to determine the appropriate level of significance. For Experiment 6.3, parametric data were analysed for both cultivars together using a 2-way ANOVA with cultivar and treatment as factors, and Duncan’s multiple range test for comparison of means. For Experiment 6.4, data were analysed using an ANOVA with 9 degrees of freedom and Duncan’s multiple range test for comparison of means.

6.2.2. Roasting kernels

From the first five replicates of each treatment of Experiment 6.1 ten whole kernels were selected at random. For roasting in Experiment 6.3 and Experiment 6.4, ten whole kernels were selected from each replicate of each treatment. Samples were also taken from the control for each moisture content for each experiment. Roasting methods and procedures were as described in detail in Chapter 5.3.1 of this thesis.

6.2.2.1. Statistical analysis

In Experiment 6.1 for nuts dropped at 20% and 3% NIS MC, counts for colour, severe patchiness of colour, and severe surface damage were tested for significance. Because data were non-parametric, cultivars were tested separately using Mann-Whitney U-tests, and a Bonferroni correction factor was used to determine the appropriate level of significance. For Experiment 6.3 and Experiment 6.4 percentages in each category were calculated. Parametric data for colour categories 4 and 5 combined were then analyzed by one-way ANOVA with 7 degrees of freedom for
each cultivar for experiment 6.3, 9 degrees of freedom for experiment 6.4 with Duncan’s multiple range test for comparison of means. Colour categories 4 and 5 combined (%) for experiment 6.3 for cultivar HAES 344 were log(x+1) transformed before analysis. For Experiment 6.3, non-parametric data for severe surface damage were tested as for Experiment 6.1.

6.3. Results

6.3.1. Dropping effects on raw kernel quality

6.3.1.1. Whole kernel weight

Repeated impacts to NIS from dropping nuts at 3% and 20% NIS MC did not reduce percent weight of whole kernel in Experiment 6.1 (Fig. 6.1). However there was a significant difference between cultivars for percentage weight of whole kernel recovered with HV A38 being higher than both HAES cultivars. HAES 741 had significantly greater whole kernel than HAES 344 except for the 3% MC treatment. This trend continued in Experiment 6.2 when nuts were dropped at 7% MC (Table 6.2) and Experiment 6.3 when nuts were dropped at 17%, 9%, 7% and 3% MC (Table 6.3). Dropping NIS did not reduce the whole kernel percentage and the controlling influence on whole kernel was cultivar.
Table 6.2  Whole weight (%) for 3 cultivars dropped at 7% NIS MC in Experiment 6.2, 2002; means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop 7%</td>
<td>75.56 (2.83)</td>
<td>30.66 (1.16)</td>
<td>35.98 (2.12)</td>
</tr>
<tr>
<td>Control 7%</td>
<td>66.88 (5.61)</td>
<td>28.01 (1.76)</td>
<td>32.43 (3.04)</td>
</tr>
</tbody>
</table>

In Experiment 6.3 when nuts were dropped at 4 moisture contents, weight of whole kernel ranged from 47% for HAES 344 to 60% for HAES 741, but there was no significant difference between treatments or cultivars (Table 6.3).

The only significant difference in whole kernel occurred in Experiment 6.4, for nuts dropped at both 10% and 20% MC onto metal plate, where dropped nuts produced a greater weight of whole kernel. The dropped treatment produced 65.4%
whole kernel weight compared with 51.2% for the 20% control and 48.0% for the 10% control (Fig. 6.2).

Table 6.3. Weight of whole kernel (%) for nuts dropped at 4 moisture contents in Experiment 6.3, 2003, for cultivars HAES 344 and HAES 741. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>49.28 (2.48)</td>
<td>49.08 (3.30)</td>
</tr>
<tr>
<td>3% Control</td>
<td>49.5 (2.49)</td>
<td>53.50 (4.12)</td>
</tr>
<tr>
<td>7% Drop</td>
<td>46.6 (2.37)</td>
<td>49.63 (4.19)</td>
</tr>
<tr>
<td>7% Control</td>
<td>47.23 (1.88)</td>
<td>56.79 (5.03)</td>
</tr>
<tr>
<td>9% Drop</td>
<td>49.32 (1.61)</td>
<td>55.80 (2.96)</td>
</tr>
<tr>
<td>9% Control</td>
<td>48.68 (1.68)</td>
<td>58.36 (2.61)</td>
</tr>
<tr>
<td>17% Drop</td>
<td>52.91 (1.55)</td>
<td>59.94 (3.74)</td>
</tr>
<tr>
<td>17% Control</td>
<td>52.28 (1.98)</td>
<td>57.73 (2.74)</td>
</tr>
</tbody>
</table>

Fig. 6.2. Whole kernel weight for macadamia kernels from cultivar HAES 344 dropped at 20% and 10% NIS MC onto NIS and metal plate, Experiment 6.4, 2004. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, P<0.05).
6.3.1.2. Shoulder damage

In Experiment 6.1, all treatments produced high levels of shoulder damage, ranging from 31% to 57%. However, while there were some differences between cultivars for shoulder damage for nuts dropped at 3% and 20% MC, for each cultivar no dropped treatment differed from its respective MC control (Fig. 6.3). HAES 344 had significantly more shoulder damage when dropped at 3% MC than HV A38, and at 20% significantly more than both the other cultivars (Fig. 6.3). In Experiment 6.2, there was no difference between nuts dropped at 7% MC and the control (Table 6.4).

![Fig. 6.3. Shoulder damage for macadamias of 3 cultivars dropped as NIS at 3% and 20% NIS MC, Experiment 6.1, 2002. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, \( P <0.05 \)).](image)

Table 6.4. Shoulder damage (%) for 3 cultivars dropped at 7% NIS MC, Experiment 6.2, 2002. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop 7%</td>
<td>34.77 (4.52)</td>
<td>63.47 (6.66)</td>
<td>55.00 (9.42)</td>
</tr>
<tr>
<td>Control 7%</td>
<td>41.78 (6.18)</td>
<td>57.75 (4.63)</td>
<td>44.67 (6.61)</td>
</tr>
</tbody>
</table>

In Experiment 6.3 there was an increase in shoulder damage in dropped treatments for the 3% MC treatments, one 9% MC treatment and one 17% treatment
(Fig. 6.4). For HAES 344, nuts dropped at 3% MC suffered greater damage than the control (30% compared with 19%). For HAES 741, nuts dropped at 3% MC had more shoulder damage than the control (24% cf. 14%), but there was also a difference in nuts dropped at 9% and 17% MC (30% cf. 18%) (Fig. 6.4).

**Fig. 6.4.** Shoulder damage (%) for macadamias of cultivars HAES 344 and HAES 741 dropped at 4 moisture contents onto a bed of NIS, Experiment 6.3, 2003. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, $P<0.05$).
When nuts were dropped onto a metal plate in Experiment 6.4, shoulder damage increased compared with controls (Fig. 6.5). Shoulder damage ranged from a low of 16.1% for the 20% control and 16.6% for the 10% control to a high of 66.5% for the nuts dropped at both MC onto the plate, that is, those nuts dropped onto plate twice (Fig. 6.5). All treatments, except the 20% nuts dropped onto NIS had significantly more shoulder damage than the controls ($P < 0.05$). There was a trend for increasing shoulder damage with lower MC, being dropped onto plate surface, being dropped twice or combinations of these.

**Fig. 6. 5.** Shoulder damage for macadamia kernels from cultivar HAES 344 dropped at 20% and 10% NIS MC onto NIS and metal plate, Experiment 6.4, 2004. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P < 0.05$).
6.3.1.3. Weight of pieces

In Experiment 6.1 there was significantly less pieces for HAES 344 and HAES 741 nuts dropped at 3% MC compared with their controls; however, dropping did not increase pieces (Table 6.5).

Table 6.5. Weight of pieces (%) for kernels dropped at 3% and 20% MC NIS, Experiment 6.1, 2002. Means and (standard errors) are presented, means with different letters are significantly different (Duncan’s, $P < 0.05$).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>5.26 (0.80)$^{de}$</td>
<td>11.97 (1.82)$^{c}$</td>
<td>9.73 (1.24)$^{d}$</td>
</tr>
<tr>
<td>3% Control</td>
<td>4.03 (0.66)$^{a}$</td>
<td>21.82 (2.15)$^{ab}$</td>
<td>18.42 (2.80)$^{ab}$</td>
</tr>
<tr>
<td>20% Drop</td>
<td>5.97 (0.78)$^{de}$</td>
<td>22.64 (1.47)$^{ab}$</td>
<td>18.81 (1.36)$^{ab}$</td>
</tr>
<tr>
<td>20% Control</td>
<td>6.02 (0.92)$^{de}$</td>
<td>23.22 (1.91)$^{a}$</td>
<td>17.48 (2.41)$^{a}$</td>
</tr>
</tbody>
</table>

When nuts were dropped at 4 moisture contents in Experiment 6.3 there were no significant differences between treatments and controls for weight of pieces (Table 6.6) with values ranging from 2% to 5% of total kernel weight. The only difference was that HAES 741 produced more pieces than HAES 344 when dropped at 3% MC. There was a much greater weight of pieces produced in 2002 than 2003, illustrating the desirability of conducting experiments over more than one season.

Table 6.6. Weight of pieces (%) for nuts dropped at 4 moisture contents for cultivars HAES 344 and HAES 741, Experiment 6.3, 2003. Means and (standard errors) are presented, means with different letters are significantly different (Duncan’s, $P < 0.05$).

<table>
<thead>
<tr>
<th>MC</th>
<th>Treatment</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>3.29 (0.50)$^{ab}$</td>
<td>5.16 (0.77)$^{c}$</td>
<td></td>
</tr>
<tr>
<td>3% Control</td>
<td>4.02 (0.58)$^{abc}$</td>
<td>3.89 (0.59)$^{abc}$</td>
<td></td>
</tr>
<tr>
<td>7% Drop</td>
<td>3.87 (0.27)$^{abc}$</td>
<td>2.66 (0.31)$^{a}$</td>
<td></td>
</tr>
<tr>
<td>7% Control</td>
<td>3.87 (0.46)$^{a}$</td>
<td>2.38 (0.54)$^{a}$</td>
<td></td>
</tr>
<tr>
<td>9% Drop</td>
<td>3.30 (0.40)$^{ab}$</td>
<td>3.91 (0.64)$^{abc}$</td>
<td></td>
</tr>
<tr>
<td>9% Control</td>
<td>4.77 (0.43)$^{abc}$</td>
<td>3.47 (0.64)$^{ab}$</td>
<td></td>
</tr>
<tr>
<td>17% Drop</td>
<td>2.46 (0.37)$^{a}$</td>
<td>3.57 (0.37)$^{abc}$</td>
<td></td>
</tr>
<tr>
<td>17% Control</td>
<td>3.46 (0.40)$^{ab}$</td>
<td>3.68 (0.56)$^{a}$</td>
<td></td>
</tr>
</tbody>
</table>
In 2004 in Experiment 6.4 when nuts were dropped at 10% and 20% MC onto NIS and metal plate, weight of pieces varied little between treatments and low values were recorded as in 2003 (Table 6.7).

Table 6.7. Total pieces weight (%) of macadamia kernels dropped at 20% NIS MC and 10% NIS MC onto NIS and metal plate, Experiment 6.4, 2004. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 20%</td>
<td>1.76 (0.29)</td>
</tr>
<tr>
<td>Plate 20%</td>
<td>1.25 (0.25)</td>
</tr>
<tr>
<td>NIS 20%</td>
<td>1.33 (0.41)</td>
</tr>
<tr>
<td>Control 10%</td>
<td>2.92 (0.64)</td>
</tr>
<tr>
<td>Plate 10%</td>
<td>2.08 (0.46)</td>
</tr>
<tr>
<td>NIS 10%</td>
<td>3.03 (0.41)</td>
</tr>
<tr>
<td>Plate 20% Plate 10%</td>
<td>2.35 (0.30)</td>
</tr>
<tr>
<td>NIS 20% NIS 10%</td>
<td>2.28 (0.40)</td>
</tr>
<tr>
<td>Plate 20% NIS 10%</td>
<td>2.53 (0.53)</td>
</tr>
<tr>
<td>NIS 20% Plate 10%</td>
<td>2.43 (0.44)</td>
</tr>
</tbody>
</table>

6.3.1.4. Oily kernels

Dropping nuts at 3% MC produced a greater percentage of oily kernels ($P<0.05$). Values were low two weeks after cracking (Table 6.8), however, by 18 weeks oily kernels rose to 40-50% in the 3% dropped treatment (Fig. 6.6). Nuts dropped at 3% NIS MC produced more oily kernels at 18 weeks after cracking than all other treatments (Fig. 6.6). The percentage of nuts with an oily appearance increased over time, e.g., for cultivar HAES 344 dropped at 3% MC from c.4% at two weeks to c.52% at 18 weeks.

Table 6.8. Percent oily kernels at 2 weeks after cracking for nuts dropped onto NIS at 4 moisture contents, Experiment 6.3, 2003. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>2.61 (0.67)</td>
<td>3.65 (0.78)</td>
<td>3.62 (0.78)</td>
</tr>
<tr>
<td>3% Control</td>
<td>0.60 (0.31)</td>
<td>1.43 (0.69)</td>
<td>1.81 (0.63)</td>
</tr>
<tr>
<td>20% Drop</td>
<td>1.00 (0.54)</td>
<td>1.00 (0.45)</td>
<td>2.40 (0.58)</td>
</tr>
<tr>
<td>20% Control</td>
<td>1.00 (0.45)</td>
<td>0.80 (0.53)</td>
<td>2.20 (0.63)</td>
</tr>
</tbody>
</table>
When nuts were dropped at 7% MC in Experiment 6.2, they were a significantly higher in percentage of oily kernels at 18 weeks post-cracking (Table 6.9). Oily kernels in dropped treatments reached high levels in this experiment, eg, 60% for HAES 344, which was three times the control.

Table 6.9. Mean ranks for oily kernels at 18 weeks from nuts dropped at 7% MC, Experiment 6.2, 2002.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Drop</th>
<th>Control</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV A38</td>
<td>21.4</td>
<td>4.4</td>
<td>0.008</td>
</tr>
<tr>
<td>HAES 344</td>
<td>25.4</td>
<td>13.0</td>
<td>0.008</td>
</tr>
<tr>
<td>HAES 741</td>
<td>21.6</td>
<td>7.2</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Fig. 6.6. Oily kernels (%) at 18 weeks after cracking for 3% and 20% NIS MC treatments, Experiment 6.1, 2002. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, $P<0.05$).
When nuts were dropped at 4 moisture contents in Experiment 6.3, percentages of oily nuts were relatively low at cracking (Table 6.10). However, at 10 weeks after cracking oiliness of dropped nuts was significantly greater ($P<0.05$) at 3% MC (Fig. 6.7). In fact, oily kernels from HAES 344 nuts dropped at 3% were 39%, double the control (Fig. 6.7). Similarly, for HAES 741, oily kernels were 47% for the 3% MC treatment, almost double the control (24%). In addition, oiliness for HAES 741 nuts dropped at 7% MC was 43%, greater ($P<0.05$) than the control (Fig. 6.7).

Table 6.10. Oily kernels (%) at cracking for nuts dropped at 4 moisture contents for cultivars HAES 344 and HAES 741, Experiment 6.3, 2003. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>5.85 (1.38)</td>
<td>4.41 (1.48)</td>
</tr>
<tr>
<td>3% Control</td>
<td>3.61 (0.63)</td>
<td>5.91 (0.88)</td>
</tr>
<tr>
<td>7% Drop</td>
<td>0.00 (0.00)</td>
<td>0.00 (0.00)</td>
</tr>
<tr>
<td>7% Control</td>
<td>0.00 (0.00)</td>
<td>2.03 (0.84)</td>
</tr>
<tr>
<td>9% Drop</td>
<td>2.68 (1.02)</td>
<td>6.55 (1.08)</td>
</tr>
<tr>
<td>9% Control</td>
<td>0.00 (0.00)</td>
<td>2.01 (1.03)</td>
</tr>
<tr>
<td>17% Drop</td>
<td>0.50 (0.50)</td>
<td>0.67 (0.44)</td>
</tr>
<tr>
<td>17% Control</td>
<td>0.00 (0.00)</td>
<td>0.78 (0.52)</td>
</tr>
</tbody>
</table>
When nuts were dropped twice, initially at 20% MC and then at 10% MC onto metal plate in Experiment 6.4 oiliness was significantly higher than both controls \((P<0.05)\) (Fig. 6.8). A similar result was found when nuts were dropped first onto NIS at 20% MC, then onto plate at 10% MC \((P<0.05)\). Oiliness for nuts dropped at both MC onto plate was 29%, compared to the highest control with 19% (Fig. 6.8).

**Fig. 6.7.** Oily kernels at 10 weeks after cracking for nuts of cultivars HAES 344 and HAES 741 dropped at 4 moisture contents, Experiment 6.3, 2003. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, \(P<0.05\)).
6.1.3.5. Dusty kernels

Dropping NIS in Experiment 6.1 produced higher (P<0.001) levels of dusty kernels than 3% MC controls (Table 6.11). There were no significant differences at 20% MC. High individual values (%) were recorded for HAES 344 (20%) and HV A38 (44%). These values for dropped nuts were 20 to 40 times those of the control means (Table 6.11). Similarly, nuts dropped at 7% MC in Experiment 6.2 produced significantly more dusty kernels (P<0.05). The controls recorded no dustiness in this experiment (Table 6.12).

![Fig. 6.8. Oily kernels at 8 weeks after cracking for nuts of cultivar HAES 344 dropped at 20% MC and/or 10% MC onto NIS and/or metal plate, Experiment 6.4, 2004. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, P <0.05).](image-url)
Table 6.11. Dusty kernels (%) at cracking for nuts dropped at 3% MC and 20% MC, Experiment 6.1, 2002. Means ranks are presented.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Moisture Content</th>
<th>Dropped</th>
<th>Control</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV A38</td>
<td>3% MC</td>
<td>15.5</td>
<td>5.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>20% MC</td>
<td>12.3</td>
<td>8.7</td>
<td>NS</td>
</tr>
<tr>
<td>HAES 344</td>
<td>3% MC</td>
<td>15.5</td>
<td>5.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>20% MC</td>
<td>11.4</td>
<td>9.6</td>
<td>NS</td>
</tr>
<tr>
<td>HAES 741</td>
<td>3% MC</td>
<td>15.5</td>
<td>5.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>20% MC</td>
<td>13.5</td>
<td>7.5</td>
<td>NS</td>
</tr>
</tbody>
</table>

Table 6.12. Dusty kernels (%) at cracking for 7% NIS MC dropped treatments, Experiment 6.2, 2002. Controls had no dusty kernels. Means and standard errors are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop 7% MC</td>
<td>27.7 (3.1)^a</td>
<td>12.4 (0.6)^b</td>
<td>14.1 (0.5)^b</td>
</tr>
<tr>
<td>Control 7% MC</td>
<td>0.0 (0.0)^c</td>
<td>0.0 (0.0)^c</td>
<td>0.0 (0.0)^c</td>
</tr>
</tbody>
</table>

When nuts were dropped at 4 MC in Experiment 6.3 the number of dusty nuts for all dropped treatments was significantly higher than respective controls (P<0.001), except for HAES 344 dropped at 9% MC and both cultivars dropped at 17% (Table 6.13). Both HAES 344 and HAES 741 dropped at 3% MC had 28% dusty nuts while their controls had virtually none (Table 6.13). Overall, number of dusty nuts for the dropped treatments was inversely related to moisture content at dropping.

Table 6.13. Dusty kernels (%) at cracking (%) for cultivars HAES 344 and HAES 741 from nuts dropped at 4 moisture contents, Experiment 6.3, 2003. Means are presented for dropped treatment and respective controls.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>HAES 344</th>
<th>P</th>
<th>HAES 741</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% Drop</td>
<td>28.23</td>
<td>&lt; 0.001</td>
<td>28.09</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>3% Control</td>
<td>0.00</td>
<td></td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>7% Drop</td>
<td>21.59</td>
<td>&lt; 0.001</td>
<td>20.47</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>7% Control</td>
<td>0.00</td>
<td></td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>9% Drop</td>
<td>10.97</td>
<td>N</td>
<td>15.43</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>9% Control</td>
<td>0.00</td>
<td></td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>17% Drop</td>
<td>0.00</td>
<td>N</td>
<td>2.14</td>
<td>NS</td>
</tr>
<tr>
<td>17% Control</td>
<td>0.00</td>
<td></td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>
In dropping Experiment 6.4, all treatments dropped onto a plate had significantly more \((P<0.05)\) dusty kernels than controls (Fig. 6.9). The treatment dropped twice onto NIS also had significantly more dusty kernels (Fig. 6.9).

**Fig. 6.9.** Dusty kernels (%) at cracking for nuts dropped at 10\% and 20\% NIS MC onto NIS and/or metal plate, Experiment 6.4, 2004. Means and standard errors are presented, treatments with different letters are significantly different (Duncan’s, \(P<0.05)\).

**6.3.2. Dropping effects on roasting quality**

**6.3.2.1. Colour of roasted kernel**

*Experiment 6.1, 2002*

When kernels dropped at 3\% and 20\% NIS MC were roasted, dropped kernels were significantly darker (Table 6.14 and 6.15). For kernels dropped at 3\%, cultivars HV A38 and HAES 741 showed more browning \((P<0.001)\) than their controls. For the dropped treatments, there were high percentages of dark (rank 4) kernels. An example of colour differences in the 3\% MC treatment for cultivar HAES 741 is presented in Fig. 6.10.
Table 6.14. Dark kernels for nuts dropped at 3% NIS MC and controls, Experiment 6.1, 2002. Mean ranks are presented.

<table>
<thead>
<tr>
<th></th>
<th>Drop</th>
<th>Control</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV A38</td>
<td>61.8</td>
<td>39.2</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>HAES 344</td>
<td>38.9</td>
<td>48.3</td>
<td></td>
</tr>
<tr>
<td>HAES 741</td>
<td>56.8</td>
<td>31.4</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Fig. 6.10. Example of roasting colour for macadamia kernels dropped at 3% NIS MC, cultivar HAES 741. D = dropped treatment, C = control.

Only HAES 344 nuts dropped at 20% MC had significantly more dark kernels (P=0.001) than their controls (Table 6.15). HV A38 and HAES 741 were not different for darker kernels. An example of the difference in colour for the 20% MC treatments for cultivar HAES 344 is presented in Fig. 6.11.

Table 6.15. Roasted kernels and controls from nuts dropped at 20% NIS MC, Experiment 6.1, 2002. Mean ranks are presented.

<table>
<thead>
<tr>
<th></th>
<th>Drop</th>
<th>Control</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV A38</td>
<td>54.1</td>
<td>47.0</td>
<td></td>
</tr>
<tr>
<td>HAES 344</td>
<td>51.4</td>
<td>49.6</td>
<td>0.001</td>
</tr>
<tr>
<td>HAES 741</td>
<td>52.7</td>
<td>46.2</td>
<td></td>
</tr>
</tbody>
</table>
When kernels dropped at 3% MC were roasted there were significantly more combined dark and very dark (reject) kernels ($P < 0.05$) only for dropped cultivar HAES 741 (Fig. 6.12). The 3% dropped treatment for HAES 741 was greater than all other treatments for dark colour, and the 17% dropped treatment was also significantly higher than its corresponding control. Cultivar HAES 344 was not affected.
Fig. 6.12. The effect of roasting on colour of kernels dropped at 4 moisture contents, Experiment 6.3, 2003. A, cultivar HAES 344; B, cultivar HAES 741. Means and standard errors are presented, means with different letters are significantly different (Duncan’s, $P < 0.05$).

An example of the difference in colour between the 17% MC treatment and control of HAES 741 for Experiment 6.3 is presented in Fig. 6.13. Although not shown, kernel dropped at 3% was much darker.
In Experiment 6.4 in 2004 there was no significant difference between treatments for dark kernels, but there was a trend for dark kernels being highest for the treatment dropped onto plate at both MC (Table 6.16). In this experiment percentages of very dark kernels were low, with the highest value being 2.22% for the nuts dropped onto plate twice while zeros were recorded for many other treatments (Table 6.16).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dark</th>
<th>Very dark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control 20%</td>
<td>11.0 (3.1)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Plate 20%</td>
<td>20.0 (6.2)</td>
<td>1.0 (1.0)</td>
</tr>
<tr>
<td>NIS 20%</td>
<td>15.00 (4.0)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Control 10%</td>
<td>9.0 (3.8)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Plate 10%</td>
<td>24.0 (5.0)</td>
<td>2.0 (1.3)</td>
</tr>
<tr>
<td>NIS 10%</td>
<td>18.8 (3.9)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Plate 20 &amp; Plate 10%</td>
<td>32.2 (7.2)</td>
<td>2.2 (1.5)</td>
</tr>
<tr>
<td>NIS 20 &amp; NIS 10%</td>
<td>21.0 (5.0)</td>
<td>2.0 (1.3)</td>
</tr>
<tr>
<td>Plate 20 &amp; NIS 10%</td>
<td>21.1 (3.5)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>NIS 20 &amp; Plate 10%</td>
<td>29.0 (4.8)</td>
<td>1.0 (1.0)</td>
</tr>
</tbody>
</table>
6.3.2.2. Patchiness of Colour

3% and 20% MC treatments, 2002

When kernels from dropping Experiment 6.1 were roasted there were no significant differences between treatments and controls for severe patchiness of colour (Table 6.17 and 6.18). Examples of severe patchiness of colour can be seen in Figs. 6.10 and 6.13.

<table>
<thead>
<tr>
<th>Patchiness of Colour</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop</td>
<td>Control</td>
<td>Drop</td>
<td>Control</td>
</tr>
<tr>
<td>Minimal</td>
<td>32</td>
<td>38</td>
<td>39.6</td>
</tr>
<tr>
<td>Moderate</td>
<td>32</td>
<td>22</td>
<td>41.7</td>
</tr>
<tr>
<td>Severe</td>
<td>36</td>
<td>40</td>
<td>18.8</td>
</tr>
</tbody>
</table>

Table 6.17. Severe patchiness of colour (mean ranks) for nuts dropped at 3% MC, Experiment 6.1, 2002.

<table>
<thead>
<tr>
<th>Surface Damage</th>
<th>HV A38</th>
<th>HAES 344</th>
<th>HAES 741</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop</td>
<td>Control</td>
<td>Drop</td>
<td>Control</td>
</tr>
<tr>
<td>Minimal</td>
<td>70</td>
<td>72</td>
<td>25</td>
</tr>
<tr>
<td>Moderate</td>
<td>12</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>Severe</td>
<td>18</td>
<td>12</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 6.18. Severe patchiness of colour (mean ranks) for nuts dropped at 20% MC, Experiment 6.1, 2002

In dropping Experiment 6.3 in 2003 there were no differences for severe patchiness of colour between each treatment and control for both cultivar HAES 344 and HAES 741.

In dropping Experiment 6.4 in 2004 treatments dropped onto a metal plate at both 20% and 10% MC were significantly greater (<0.001) than both controls (Table 6.19).
Table 6.19. Severe patchiness of colour for kernels from nuts dropped at 20% and 10% MC onto metal plate, Experiment 6.4, 2004. Mean ranks are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean rank</th>
<th>Sig. Diff. from C20</th>
<th>Sig. Diff. From C10</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20</td>
<td>29.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20</td>
<td>59.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20</td>
<td>40.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>40.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10</td>
<td>47.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N10</td>
<td>40.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20 P10</td>
<td>84.6</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>N20 N10</td>
<td>54.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20 N10</td>
<td>36.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20 P10</td>
<td>62.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.3.2.3. Surface damage

For nuts dropped at 3% and 20% MC in Experiment 6.1, there were no differences for severe surface damage (Table 6.20). An example of severe surface damage can be seen in Fig. 6.13.

Table 6.20. Severe surface damage for nuts dropped at 20% MC and 3% MC in Experiment 6.1, 2002. Mean ranks are presented.

<table>
<thead>
<tr>
<th>Moisture Content</th>
<th>Surface Damage</th>
<th>A38</th>
<th>344</th>
<th>741</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drop</td>
<td>Control</td>
<td>Drop</td>
<td>Control</td>
</tr>
<tr>
<td>20%</td>
<td>Minimal</td>
<td>70</td>
<td>72</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>12</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>18</td>
<td>12</td>
<td>50</td>
</tr>
<tr>
<td>3%</td>
<td>Minimal</td>
<td>54</td>
<td>72</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>36</td>
<td>22</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>Severe</td>
<td>10</td>
<td>6</td>
<td>41.7</td>
</tr>
</tbody>
</table>

When kernels from nuts dropped at four MC in Experiment 6.3 in 2003 were roasted, severe surface damage was greater ($P<0.001$) for HAES 344 dropped at 3% MC (Table 6.21).
Table 6.21. Severe surface damage for kernels from nuts dropped at four MC onto NIS, Experiment 6.3, 2003. Mean ranks are presented. NS = not significant.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>MC</th>
<th>Drop</th>
<th>Control</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAES 344</td>
<td>3%</td>
<td>14.9</td>
<td>6.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>7%</td>
<td>7.7</td>
<td>13.4</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>9%</td>
<td>8.5</td>
<td>12.5</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>17%</td>
<td>9.8</td>
<td>11.3</td>
<td>NS</td>
</tr>
<tr>
<td>HAES 741</td>
<td>3%</td>
<td>12.4</td>
<td>7.8</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>7%</td>
<td>12.0</td>
<td>7.8</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>9%</td>
<td>10.2</td>
<td>10.8</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>17%</td>
<td>13.3</td>
<td>7.8</td>
<td>NS</td>
</tr>
</tbody>
</table>

Roasted kernels of nuts dropped twice onto a metal plate at 20% and 10% MC in Experiment 6.4 produced greater severe surface damage ($P<0.001$) than for the 20% MC control, the 10% MC control and the NIS 20% MC dropped treatment (Table 6.22).

Table 6.22. Severe surface damage for kernels from nuts dropped at 20% and 10% MC onto metal plate, Experiment 6.4, 2004. Mean ranks are presented.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean rank</th>
<th>Sig. Diff. C20</th>
<th>Sig. Diff. C10</th>
<th>Sig. Diff. N20</th>
</tr>
</thead>
<tbody>
<tr>
<td>C20</td>
<td>32.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20</td>
<td>40.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20</td>
<td>32.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>36.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P10</td>
<td>51.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N10</td>
<td>49.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20 P10</td>
<td>80.2</td>
<td>$&lt;0.001$</td>
<td>0.001</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>N20 N10</td>
<td>52.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20 N10</td>
<td>52.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20 P10</td>
<td>69.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The 2004 dropping experiment demonstrates the type of impacts likely to produce visible deterioration in quality (Table 6.23). Deterioration in roasting quality is evident only in the treatment dropped twice onto metal plate (Table 6.23). Shoulder damage, oiliness, dust, patchiness of colour and surface damage are all significantly increased by dropping at both MC onto plate (Table 6.23).
Table 6.23. Summary of damage from dropping macadamia NIS onto NIS and metal plate at 10% and 20% NIS MC, Experiment 6.4, 2004. ■ denotes the treatment where significant difference from controls occur.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Shoulder damage</th>
<th>Oiliness</th>
<th>Dusty</th>
<th>Patchiness of colour</th>
<th>Surface damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>C 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P 20</td>
<td>■</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C 10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P 10</td>
<td>■</td>
<td></td>
<td>■</td>
<td></td>
<td>■</td>
</tr>
<tr>
<td>N 10</td>
<td>■</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P20 P10</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>N20 N10</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>P20 N10</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>N20 P10</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
</tbody>
</table>

6.4. Discussion

The degree of damage incurred by macadamia kernels when NIS are dropped depends on a number of conditions at the time of dropping, e.g., moisture content of nuts, height of drop and the nature of the receiving surface. This study found that most damage to kernels occurred in nuts dropped at low MC (3% NIS MC) in the form of shoulder damage, oiliness and dustiness. In a previous study, for macadamias suffering multiple drops, lower MC had a significantly increased effect on shoulder damage (Wallace et al., 2001). Other workers found that kernels at intermediate moisture content (7-17%) appear to be more susceptible to damage than those at higher or lower levels (Cavaletto, 1990). In the current study the only damage recorded at intermediate MC was significant shoulder damage for nuts dropped at 9% in 2003. However, significantly more dark kernels were reported above when nuts dropped at high MC were roasted.

In many seeds there is an inverse relationship between MC and seed damage at impact. For example, the resistance of seed grains to damage increased as MC
increased (Bilanski, 1966). Navy beans were more subject to damage from impacts at low MC (Hoki and Picket, 1973). Mechanical damage in processed soybean seeds increased as MC decreased (Viera et al., 1994). In contrast, while low MC peanuts impacted at low velocities suffered less damage than those at high MC, at high impact velocity low MC nuts suffered more damage (Turner et al., 1967). In all cases with peanuts intermediate MC nuts suffered the least damage (Turner et al., 1967). The current study has shown that this is also generally the case for macadamias (Experiment 6.3), when intermediate MC (9%) nuts suffered increased shoulder damage. However, high MC kernels also were damaged by dropping.

The current results clearly show that visible damage to raw macadamia kernel from dropping is inversely related to moisture content as is the case for a number of other seeds. However, a new finding is that when kernels from nuts dropped at high MC are roasted they are also subject to significant ARD. This indicates that dropping nuts at high MC causes damage even though this concealed damage is not visible in raw kernel. This is an important finding for the macadamia industry as it shows that repeated dropping from low heights at high MC can cause significant loss of roasting quality. Multiple drops of four and six times from a height of one metre have been found to increase shoulder damage (Wallace et al., 2001). In this experiment, four drops from 2 m onto NIS increased shoulder damage. NIS may be dropped up to six times while on the farm during various operations, including dropping into the truck which transports nuts to a processor (McConachie, pers. comm., 2002). An example is in Chapter 8 when there were five drops before consignment. The receiving surface may be NIS or metal plate depending on how full the receiving container is at the time of dropping. In addition, nuts may be subject to up to 15 drops at heights of from 0.3m to 4m in a factory before cracking (McConachie, pers. comm., 2002). The
current results show that repeated drops of nuts even from a low height cause damage and loss of kernel quality.

The nature of the receiving surface is important in determining the effect of the energy involved in dropping, and the surface would affect the dispersal of energy at impact. Wallace et al. (2001) found that nuts dropped onto a steel surface at 13% MC suffered more damage than those dropped onto NIS. A NIS surface, such as in a silo or bin, is not rigid, as individual nuts can move slightly, thus transferring some kinetic energy. A NIS surface is irregular so that a nut striking the surface can be deflected in a glancing blow, absorbing some energy. Very few nuts would strike another at exactly 90°. Conversely, a metal plate is for all practical purposes completely rigid. The plate cannot move, so most of the kinetic energy of the falling nut would be retained in the energy of rebounding from the plate, with small amounts being lost as sound and heat. At 20% MC the kernel is tightly contained within the shell with no space, but at 10% MC moisture loss has allowed some space to develop around the kernel. Many macadamia kernels adhere to the interior of the shell (Hartung and Storey, 1939; Cavaletto, 1986). This means that the energy of impact is likely to detach many kernels that have adhered to the shell. Once detached, the kernel can move independently from the shell in response to the force of impact. For a nut weighing 10g dropping from 4m, at impact the shell would experience a force of, e.g., 0.073N, but the kernel only 0.025N due to their different mass. This means that loose kernels will rebound at a different rate and will reverberate within the shell until the energy is dispersed. Turgor pressure can also be involved in damage from dropping. Nuts at high MC, e.g., immediately after harvest, are highly turgid and turgor pressure can be added to the force of impact when considering the stress on cells (Pitt and Chen, 1983). In summary there are many factors interacting to determine the severity
and type of damage to kernel occurring when macadamia NIS is dropped. More specific aspects of damage will now be discussed.

6.4.1. Whole kernel

Dropping nuts did not lower whole kernel weight in the dropping experiments. This was a consistent finding of all dropping experiments. The main influence on whole kernel was genetic, i.e., cultivar. These results agree with Wallace et al. (2001) that the main determinants of whole kernel are genetic in nature. This strong genetic control is an important finding both for the industry and for the grower. For the industry it reaffirms the importance of plant breeding programmes and for the grower the importance of cultivar selection.

The finding from Experiment 6.4 in 2004 that dropping onto metal plate at 20% MC and 10% MC increased whole kernel by 10% deserves special mention. The explanation for this apparent anomaly could be that many kernels adhere to the inner shell surface, and was especially true of cultivar HAES 344 in these and other experiments. It may be that the extra energy transmitted by dropping onto metal twice frees the kernel from the shell, resulting in less stress being applied to the kernel by the shell during cracking, resulting in higher wholes. Because dropping causes other serious problems, namely, shoulder damage, oiliness, dustiness and loss of roasting quality it would be a serious error to presume that dropping is beneficial because it may increase whole kernel. Without further research on this finding no firm conclusions could be drawn about the effect of dropping nuts onto metal surfaces on whole kernel.
6.4.2. Shoulder damage and weight of pieces

Shoulder damage increased significantly when nuts were dropped, with nuts from the 2002 season most affected. While shoulder damage is more likely to occur at low MC, e.g., 3%, it may also be an issue at intermediate MC such as 9%. The 2002 dropping experiments showed that nuts at low MC are more susceptible to visible impact damage in the form of shoulder damage. Dropping nuts onto a metal plate increases shoulder damage in relation to the number of drops and MC. The final dropping experiment identifies the greatest potential for shoulder damage is for nuts dropped onto a plate at both high (field) and intermediate (10%) moisture contents. For NIS moving to processors there may be as many as 3 additional drops of from 3.5 to 4 m onto steel floors, despite the fact that industry sound practice guidelines stipulate drop heights of no more than 2 m (Anon., 2002). This means that the potential for shoulder damage and other damage from dropping is greater than reported here. Risk factors for shoulder damage can be summarized as 1), dropping onto a hard surface such as metal, 2), lower MC and 3) multiple drops. Dropping at 10% and 20% MC onto metal surfaces has the potential to produce very high values for shoulder damage. The 2004 results are a concern as the conditions applied in the experiment closely represent the treatment nuts receive between dehusking and factory, but with limited drops. Dropping macadamia nuts, especially onto metal, causes a significant amount of shoulder damage.

Adhesion of the kernel to remnants of the inner epidermis of the inner integuments has been suggested as a reason for kernels adhering to the white enamel region of the shell (Hartung and Storey, 1939). Cultivar differences for shoulder damage may be related to differences in the nature of this enamel layer. Shoulder damage affects the quality of macadamias in a number of ways. First, it involves
damage to tissue and therefore to cells. This may make oils more prone to lipolysis. In hazelnuts lipolytic enzymes exist just below the testa and while nuts remain undamaged they cannot attack the oils (Riedl and Mohr, 1979). However, when nuts have lesions or are ground, deterioration may occur (Riedl and Mohr, 1979). This process may be comparable to shoulder damage in macadamia. Second, damaged tissue is also likely to have free oil exposed to oxidation and rancidity. Not all shoulder damage could be attributed to dropping as some is undoubtedly caused by the stresses of dehusking and cracking. However, the dropping experiments show clearly that dropping macadamia nuts increases shoulder damage. Third, shoulder damage may be the site of dark, patchy colouring when dropped kernels are roasted. Cell damage caused by freezing has been proposed as a contributing factor to After Roast Darkening (ARD) of macadamias (Albertson and McConchie, 2003; Albertson et al., 2005). The damage from dropping macadamia NIS may be similar to that caused by freezing, that is, cell and tissue damage, as discussed below. These damaged areas may be more subject to patchiness of colour when kernels are roasted. Fourth, shoulder damage involves loss of product when the torn kernel remains attached to the shell. This loss was not assessed in this study, but is recommended in any future work on shoulder damage.

Shoulder damage was markedly lower in 2003 and it appears that there may be seasonal effects involved in the change from year to year. Weather for the 2001-2002 growing and harvest season was the driest and hottest on record for the macadamia growing regions in eastern Australia (Heap, 2002). Shoulder damage also may be influenced by genetics with significant differences occurring between cultivars (Chapter 4).
Dropping nuts did not increase weight of pieces although there were some cultivar differences. Weight of pieces was reduced by dropping at 3% MC in 2002. This may be explained by the impact shattering larger pieces so that kernel was lost in very small pieces and dust, reducing measured weight of pieces. The most noticeable feature of these results was that weight of pieces was much higher in 2002, almost double the weight for 2003, a trend that was similar to that for shoulder damage. Wallace et al. (2001) found that cultivar HAES 246 produced more pieces at intermediate MC (13%) than at 7% MC and 4% MC, but in the current experiment greater weight of pieces was generated at low MC (3%). Results for pieces seem to be variable. Dropping nuts did not generate more pieces although drought may favour an increase in pieces. These studies did not investigate the loss of kernel adhered to the shell, or as dust. This is an exonomic loss that could be the subject of further study.

6.4.3. Oily kernels

These results show that dropping nuts can cause significant oiliness of kernels to develop and oiliness can be increased by both low MC and dropping onto a hard metal surface. Kernels exhibiting oiliness are likely to be bruised from the energy of impact causing cell and tissue damage. Bruising can be defined as tissue damage that results from strain energy being dissipated in the tissue, and the amount of bruising depends on the amount of energy involved and the nature of the tissue (Wills et al., 1998). Bruising from impact in apples has been characterised as a spherical portion with a large proportion of broken cells, which turns brown (Roudot et al., 1991). In broad terms, there are two possible types of damage: impact causes cell breakage and compression causes cell displacement (Roudot et al., 1991). Macadamia kernels are subject to impact when dropped nuts hit a surface, and to compression of the kernel at the time of impact because of the hard, inflexible nature of the shell. Impact damage
could cause many ‘broken’ cells, the number depending on the severity of impact. In less dense tissue, intercellular spaces are thought to act as a stress absorber (Roudot et al., 1991). TEM in Chapter 2 and by Walton and Wallace (2005) has shown macadamia kernel tissue to be dense with little intercellular space. Therefore, little stress absorbance by intercellular space could be expected in macadamia tissue.

Results for oily kernels in Experiment 6.3 showed that low MC macadamias, e.g., 3%, are more susceptible to oiliness from dropping onto NIS than those at high MC. Oiliness of kernels increases with storage time, indicating that release of oil from damaged cells is gradual. Dropping nuts onto a metal surface at higher MC, e.g., 10% and 20%, also generated significant oily kernels. In the latter experiment nuts were dropped under conditions closely resembling dropping surfaces on farms, although frequency of drops and drop height were conservative. These results show that dropping nuts twice from 4 metres, with at least one drop onto a metal plate at 10% MC, can cause significant oiliness (25 to 30 % in this instance). The number of drops and drop heights on-farm would be greater, so that more damage would be expected. An oily appearance signifies free oil, confirmed in kernel assessment methods by gently rubbing kernels of an oily appearance on white paper. Oil in seeds is stored in membrane-bound organelles termed oil bodies, sometimes also termed lipid bodies, oleosomes or spherosomes (Velasco et al., 2004). Free oil suggests cell damage, rupture of the oil body ‘membrane’ and damage to the cell membrane. For hazelnuts, stresses from the shelling operation result in ‘concealed damage’ from the explosion of oil inside the cotyledons (Özdemir and Devres, 1999). Oiliness of macadamias from dropping could be a similar type of damage.

Yielding of a cell as a result of damage may be due to cell wall failure or migration of fluids out of the cell (Pitt and Chen, 1983). In vegetative tissue, highly
turgid cells are more prone to bruising (Pitt and Chen, 1983). This is because the
turgor pressure can be added to other forces when calculating total forces involved.
This may explain why nuts dropped at 20% MC showed damage in the form of ARD
at roasting.

There are many possible consequences of oiliness of kernels. Free oil is subject to
peroxidation resulting in a reduction in shelf life of macadamias (Fourie and Basson,
1989), Brazil nuts (Ribeiro et al., 1993), pecans (Forbus et al., 1980) and hazelnuts
(Özdemir and Devres, 1999). A further consequence is that cell damage such as is
cause by freezing and indicated by oiliness may predisposes kernels to ARD on
roasting (Albertson and McConchie, 2003). The gradual appearance of oiliness in
these results means that kernels may appear normal shortly after cracking, but develop
an oily appearance when they are stored. For such stored nuts, ARD will appear when
kernels are roasted. ARD may be worse for stored kernels, although this hypothesis is
untested. An oily appearance is undesirable as it makes the kernels appear unattractive
to consumers. In summary, oiliness of kernels is an indicator of cell and tissue
damage which may lead to shorter shelf life and reduced roasting quality. Future
studies are needed to establish any links between oiliness of macadamias, shelf life
and roasting quality.

6.4.4. Dusty kernels

Dropping nuts at low MC onto NIS causes significant numbers of dusty kernels
and differences exist between cultivars. Dropping onto a metal plate can further
increase dusty kernels. The counts for dust are very conservative. Many nuts were
dusty to the touch when cracked, but only those visibly dusty were included in the
count. This means that the real damage evidenced by dust may be worse than
reported. The likely cause of dustiness is kernels reverberating within the shell in
response to impacts from dropping. Dropped nuts also showed evidence of severe surface damage in these dropping experiments. Surface damage is abraded or torn tissue and may also contribute to dust. It is likely that the dust is composed of abraded cuticle and even some cell remnants if damage is severe enough, as reported in SEM images in Chapter 2. Dust on kernels after harvest was reported by Cavaletto (1986), in this case suggested to be related to impacts during transport as nut-in-shell. Impacts during transport would be far less severe than impacts from dropping.

An aspect of tissue damage due to mechanical damage is that intercellular bonds may be broken (Pitt and Chen, 1983). This may help to explain a mechanism for generation of dust and pieces in damaged macadamia nuts because tissue is less stable due to the broken intercellular bonds. These results show that dropping nuts at 7-10% causes significant kernel damage, as evidenced by oiliness and dust. Dusty kernels may be more prone to microbial attack due to disrupted cuticle. This could be tested by inoculating dusty kernels with fungi.

6.4.6. Colour of roasted kernel

A high proportion of processed macadamia kernel is retailed as roasted kernel (Mason et al., 1995). Roasting is considered to improve the shelf life of some foods, and improved stability is probably related to increased hydrophobicity and reduced water binding sites on roasted nuts (Martinez-Navarette and Chiralt, 1996). The amount of macadamia sold as roasted kernel means that any factor influencing the roasting quality of macadamias is important. The quality of roasted kernels could be divided into two broad categories, 1) appearance and 2) flavour. Only appearance is evaluated in this report in regard to a) colour, b) patchiness of colour and c) surface damage. Roasting macadamias can sometimes result in some excessively brown kernels, a phenomenon termed ARD. There is some evidence that susceptibility of
Macadamias to ARD is due to cell damage such as is caused by freezing (Albertson and McConchie, 2003; Albertson et al., 2005). However, the effect of dropping and cultivar differences on ARD is not clear.

In this study, dropping nuts at low MC and high MC resulted in significant numbers of dark roasted kernels. Kernels from nuts dropped at low MC, e.g., 3%, are more susceptible to ARD, but kernels from nuts dropped at 20% are also affected. Very high levels of rejects can sometime occur, as for HAES 741 dropped at 3% MC in Experiment 6.3. Another problem is that while dark kernels may be acceptable in colour if in a separate grade, their different appearance in ungraded product would be unacceptable. Macadamias at low MC (e.g., 3% NIS MC) are particularly susceptible to visible damage from dropping, and the concealed damage which predisposes kernels to ARD. It is interesting that nuts dropped at high MC (20%) also show ARD. This is probably influenced by the high turgor pressure in cells of high MC kernels adding to stress on cells during dropping (Pitt and Chen, 1983). The effects of damage to high MC kernels are not evident until kernels are roasted and dropped nuts show significantly more dark nuts than controls. This result is contrary to previous widely-held opinions that nuts at high, field MC are not susceptible to damage by stresses such as impacts (Pearce, pers. comm., 2002).

In summary, dropping nuts at both low and high moisture content can result in significant numbers of dark kernels at roasting. Further, in some circumstances significant numbers of very dark (reject) kernels can occur in dropped nuts. Numbers of very dark and dark kernels in these experiments varied from experiment to experiment, and there may have been seasonal effects involved. An example is that there were significant numbers of dark kernels in 2002 and 2003, but not in 2004. However, in Experiment 6.4 in 2004 both dropping regime and the dropping surface
were different to 2002 and 2003, making direct comparison difficult. In summary, the
effect on roasting colour may be the most important and most costly effect of
dropping macadamia NIS.

The chemical processes involved in food browning, the PAL-PPO pathway, the
Maillard reaction and caramelization, have been covered in Chapter 5 of this report.
However, the reasons for ARD in dropped nuts appear quite different from those
involved in delayed harvest. It has been proposed that ARD is related to plant cell
damage (Albertson and McConchie, 2003; Albertson et al., 2005, in press). The
results in this thesis clearly show that tissue damage from dropping begins processes
that predispose kernels to ARD.

Physical wounding has been listed as a cause of induced senescence of plant cells
leading to premature cell death (Owusu-Apenten, 2005). This type of senescence is
the result of breakdown of compartmentation, which is the separation of enzymes and
substrates within different cellular compartments (Owusa-Apenten, 2005). Senescence
typically involves deterioration of the plant cell membranes (McKersie and
Thompson, 1977; Thompson et al., 1997; Paliyath and Droillard, 1992) and mixing of
components which should not be mixed (Owusa-openten, 2005). In an example of
induced senescence, bruising of potato tubers led to death of all bruised cells in 16
hours, while by contrast cutting tuber tissue initiated healing processes (Partington et
al., 1999). Induced senescence can provide reagents needed for browning in the non-
 enzymatic Maillard reaction, or for caramelization.

The Maillard reaction requires the presence of reducing sugars and amino acids
(or suitable proteins with lysine residues), while caramelization results from heating
of sugars. Macadamias probably contain sufficient amino acids to facilitate the
Maillard reaction (Albertson, pers. comm., 2004). However, if additional amounts are
required there may be other sources of protein in damaged kernels. Damage caused by dropping impacts may allow proteins to be accessed for proteolysis by the breakdown of compartmentation. Protein storage vacuoles (PSV), also known as protein bodies, and lytic vacuoles contain protein processing enzymes (Jiang and Roger, 2001; Feller, 2004) and the vacuole has a likely role in intracellular proteolysis (Vierstra, 1993). As shown in Chapter 2 of this thesis, the epidermal cells of macadamia kernels contain numerous PSVs, and impacts to kernels may damage these vacuoles, as well as causing damage to lytic vacuoles both within the PSV and exterior to it. In this way dropping nuts may allow a breakdown of compartmentation. However, protein degradation is not limited to vacuoles as most, if not all, cellular compartments have their own proteolytic machinery (Vierstra, 1993).

Damaged proteins do not generally accumulate in the cell and damaged proteins can be subject to proteolysis in the plant cell, releasing peptides or amino acids (Feller, 2004). Cell death associated with senescence is normally a highly organized sequence of events with proteolysis used to recover valuable amino acids before total decay of the cell (Ko, 1997; Feller, 2004). A living cell may be necessary for such reactions because ATP is necessary for them to proceed (Ko, 1997). However, certain metabolic processes are still possible in some embryos even when viability has been lost (Berjak and Villiers, 1972).

Dropped kernels must also have an additional source of sugars compared with controls for caramelization and, more specifically, hexoses for the Maillard reaction. Mature seeds usually contain very low levels of reducing sugars (Cochrane, 1999). The source of increased reducing sugars in damaged kernels may be the cleavage of sucrose into glucose and fructose, and macadamia contains around 4% sucrose (Fourie and Basson, 1989). A possible source of sucrose is that stored in the vacuole
(Kruger, 1997), but soluble sugars such as sucrose are also found in the cytoplasm (Cochrane, 1999). The most likely route for the mobilization of sucrose stored in the vacuole is splitting by the enzyme acid invertase in an irreversible reaction. Invertase exists in the plant cell in three forms, acid-soluble invertase, which is found in the vacuole, alkaline-soluble invertase, found in the cytosol (Kruger, 1997) and acid-insoluble invertase associated with the cell wall (apoplast) (Tymowska-Lalanne and Kreis, 1998; Albertson et al., 2001). Bruising of cassava resulted in immediate production of invertase (Wenham, 1995). Infection by fungi and bacteria is known to raise the level of invertase activity (Billett et al., 1997), no doubt due to disruption of the cell wall, and it may be that tissue damage from bruising promotes a similar result. In the cytosol, sucrose is split in a reversible reaction by sucrose synthase, or an irreversible action by alkaline invertase, although these processes are poorly understood (Kruger, 1997). The most likely source of hexoses in dropped kernels is splitting of sucrose by acid invertase released from damaged cell walls. The activity of invertase in bruised cassava (Wenham, 1995) supports this hypothesis. Macadamia kernels evidencing high levels of ARD were found to have elevated levels of the hexoses glucose and fructose, and reduced sucrose (Albertson et al., 2005, in press). Elevation of hexoses may also be the result of the seed converting oil to mobile sugars for export of valuable resources before cell death in response to damage. The possibility that lipolysis of this nature is occurring cannot be ruled out (Berjak, pers. comm., 2005).

The Maillard reaction can produce some beneficial compounds. Some by-products of the reaction have antioxidant properties. It is possible that some darker kernels may have longer shelf life than less coloured kernels. This could be the subject of further research. Another issue is that oiliness of kernels increased over an
18 week period above. It is possible this oiliness is an indication of tissue damage and predisposes kernels to ARD. The connection between development of oiliness and ARD could be investigated.

6.4.7. Patchiness of colour

Dropping nuts at high MC (e.g., 20%) and intermediate MC (e.g., 10%) is likely to cause severe patchiness of colour. General appearance, especially colour, is used by consumers to evaluate quality of food products and perceived abnormal colouration is associated by them with deterioration in eating quality or spoilage (Clydesdale, 1976). Patchiness of colour is often associated with torn tissue, as in shoulder damage, and may also be associated with bruising. The patchiness is due to uneven roasting colour, and the dark colours would have the same causes as discussed above. The 2004 dropping experiment was the only one in which patchiness of colour was significantly different, but also employed methods that were close to commercial dropping practice. The current methods used for handling nut-in-shell can cause severe patchiness of colour.

6.4.7. Surface damage

Dropping nuts onto NIS and/or metal plate can cause severe surface damage, as found in the 2003 and 2004 dropping experiments. Some of the surface damage may be the result of tearing due to kernel separating from the shell when nuts are dropped. Some surface damage may also result from the kernel reverberating within the hard shell following an impact, as discussed above. Surface damage is obvious evidence of cell damage. It is a site for oxidation of oils to take place and for possible microbial attack. Surface damage is visibly unattractive to consumers, particularly when it may be combined with patchiness of roasted colour and dark colour. Roasting seems to accentuate the appearance of surface damage, perhaps because the high roasting
temperatures cause further deterioration of tissue with a damaged cuticle. Current handling practices for macadamia nut-in-shell are likely to cause severe surface damage to dropped nuts.

6.5. Summary

Dropping macadamia nuts at low moisture content causes serious reduction in kernel quality. However, the loss of quality caused by dropping nuts at high moisture content cannot be ignored. In addition, the potential for many drops from low heights to cause significant loss of quality cannot be ignored. Dropping NIS causes visible damage to raw kernel as shoulder damage, oiliness and dust. However, the most important, concealed damage to kernels is revealed when they are roasted and roasting quality is significantly reduced. In particular, dropping at both low and high MC causes ARD of kernels.

6.6. Recommendations to industry

The macadamia industry should:

- keep the number of drops to a minimum;
- convert tall silos to low bed-depth silos to reduce impacts;
- install easy let-downs in all handling equipment where practicable
- design new equipment to reduce impacts when nuts are augered into silos and trucks.

Further research into dropping effects could be conducted on:

- biochemical changes induced by dropping kernels that predispose to ARD;
- the amount of force required to bruise macadamia kernels;
- the effect of different drop heights on quality loss;
- the effect of different numbers of drops on quality loss;
- the effect of dropping onto different surfaces on quality loss.
CHAPTER 7: How drying and short-term storage affect macadamia quality

7.1. Introduction

Macadamia NIS is dried to 3% NIS MC before cracking. The drying regime commonly used is two days at 38°C, two days at 45°C and two days at 58-60°C (Cavaletto, 1983). It is unknown whether the rapid drying rate and high final drying temperature causes kernel breakdown or affects kernel quality in terms of whole kernel, shoulder damage and pieces. Another question concerning drying macadamias is whether the maximum temperature of 60°C is sufficient to affect the viability of macadamias. The biochemical activity of the seed depends on viability, and this may have implications for roasting quality. The macadamia is considered a recalcitrant seed, that is, a seed that continues progress toward germination following abscission and is viable for a relatively short period of time at ambient conditions (McDonald, 2004). Seed viability varies from 42-83% in different cultivars (Doijode, 2001).

Macadamia NIS must often be stored for a period of time due to inability of processors to crack NIS immediately after drying. This is particularly the case during peak harvest season. There may be deterioration in quality of kernel during storage, particularly in relation to brittleness, chipping and production of pieces (Bell, pers.comm., 2003), but this has not been tested.
The aims of this study were: 1) to test whether nuts dried under fast and slow drying regimes differed in kernel quality; 2) examine whether kernels from stored nuts were more prone to loss of quality; 3) test the viability of nuts dried at high temperature.

7.2. Materials and methods

For an experiment on the effects of two different drying regimes, cultivars HAES 344 and HAES 741 were harvested at Sahara Farms, Glasshouse Mountains (26°53.44’S, 152°56.16’E), and HV A38 at Hidden Valley Plantation at Beerwah (26°50.06’S, 152°55.01’E) in May 2002. There were two treatments: 1) slow-drying treatment (2d at 38°C, followed by drying for 3d 8h to 3% NIS MC at 45°C TO 3% NIS MC); 2) fast-drying treatment (2d at 38°C, 2d at 45°C, and 2 days at 58°C. The air was not dehumidified. After cracking, means for weight of whole kernel (%), shoulder damage (%), weight of pieces (%), oiliness (%) and dustiness (%) were calculated. Differences between fast and slow drying for whole kernel, shoulder damage and weight of pieces were tested by 2-way ANOVA with cultivar and treatment as factors, 5 degrees of freedom and Duncan’s multiple range test for comparison of means.

For an experiment of the effects of storage, nuts from the cultivars HAES 344 and HAES 741 were harvested from Sahara Farms at Glasshouse Mountains in June, 2004. Trees were regarded as blocks and one control and one treatment were harvested from each of ten trees for each cultivar. Nuts were dried according to the fast-drying method above. There were two treatments: 1) control, cracked immediately after drying and 2) storage, stored as nut-in-shell for one month in polythene bags at ambient laboratory temperatures (10ºC-25ºC) before cracking. Weight of whole kernel (%), shoulder damage (%), weight of pieces (%), oiliness (%)
and dustiness (%) were calculated. For each cultivar, these variables were tested for significant difference by independent samples t-tests.

To examine the effect of drying at high temperature on viability, nuts of cultivar HAES 344 harvested from Sahara Farms, Glasshouse Mountains in June 2004 were dehusked and dried as described in Chapter 4, the final drying temperature being 58°C. Nuts were stored as NIS after drying in a sealed domestic plastic food storage container at ambient temperatures of 12°C to 25°C in the laboratory. Storage moisture contents was c.3-4% NIS MC (1.5-2% kernel MC). In December 2004, fifty nuts were planted in commercial seed raising mix with half of the nut exposed and the micropyle end buried perpendicular to the surface. The nuts were placed on a laboratory bench at ambient temperatures of 12°C to 25°C. After 26 weeks in the potting mix germination percentage was calculated.

7.3. Results

7.3.1. Drying results

The fast and slow drying regimes did not affect whole kernel or shoulder damage (Fig. 7.1). However, both were strongly affected by variety with HV A38 producing double or more that of HAES 344 and HAES 741 (Fig. 7.1).

Drying regime did not significantly affect shoulder damage but there were significant differences between cultivars. Cultivar HV A38 had 28% shoulder damage, more than double that of cultivars HAES 344 and HAES 741 (Fig. 7.1).

The slow drying treatment produced significantly more pieces ($P<0.05$) than the faster treatment for and HAES 741 (Fig.7.2), but not for HV A38. HAES 344 produced more pieces than HAES 741, which in turn produced more than HV A38 ($P<0.05$).
Fig. 7.1. A, Whole kernel weight (%) and B, shoulder damage (%) for three cultivars of macadamia under two different drying regimes. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P<0.05$).
7.3.2. Storage effects on quality

There were no significant differences between storage treatments for whole kernel, shoulder damage and weight of pieces (Table 7.1).

![Weight of pieces (%) for three cultivars of macadamia under two different drying regimes. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P<0.05$).](image)

**Table 7.1** Whole kernel weight (%), shoulder damage (%) and total pieces weight (%) for macadamia kernels following storage as nut-in-shell for one month. Means and (standard errors) are presented.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Treatment</th>
<th>Whole kernel wt. (%)</th>
<th>Shoulder damage (%)</th>
<th>Weight of pieces (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAES 344</td>
<td>Control</td>
<td>52.35 (2.84)</td>
<td>24.59 (2.86)</td>
<td>4.70 (0.77)</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>58.31 (3.19)</td>
<td>18.64 (2.78)</td>
<td>4.13 (0.58)</td>
</tr>
<tr>
<td>HAES 741</td>
<td>Control</td>
<td>38.62 (3.20)</td>
<td>12.03 (1.96)</td>
<td>6.18 (0.80)</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td>39.40 (2.78)</td>
<td>11.04 (2.55)</td>
<td>5.50 (0.74)</td>
</tr>
</tbody>
</table>
7.3.3. Germination of dried and stored nuts

Macadamia nuts subjected to a typical drying regime remained capable of normal germination. Germination percentage at 15 weeks was 44%, and increased over the storage period to 66% at the termination at 26 weeks.

7.4. Discussion

7.4.1. Drying

Different drying regimes did not affect whole kernel or shoulder damage. The only difference between drying regimes was for weight of pieces. Slower drying significantly increased pieces for HAES 344 and HAES 741, with 25% of kernel weight downgraded to pieces for HAES 344. This represents significant loss of product value. Adopting slower drying regimes because of other perceived benefits should not be considered without further research into the effect of slow drying on pieces. Using dehumidified air would reduce drying times.

Slow drying may reduce tissue strength and make kernel tissue more brittle and more likely to shatter when stressed. The only stress applied to these nuts after drying was hand cracking with the TJ’s nutcracker, however, this is a great stress owing to the fact that the shell of macadamia is considerably stronger than concrete (Jennings and Macmillan, 1986). In general terms, compression causes cell displacement while impact cause cell breakage (Roudot et al., 1991). Compression is experienced during cracking, due to the degree of shell deformation required for breakage (Chun-Hui and Yiu-Wing, 1994/1995). In addition, the kernel may be impacted when the nut shell fractures. Both cell displacement and cell breakage may be involved in production of pieces. Drying more rapidly (with a higher final temperature) appears to make the
kernels less susceptible to cracker damage. The higher temperature may remove more of the tightly bound cell water than lower temperature slow drying, resulting in a different distribution of water at the same moisture content. This may create a different distribution of intercellular space in critical areas and provide a stress-absorbing effect against compression and impact.

Cultivar HV A38 did not suffer significant increase in weight of pieces or shoulder damage from different drying regimes, but had significantly more shoulder damage than the other cultivars. This illustrates the difficulty of cultivar selection as genetic controls can affect numerous traits. Choosing for a particular desirable trait may also introduce undesirable characteristics.

The result of this experiment raises some issues for the macadamia industry. There has been a move in recent years to dry nuts at lower temperatures, for example, 2 days at 30ºC, 2 days at 35ºC and finishing at 42ºC as this is considered to result in better roasting quality (Underhill, pers. comm.). However, this experiment indicates that a slow drying regime at low temperatures may result in the production of more pieces. The use of dehumidified air would reduce drying times, and may alter this effect.

### 7.4.3. Germination

The germination percentage of 66% was well within the range of 42-83% expected for this seed (Doijode, 2001). Macadamia is considered a recalcitrant (non-orthodox) seed (Doijode, 2001), which means that it is intolerant to desiccation and does not become dormant. However, it is clear that drying the nuts to 1.5% kernel MC did not seriously affect viability. In other words, macadamia is not desiccation-intolerant. This indicates that macadamia cannot be correctly placed in the strictly recalcitrant (non-orthodox) category, and could more properly be described as an
intermediate seed in the continuum of seed classification suggested by Berjak and Pammenter (2004).

While macadamia is non-dormant and prone to germinate immediately following abscission (Mason and Wells, 1984), and even sometimes while still on the tree (Jones, 1939), this experiment has demonstrated that macadamia has a degree of desiccation-tolerance, as it can be dried to 1.5% MC and retain viability. Normally dessication tolerant seeds can be stored for extended periods (Berjak and Pammenter, 2004), however, despite being desiccation-tolerant the macadamia seed cannot be stored for extended periods and is quoted as having a viability storage life of only 4 to 12 months (Doijode, 2001). The germination biology and storage of macadamia seed, including the possibility of cryo-preservation, is a subject that warrants further investigation.

The fact that macadamia nuts are still able to germinate after a rigorous drying regime is a very important finding. It means that cells are alive, many enzymes are undamaged and enzymic processes such as hydrolysis of lipids and conversion to sugars are possible (See discussion, Chapter 5). This could be particularly important for nuts from a delayed harvest when nuts left on the ground have been subjected to conditions favouring germination (Chapter 5), for nuts stored at high MC in silos where germination is again favoured (Chapter 8) and for nuts damaged by dropping (Chapter 6). In freshly harvested macadamia seeds at field MC germination dropped to 35% at 6 months (Hamilton, 1957). These seeds (Hamilton, 1957), stored at high MC, would have been metabolically active and could be expected to rapidly lose viability. In contrast, the seeds in the current experiment, stored at low moisture content, maintained high viability after storage for 6 months, achieving a final germination count of 66% at 26 weeks after planting.
7.5. **Summary and recommendations to industry**

Drying macadamia nuts more slowly increased the weight of pieces. This indicates that caution should be exercised before changing drying regimes to dry nuts more slowly. This change in drying regimes has been suggested to achieve more even drying and possibly reduce ARD caused by inadequately dried centres at roasting. However, such a change may result in greater losses to pieces. The issue of slower drying regimes could be a subject of further research, particularly in relation to pieces and ARD.
CHAPTER 8:

Quality changes in macadamia kernel between harvest and farmgate

8.1. Introduction

Previous experiments in this thesis have focussed on how on-farm and off-farm handling of NIS impacts on kernel quality, investigating the effect of such factors as dehusking, delayed harvest and impacts resulting from the dropping of nuts. Actual damage in a typical postharvest chain will be the result of an accumulation of these and other factors. Before consignment to a processor, NIS is typically subjected to a number of drops into storage silos following dehusking, the number of drops being determined by the degree of re-sorting necessary. The number of drops will vary from farm to farm and season to season. A typical silo may be 4 or more metres in height, subjecting nuts to considerable impacts. In addition to the effect of height, the surface the nuts are dropped onto may influence damage.

Another factor influencing the quality of nuts leaving a farm is the time of storage on the farm. This is affected by such considerations as farm storage capacity, distance from a processor, seasonal conditions and their relationship to peak harvest, and capacity of processors to receive nuts. Quality of nuts stored on-farm is also affected by the moisture content of the nuts. Rapid drying to 10% MC is recommended to maximize macadamia quality (Mason, 2000). This study investigates how quality is lost in a postharvest chain on a commercial farm to the point of consignment to the factory. Following a batch of NIS through the postharvest chain to farmgate may give a realistic indication of the effect of on-farm handling practices on quality, including roast quality. Roasting is an important stage in the processing of macadamia kernel.
The aim of this study was to examine where kernel quality is lost as nuts progress through a typical on-farm postharvest handling chain to the last silo awaiting consignment.

8.2. Materials and methods

Nuts were sampled from cultivar HAES 246 grown at Mt. Beerwah Plantation, Peachester (26° 51.1'S; 152° 51.4'E) in south east Queensland. Nut in shell was sampled at various stages from dehusking to the final storage silo before consignment to a factory. NIS was sampled first at Peachester following dehusking and then after transport, at Como Park, Kin Kin.

The stages for sampling and respective MC were: 1) Dehusker: at dehusker exit (this served as a control) (23% MC); 2) Silo 1: from the base of the receiving silo at Peachester after dehusking (23% MC); 3) Silo 2 and Truck: from the base of a truck before shipment to Como Park (18% MC); (these NIS had been resorted and dropped into a silo again before transport); 4) Silo 3: sampled from base of silo at Como Park after transfer from the truck to a silo (18% MC); 5) Silo 4: sampled from base of a silo at Como Park after resorting (16.5% MC). A hand dehusked control was not used as this was a study conducted as closely as possible to actual field conditions.

Nuts were harvested in mid-June 2004, and at each stage 20 replicates were sampled, each of 50 NIS. The high number of replicates was designed to help overcome inherent difficulties in sampling due to the variability of nuts in the commercial operation. It should be noted that four drops into silos occurred, plus one into a truck. The dehusker was of the Shaw type. NIS were sampled on 17th June and the final sample was taken on 2nd July. Every effort was made to follow the same batch of NIS through the handling chain. NIS were dried to 1.5 % kernel moisture content, and assessed for whole kernel weight (%), shoulder damage (%), weight of
pieces (%), and unsound kernel (%) (discoloured, mouldy, insect damaged and immature).

Samples from each treatment were roasted to assess the effect of postharvest handling on the quality of roasted kernels. Roasting methods are described in Chapter 5. Ten whole kernels were selected at random from replicates one to ten of each stage for roasting. Ranks for colour, patchiness of colour and surface damage were recorded.

8.2.1. Statistical analysis

Means for whole kernel weight (%), shoulder damage (%), weight of pieces (%), and unsound kernel weight (%) were calculated. Means were analysed for significant difference by ANOVA with four degrees of freedom and Duncan’s test for comparison of means. For roasted kernels, numbers of kernels in categories for dark colour (rank 4) and very dark colour (rank 5) combined, for severe patchiness of colour (rank 3) and severe surface damage (rank 3) were converted to percentages. Parametric data were tested for significant difference by ANOVA and Duncan’s multiple range test for comparison of means. Data for severe patchiness of colour were log+1 transformed before analysis.

8.3 Results

Significant differences between treatments (P<0.05) were found for shoulder damage, weight of pieces and unsound kernel (Fig. 8.1). Shoulder damage increased from a low of 27.6% at the dehusker to a high of 47.4% at silo 4. Significantly greater weight of pieces was produced only at Silo 2 (Fig. 8.1). Unsound kernel weight increased through the stages of the postharvest chain (Fig. 8.1). Unsound was 9.5% at
the dehusker, but increased to 25.0% at the last silo. Means for whole kernel weight % at the various stages did not differ significantly.

Fig. 8.1. A, Shoulder damage, B, pieces weight and C, unsound kernel weight of macadamia kernels at various on-farm postharvest stages. Means and standard errors are presented; means with different letters are significantly different (Duncan’s, $P<0.05$).
Dark kernels at roasting increased progressively through the postharvest chain (P<0.05) (Fig. 8.2). Combined dark and very dark kernels rose significantly between the dehusker and silo 2, and reached a maximum of 80% at the final silo before consignment (Fig. 8.2).

![Graph showing combined dark and very dark kernels across different stages](image)

**Fig. 8.2.** Combined dark (rank 4) and very dark (reject, rank 5) kernels for macadamias sampled at various postharvest stages. Means and standard errors are presented; columns with different letters are significantly different (Duncan’s, P<0.05)

Severe patchiness of colour also increased significantly (P<0.05) over the stages of the experiment, rising from 7.5% at the dehusker to a very high 65.5% at the final stage (Fig. 8.3). Similarly, severe surface damage also was lowest at the dehusker (17.5%), and rose to 47.8% at the final silo (P<0.05).
A comparison of the colour difference after roasting between the dehusker treatment and the final silo is shown in Fig. 8.4.

![Graph A](image1)

**Fig. 8.3.** A, Severe patchiness of colour and B, severe surface damage for kernels at various stages of the postharvest handling chain. Means and standard errors are presented; columns with different letters are significantly different (Duncan’s, \( P < 0.05 \)).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Dehusker</th>
<th>Silo 1</th>
<th>Silo 2 &amp; Truck</th>
<th>Silo 3</th>
<th>Silo 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe surface damage [%]</td>
<td>[A]</td>
<td>[ab]</td>
<td>[ab]</td>
<td>[b]</td>
<td>[c]</td>
</tr>
<tr>
<td>Severe patchiness of colour [%]</td>
<td>[A]</td>
<td>[A]</td>
<td>[ab]</td>
<td>[b]</td>
<td>[c]</td>
</tr>
</tbody>
</table>

A comparison of the colour difference after roasting between the dehusker treatment and the final silo is shown in Fig. 8.4.
Fig. 8.4. Roasted kernels from two replicates sampled after dehusking (left), and at Silo 4 before consignment.
8.4. Discussion

There was a progressive decline in kernel quality as nuts moved through to Silo 4 as indicated by shoulder damage, weight of pieces, unsound kernel, ARD, severe patchiness of colour and severe surface damage.

8.4.1. Shoulder damage

Shoulder damage increased progressively as nuts moved toward the final silo. Shoulder damage was at a high level for all treatments, beginning at 27.6% at the dehusker and increasing significantly for each of the last three handling steps to 47.4% at the final silo. High levels of shoulder damage may have been related to the dehusker used, dehusker adjustment or cultivar effects. However, shoulder damage increased with each drop into a silo from Silo 2 onward showing a sensitivity to postharvest handling. Such a high level of shoulder damage results in unattractive kernels and may lead to oxidative deterioration and further surface deterioration.

8.4.2. Weight of pieces

There was significant loss as pieces in this experiment. Weight of pieces was significant at Silo 2, with a value of 6%, indicating that loss as pieces may be more variable than shoulder damage. However, this result still indicates that surface damage to kernels was taking place at significant levels. A 6% loss or downgrading of kernel is a considerable loss, e.g., at a retail kernel price of $30 per kg, this equates to a loss of $1.80 per kg if kernel is lost. This does not account for the loss as pieces <5mm diameter, dust and adhered kernel. At present, with payment on a NIS basis, this is a loss borne by processors. At present while payments for NIS are not based mainly on quality it is difficult to institute effective changes in the farm to factory system.
8.4.3. Unsound kernel

Unsound kernel was at an unacceptably high level throughout this experiment, increasing from 10% at the dehusker to 30% at the final silo. One factor may be the cultivar, as HAES 246 is known to be highly variable with growing location (Radspinner, 1971). High levels of unsound can be explained to some extent by the high incidence of brown centres, which was a problem for this orchard in the 2004 season. There was little microbial activity. However, there was still a trebling of unsound kernels (brown centres, discolouration and mould) by the final silo, indicating that conditions of handling and storage were compromising quality. Although the cause of brown centres in macadamia is still unclear, this problem has been associated with elevated levels of hexoses (McConachie, 1992) and as discussed below, conditions in this study were conducive to increase of these reducing sugars. This study shows a deterioration in quality as nuts moved through the postharvest chain. The length of time NIS was stored at high moisture content awaiting shipment may have contributed to increase in unsound kernel. Dehumidified air at ambient temperature (5-20°C) was used to dry the NIS at Como Park, and drying was very slow, as can be seen from the MC values reported above. Increase in unsound kernel as the nuts moved through the postharvest chain could be attributed to the MC of the nuts and the time and temperature of storage. It is very likely that there was heating in the storage silos due to the respiration of the nuts and the high MC. The lowest MC achieved by the nuts in Silo 4 was 16.5%. Macadamia NIS stored at 15% MC at equilibrium relative humidity in aerated plastic drums had a shelf life of only 2 weeks at 25°C (Kowitz et al., 1996), which approximates the time that the nuts in Silo 4 had been in the processing chain. A temperature of 25°C may have been reached due to the heat of respiration in the silos. This may have helped cause some brown centres
(Prichavudhi and Yamomoto, 1965). Recalcitrant seeds such as macadamia typically maintain high respiration rates after maturity (Berjak and Pammenter, 2004) and respiration could build up heat in a silo, particularly in older style silos greater than three metres high (Bungay, 2004). Kowitz and Mason (2001) recommend a nut bed depth in a silo of no more than one metre to ensure adequate airflow and drying during on-farm storage of nuts. The silos in this experiment had a maximum bed depth of around three metres. To summarise, because a processor could not receive the nuts sooner they were stored at a MC (16.5%) and for a period of time (2 weeks) and at a temperature (>20°C) likely to reduce shelf life (Kowitz et al., 1996). The macadamia industry would benefit from greater understanding of how nuts are handled on-farm.

The possibility of microbial activity, especially fungi, cannot be discounted when nuts are stored under such conditions. The high MC and warmth from respiration provide a favourable environment for fungal activity. Fungi can enter the micropyle of some seeds, eg, soybeans (Lisker and Ben-Efraim, 1985). Some macadamia shells have an enlarged micropyle enabling easy access by fungi (AMS Kernel Assessment Guide, 2002) and some kernels may be contaminated. In addition, macadamia shells have an oil content up to 2% (Cavaletto, 1983), which may encourage fungal growth on moist shells. Fungal activity in oily seeds can result in lipolysis (Lisker and Ben-Efraim, 1985). Infection of macadamia NIS by fungi during storage on-farm while awaiting consignment may be a factor in increasing unsound kernel by fungal infection of kernels.

8.4.4. Roasting quality

Very dark (reject) and dark kernels increased significantly over the stages of this experiment. Excessive browning of heated foods is associated with elevated levels of
sugars acting as reagents in the Maillard reaction and/or caramelisation (Belitz et al., 2004; Coultate, 2002). The frequent dropping of nuts into silos would have contributed to ARD as discussed in Chapter 6. In addition, the conditions the NIS experienced during this experiment would have been very conducive to a rise in levels of reducing sugars. Storage of seeds under warm, humid conditions may result in increase in hexoses (reducing sugars). When soybeans were stored under simulated tropical conditions (30°C, 82% RH) substantial hydrolysis of disaccharides occurred, resulting in release of the hexoses glucose and galactose (Locher and Bucheli, 1998). These conditions may be produced in a silo of macadamias at 16-18% MC, as in this experiment, resulting in elevation of glucose and fructose levels from hydrolysis of sucrose. MC of macadamias can be as high as 25-30% at harvest (Kowitz and Mason, 2001), creating high RH levels in the early stages of storage. Elevation of hexose levels may result from preparation of the nuts for germination (Chapter 5). A further problem is that lipases in macadamias may be activated by such conditions and hexoses may be produced (Olias and Garcia, 1997), predisposing kernels to excessive browning when roasted. Many dark kernels were produced at roasting in this study (Fig. 8.4), probably the result of increased reducing sugars caused in part by conditions of storage.

Severe patchiness of colour of roasted kernel also increased at the last 2 silos in this experiment. Patchiness of colour may be related to bruising from impacts at dropping. Nuts were dropped following dehusking into four different silos from a height of over four metres, and once into a truck during resorting and transport procedures. The dropping experiment in 2004 (Experiment 6.4) caused significant shoulder damage and oiliness when nuts were dropped onto a metal plate. Considering that nuts were dropped at least 5 times, many would have suffered similar impacts and
be predisposed to damage. In addition, nuts were exposed to the cumulative effects of multiple drops (Chapter 6). These factors may have led to the high levels of severe patchiness of colour when kernels were roasted.

Kernels also exhibited severe surface damage at the final silo when evaluated after roasting. The high levels of shoulder damage no doubt contributed to this result. The frequency of movement and dropping of NIS resulted in very unattractive roasted product with severely damaged surface. Surface damage is a defect of both roasted and unroasted kernels which seems to worsen when kernels are stored, a more powdery surface developing.

These results raise serious concerns about how nuts are handled on-farm. A survey of representative farm operations for handling procedures and times would provide further insight into potential postharvest handling damage. Monitoring silos of selected farm operations for temperature variations in nut-beds and conducting tests of kernels from nuts stored on-farm for biochemical indicators of germination would provide valuable information about likely causes of quality loss in the postharvest chain.

8.5. Summary

These results demonstrate significant loss of macadamia kernel quality between dehusking and consignment to a processor. Major losses were in shoulder damage, unsound kernel, and pieces. Most importantly, roasting quality was seriously affected and deteriorated at each stage of the chain, particularly with large increases in ARD. This demonstrates that, in a typical postharvest chain, quality is lost due to current handling practices. Whole kernel was not affected during postharvest handling.
8.6. Recommendations to industry:

The macadamia industry should:

- minimise resorting of nuts on-farm as each resorting operation normally involves dropping into a silo and consequent impacts and effects on quality;
- avoid transport to another location for further sorting because of the need for an extra drop into a truck;
- dry nuts on-farm as rapidly as possible to an acceptable MC to reduce loss of quality due to excessive respiration and the tendency to germinate;
- avoid storage silos with excessive bed-depth;
- monitor temperature in silos to avoid excessive heating that promotes germination and consequent ARD.

The following research could be conducted into issues arising from this study:

- survey selected farm operations for handling procedures and times;
- monitor silos of selected farm operations for temperature variations in nuts;
- conduct tests of kernels from nuts stored on-farm for biochemical indicators of germination.
CHAPTER 9
General summary and recommendations

9.1. Summary

The main focus of macadamia research in the 20th century was on cultural issues to improve yield and efficiency of handling. In recent years increasing production has resulted in a greater focus on research to improve quality of kernels. Important issues of quality are whether kernels remain whole after cracking, the degree of shoulder damage, weight of pieces produced, kernels of oily or dusty appearance and whether kernels develop ARD or other defects when roasted. The aim of this study as to investigate the effect of kernel ultrastructure, differences in site and season, and effects of mechanical dehuskers, delaying harvest and dropping macadamia NIS on kernel quality. The principal quality parameters affected were roasting quality, oily and dusty kernels, whole kernel, shoulder damage and pieces.

9.1.1. Roasting quality

Significant ARD resulted from dropping NIS in Chapter 6. ARD of dropped kernels is probably due to biochemical reactions resulting from tissue damage. In Chapter 5, nuts from delayed harvest also showed ARD, probably mainly as a result of nuts on the ground beginning to germinate. In Chapter 8 significant ARD occurred in the on-farm posharvest handling chain, probably due to dropping of NIS and initiation of germination. Further loss of roasting quality was evident when severe patchiness of colour and severe surface damage were found in dropped kernels in Chapter 6, delayed harvest kernels in Chapter 5 and during the on-farm posharvest handling chain in Chapter 8.

ARD has important implications for the macadamia industry as appearance is a critical determinant of quality. Excessively dark kernel colour is associated by the
consumer with poor quality, even if the product is sound. The worst situation is a
great contrast of colouring. The minimum requirement to obtain uniform quality is to
grade kernels for colour at considerable cost. Further research could be conducted into
the biochemistry involved in ARD. In particular, correlation of cell wall invertase
with ARD for dropped kernels may provide useful information.

ARD of macadamia kernels may have some positive aspects. Not all affected
kernels are of reject quality, and in the delayed harvest experiments and some
dropping experiments, most dark kernels were still marketable. Some Maillard
reaction by-products can have antioxidant properties, so some darker kernels may
have good shelf life. It may be possible to sort affected roast kernel into a separate
grade such as ‘premium roast’. This product may have a niche market for those who
prefer a darker roast. Research could be conducted to compare shelf life of acceptable
darker roasted kernels with lighter coloured kernels of dropped nuts to test if Maillard
by-products may be involved in antioxidant activity.

9.1.2. Oiliness and dust

Dropping NIS produced oily kernels and oiliness increased over time (Chapter 6).
Oiliness is probably due to gradual release of oil from cells after the integrity of cell
membranes has been compromised by dropping impacts. Gradual development of
oiliness may indicate that there is a lag effect in the development of the damaging
effects of impacts, not only for oil release, but perhaps also for mixing of substrates
and reagents. The oiliness of kernel from dropped nuts is not a cause of ARD, but
symptomatic of concealed damage to membranes resulting in breakdown of
compartmentation, and mixing of substrates and reagents which ought not to be
mixed. Chapter 2 shows visual damage to the surface of dropped kernel as an example
of the effect of dropping nuts.
Dropping NIS also causes dusty kernels. Dust is immediate visible evidence of damage to the cuticle, as shown in SEM images in Chapter 2. Industry has previously assumed that dropping from low heights does not cause damage, especially at high MC, but this study clearly shows that numerous drops from low height cause significant damage as ARD, oiliness and dust. Kernels damaged in this way would be more prone to rancidity and microbial attack. Differences in cuticle surface morphology may be an indication that the macadamia cuticle is easily damaged and emphasise the need to handle nuts with the utmost care at all times. While the embryo is well protected in many respects by the durable seed coat, the embryo is sensitive to impacts. Dust such as that evident on dropped samples in these experiments is very common on packed, commercial kernel.

9.1.3. Whole kernel

Whole kernel is mainly determined by cultivar, that is, by genetic factors. This was consistently found in Chapter 4 for three cultivars over three seasons at three sites, in the dehusker experiments in Chapter 5 and in dropping experiments in Chapter 6. Dropping macadamia nuts in these experiments did not lower whole kernel. This is a positive result, as it reassures that dehusking and handling NIS in most cases do not lower wholes and confirms the direction that efforts to improve whole kernel should take. In all the experiments in this thesis, dehusking at intermediate MC (10%) and delayed harvest were the only cultural factors which caused a drop in whole kernel. These results emphasise the importance of harvesting frequently. However, acceptable levels of whole kernel will mainly be achieved by selecting and planting cultivars that produce more whole kernel. Despite this genetic control, it would be unwise to assume that dropping nuts cannot reduce whole kernel.
Repeated drops at excessive drop heights, especially onto metal surfaces, may reduce whole kernel in susceptible cultivars, and this is something that needs to be tested.

The factors controlling whole kernel are still not clear, however, Chapter 2 suggests that the presence and nature of a gap between cotyledons strongly influences the tendency of cotyledons to separate. The size (length and width) of gaps between cotyledons and the concave shape of the inner cotyledon surface may be due to shrinkage during drying. In addition, the gap may result from incomplete filling of the shell during embryo development. Chapter 2 also shows that low whole kernel cultivars may have more epicuticular wax than high whole-kernel cultivars, and high whole kernel cultivars may be more strongly bonded at the wax interface between cotyledons (Chapter 2).

There are several features of epicuticular wax that could affect kernel breakage: 1) the amount of wax present on each cotyledon, 2) the structure of wax crystals, 3) the chemical composition of the wax. Genetic controls and environmental conditions may combine to determine these features. Different cultivars of macadamia may differ in the chemical composition of cuticular wax.

While whole kernel is genetically determined, it can vary markedly from season to season (Chapter 4). A drought year produced low whole kernel in cultivars HAES 344 and HAES 741. How drought conditions could affect whole kernel is not clear, but such conditions are known to influence the nature of plant cuticle. Epicuticular wax load on leaves reduces surface transpiration and improves crop water efficiency (Samdur et al., 2003). Maximum deposits of wax occur under conditions of high radiant energy and low RH consistent with drought conditions with a decrease in RH stimulating wax production (Baker, 1974). While these conclusions are based on studies of plant leaves, the principles may apply equally to seed cuticles, for example,
while the composition of epicuticular waxes varies between leaves and seed coat of jojoba, these structures are covered with similar amounts of waxes per surface area (Gülz, 1984). Simulated drought conditions increased peanut epicuticular wax load (Samdur et al., 2003). Whether the amount of epicuticular wax produced is a factor in whole kernel yield is not clear. Different peanut genotypes responded differently to drought stress in production of epicuticular wax (Samdur et al., 2003). This difference may also be found in macadamia cultivars, but further research would be needed to determine this.

This study achieved acceptable whole kernel for ‘low’ cultivars in 2003 and 2004. Industry figures are far lower (Stephenson and Gallagher, 2000). This difference may be due to the fact that nuts in our experiments were cracked very carefully to minimize stresses on the kernel. This discrepancy indicates that the bond between halves is fragile for some cultivars, and may be readily broken at cracking. Cracking ease is determined by shell structure and nut orientation at cracking, which is very difficult to control with random cracking. Random cracking will increase damage due to greater forces required to open randomly oriented nuts (Braga et al., 1999). Technologies which reduce stress on kernels at cracking, such as sonic cracking, could be expected to increase whole kernel.

9.1.4. Shoulder damage and pieces

Delaying harvest and the use of mechanical dehuskers significantly increase shoulder damage (Chapter 5). Dropping NIS also increases shoulder damage (Chapter 6), and shoulder damage increased during the postharvest handling chain (Chapter 8). Shoulder damage was lower during the drought year, 2002 (Chapter 4). Shoulder damage is important for reducing visual quality and downgrading of product. The damaged tissue may be a site for development of rancidity and microbial attack.
In Chapter 5, weight of pieces increased significantly following a delay in harvest. Pieces also increased significantly through the postharvest chain to farmgate (Chapter 8). Weight of pieces was highest during the drought year, 2002, but decreased in 2003 and 2004 and increased significantly in a slow drying regime for NIS in Chapter 7. Pieces are themselves lower-value product, and also point to other product that has been lowered in quality, quality and possibly value. Slower drying regimes should not be adopted by processors without further research into the effects of slower drying, particularly on pieces.

9.1.5. Rancidity

This study found difficulty in inducing rancidity as defined by industry standards and assessed by chemical methods (Chapter 3). Nevertheless, rancid kernels are of concern to the macadamia industry (Mason et al., 2004). Testing for peroxide values and free fatty acids (Chapter 3) showed that while the oily appearance of dropped kernel is unattractive, it is not necessarily accompanied by significant oxidation of oil over a six month period of time at moderate to low temperatures. The results suggest that FFAs are of greater concern than oxidative rancidity. It is conceivable that off-flavours that are being described as rancidity have other origins. Examples are the unpleasant taste of brown centre kernels (McConachie, 1992), and the off-flavours associated with cultivar HAES 246 (O’Riordan, pers. comm., 2005).

With the advance of technology, a simple instrumental method may become available to test for rancidity. Aldehydes are a likely cause of rancid flavours (Eriksson et al., 1976; Robards et al., 1998a; Himstedt, 2002) and a quick test for volatile aldehydes could be a good indicator of rancidity. In this study nonanal was detected, a volatile that has been suggested a suitable indicator of rancidity for olive oil (Vichi et al., 2003). Due to the similarity between olive oil and macadamia oil,
nonanal may be a suitable indicator of rancidity for macadamias. Further studies could be conducted using taste panels to evaluate dropped kernels for rancidity, correlated with headspace analysis for volatile by-products of rancidity.

9.2. **Recommendations to industry:**

- harvest rounds during harvest season should be as frequent as possible, preferably with intervals of no more than two weeks;
- more frequent harvesting of nuts exposed to the sun, *e.g.*, on edges, should be considered;
- careful and frequent dehusker adjustment is essential to minimise damage and loss of quality;
- improved dehusker design should be investigated;
- avoid dehusking at low MC if possible;
- place strong emphasis on whole kernel in macadamia breeding and selection programmes;
- growers should be encouraged to plant cultivars that produce acceptable whole kernel;
- cultivar selection by growers should be based on data for the grower’s own region, not industry-wide figures;
- the number of drops both on-farm and at the processor should be kept to a minimum;
- drops at low MC especially should be minimised, even from low heights;
- reduce drop heights as much as possible to reduce force of impact;
- convert tall silos to low bed-depth silos to reduce impacts;
- install easy let-downs in all handling equipment, where practicable, to reduce severity of impacts;
• design new equipment to reduce impacts when nuts are augered into trucks;

• minimise resorting of nuts on-farm as each resorting operation normally involves dropping into a silo and consequent impacts and effects on quality;

• dry nuts on-farm as rapidly as possible to an acceptable MC to reduce loss of quality due to excessive respiration and the tendency to germinate. However, this should not be attempted at high temperatures or kernel damage will result.

• avoid storage silos with excessive bed-depth;

• slower drying regimes should not be adopted without further research into the effects, especially on pieces.
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