STUDIES ON MACADAMIA NUT QUALITY

By

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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SUMMARY

The South African macadamia industry is centred in the sub-tropical regions of South Africa with 40% of the plantings in the Lowveld. Growers receive higher pay-outs for high kernel recovery and unblemished (not discoloured) whole kernels. It is known that the same cultivar in the Lowveld region, produces nuts that differ in kernel recovery, whole kernel recovery and kernel discolouration. Therefore to develop optimal management strategies to maximize productivity and profitability of macadamias, factors that influence kernel recovery, whole kernel recovery and kernel discolouration needed to be investigated.

The fruit structures are formed the first 90 days after anthesis and the fruit continues to grow until 12 to 15 weeks after anthesis until the shell hardens. Climate, soil moisture, cross-pollination and nutrition influence this process which determines the shell thickness and kernel size which in turn both determine kernel recovery.

A large set of historical data from different regions were used to establish and isolate possible factors involved in kernel recovery, whole kernel recovery and kernel discolouration. These differed between the six regions over two seasons. High kernel recovery was associated with high orchard altitude, good cross-pollination, high crop load (high yield), early season harvesting and processing of nut-in-shell (NIS), high leaf boron concentrations in Nov., water management using deficit irrigation and low daily maximum relative humidity during the nut growth stage (Oct. to middle Jan.). High whole kernel recovery was associated with high kernel recovery, early season harvesting and processing of NIS, Bungay curing system of NIS compared to ambient air, low vapour pressure deficit during the nut maturation period (middle Jan. to harvest), elevated leaf boron and copper concentrations and low manganese leaf concentrations in Nov. High crop load, no cross pollination, low leaf nitrogen and zinc and high leaf potassium concentrations in Nov. were associated with low kernel discolouration.

In order to develop possible orchard practices that increase kernel recovery, whole kernel recovery and decrease kernel discolouration, two irrigation trials and one kaolin trial were conducted.

In the two irrigation trials, water stress was induced over two growing seasons (2011-2013) by applying different levels of irrigation at different phenological stages. Kernel recovery was not affected by any of the treatments, but water stress could not be applied continuously due to frequent high rainfall. Moderate water stress did not influence yield, only trees that were over watered during a drier premature nut drop stage during the 2011/12 season increased yield, although it could not be repeated the following season during a wetter premature nut drop stage.

In the kaolin trial, the efficacy of kaolin foliar application was evaluated to reduce heat stress. Kaolin applications did not affect kernel recovery, nut yield or quality. Temperature during the study was not continuously high (>30 ^{0}C), thus heat stress could not be mitigated. We did however establish that up to five layers of foliar applied kaolin did not significantly reduce individual leaf photosynthesis.

OPSOMMING: Studies oor makadamia-neutkwaliteit

Die makadamia-industrie in Suid-Afrika, is gesentreer in die sub-tropiese streke van die land met 40% van die aanplantings in die Laeveld. Produsente ontvang hoër uitbetalings vir neute wat 'n hoë uitkraak (kernherwinning) persentasie lewer asook ongeskonde (nie verkleurde), heel-kern neute. Daar is gevind dat dieselfde kultivar verskil ten opsigte van kernherwinning, heel-kernherwinning en kernverkleuring in die Laeveld. Om 'n optimale bestuurstrategie te ontwikkel en so maksimale opbrengs en wins te verkry, moes die faktore wat kernherwinning, heel-kernherwinning en kernverkleuring beïnvloed ondersoek word.

Die eerste 90 dae na blom word die vrugstrukture gevorm en vrugte groei tot en met 12 tot 15 weke na volblom totdat die dop verhard. Klimaat, grondvog, kruisbestuiwing en voedingstowwe beïnvloed die prosesse wat dopdikte en kerngrootte beïnvloed en wat beide kernherwinning bepaal.

'n Groot stel historiese data vanaf verskillende streke is gebruik om die moontlike faktore wat kernherwinning, heel-kernherwinning en kernverkleuring beïnvloed te bepaal. Hierdie aspekte het verskil in die ses streke oor twee seisoene. Hoë kernherwinning was geassosieer met hoër liggende boorde (hoogte bo see spieël), goeie kruisbestuiwing, hoë oeslading, vroeë seisoen oes en prosessering van neut-in-dop, hoë boor blaarkonsentrasie in Nov., waterbestuur met onthoudingsbesproeïng en lae daaglikse maksimum relatiewe humiditeit gedurende die neut-groei-stadium (Okt. tot middel Jan.). Hoë heel-kernherwinning was geassosieer met hoë kernherwinning, vroeë seisoen oes en prosessering van neut-in-dop, Bungay droging, lae waterdampdruk tekort gedurende die neut-rypwording stadium (Jan. tot oes), hoë boor en koper blaarkonsentrasies en lae mangaan blaarkonsentrasie in Nov. Hoë oeslading, geen kruisbestuiwing, lae stikstof, sink en hoë kalium blaarkonsentrasies in Nov. was geassosieer met lae kernverkleuring.

Twee besproeïngsproewe en een kaolienproef is uitgevoer om moontlike boord praktyke te ontwikkel wat kernherwinning en heel-kernherwinning verhoog en kernverkleuring verlaag.

In die twee besproeïngsproewe is watertekorte aangewend oor twee seisoene (2011-2013) deur verskillende hoeveelhede te besproei gedurende verskillende fenologiese stadiums. Kernherwinning was nie geaffekteer deur die behandelings nie, maar dit moet ingedagte

gehou word dat watertekorte nie deurlopend toegepas kon word nie as gevolg van hoë reënval. Gematigde watertekorte het nie die opbrengs beïnvloed nie, slegs bome wat oor-besproei was in ’n droeër voor-rypwording-neut-val stadium in die 2011/12 seisoen het 'n verhoging in opbrengs getoon, maar dit kon nie herhaal word die daaropvolgende natter seisoen nie.

In die kaolienproef, is die gebruik van kaolien blaarbespuiting geëvalueer om hitte stress te verminder. Kaolienbespuitings het geen effek op kernherwinning, neut opbrengs of neutkwaliteit gehad nie. Temperature gedurende die studie was nie deurlopend hoog nie (>30 ^{0}C) en dus kon hitte stress nie gemanipuleer word nie. Daar is wel vasgestel dat tot vyf lae kaolien nie enkel-blaar fotosintese verminder het nie.

This thesis is a compilation of chapters, starting with a literature review, followed by three research papers. Each paper is prepared as a scientific paper for submission to *Southern African Journal for Plant and Soil*. Repetition or duplication between papers might therefore be nessecary.

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GENERAL INTRODUCTION

Macadamia F Muell is believed to have originated in the Australian coastal rainforests of northern New South Wales and southern Queensland (Hardner 2009). Although macadamias originated in Australia, the industry was first established in Hawaii in the 1930's (Shigeura and Ooka 1984). Macadamias were introduced to South Africa around 1935, with the first commercial plantings along the eastern seaboard region in the early 1960's (Allan 1996).

The South African macadamia industry is centred in the sub-tropical regions of the Lowveld (Nelspruit area), Levubu and KwaZulu-Natal. The Southern African Macadamia Growers' Association (2012) census revealed that, more than 40% of the 20 000 ha macadamia orchards are planted in Mpumalanga, 29% in Limpopo and 19% in KwaZulu-Natal. Orchards consist of Hawaiian, Australian and South African selections but the cultivar Beaumont makes up 24% of all plantings.

Macadamia nuts are highly sought after and one of the highest priced processed nuts available in the world market (Grimwood 1971, Duncan 2011). The economic value of the macadamia crop is determined by the yield per tree, kernel recovery, nut quality and nut style distribution (Hancock 1991). The fruit of the macadamia is described as a follicle (hereafter referred to as nut) and it consist of an embryo (hereafter referred to as kernel), testa (hereafter referred to as shell) and a pericarp (hereafter referred to as husk) (Hardner et al. 2009). Most studies on macadamia have focused on increasing yield and quality; however no in-depth study has focused on kernel recovery. By increasing the kernel recovery, the kernel yield as a ratio of kernel to shell mass increases, leading to fewer nuts having to be cracked for the same amount of kernel and therefore improving financial return to the grower (Hancock 1991). Currently, the snack market also pays a premium for whole unblemished kernels compared to halves, pieces and commercial grade (blemished nuts) (Penter et al. 2007, 2008). Clearly there is considerable potential for increasing profit by increasing the whole kernel percentage and limiting the discolouration of kernels.

In the Lowveld region, the same cultivar differs in yield in terms of kernel recovery, whole kernel recovery and kernel discolouration (personal observation). In order for the industry to make more informed decisions on where to establish new orchards and to improve current orchard practices, the factors that determine kernel recovery, whole kernel recovery and kernel discolouration need to be investigated.

Firstly, a literature study was conducted on the botany and phenology of the macadamia to determine at what stage of fruit development these quality parameters are determined. Kernel recovery, whole kernel recovery and kernel discolouration were reviewed including the factors that cause variation in orchards, and between seasons and growing regions.

A wide range of factors are known to have an effect on kernel recovery which include cultivar, climatic conditions and tree age (Stephenson and Gallagher 1989). Therefore a historical data set on 'Beaumont' from 40 farms, from different orchards and regions over two seasons, was used to isolate the factors that possibly influence kernel recovery, whole kernel recovery and kernel discolouration. These orchards were planted at different altitudes, slopes, tree spacing, row direction and received different cultural practices. In addition, cross-pollination (Trueman and Turnbull 1994), tree water relationships (Stephenson et al. 2003) and carbohydrate levels in the trees (Wilkie 2009) also differed.

The second aim of the study was to develop orchard practices to increase kernel recovery, whole kernel recovery and to decrease the occurrence of kernel discolouration. As mentioned before, kernel recovery is influenced by water relationships (Stephenson et al. 2003) but also by temperature extremes (Stephenson and Gallagher 1986), therefore trials were conducted to investigate whether irrigation practices or foliar kaolin application could mitigate these conditions to such an extent that kernel recovery is improved and kernel discolouration decreased.

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LITERATURE REVIEW: FACTORS INFLUENCING MACADAMIA KERNEL RECOVERY, WHOLE KERNEL RECOVERY AND KERNEL DISCOLOURATION.

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1. Introduction

Australia is the biggest macadamia producing country in the world, followed by South Africa and Hawaii. These three countries supply 70-80% of the world market. The rest of the volume is made up mostly by Kenya, Guatemala, Malawi, Brazil (International Tree Nut Council (INC) 2010). Although world production of macadamia kernels was estimated at 27 639 metric ton in 2009, it represented only 1% of the world nut kernel market.

Baptized as the queen of nuts, macadamias are highly sort after for their remarkable flavour, texture and health benefits (Grimwood 1971, Hardner et al. 2009, Duncan 2011). High in mono- and/or polyunsaturated fatty acids, macadamias are known to benefit health, such as decreasing low density lipoprotein cholesterol in humans (Garg et al. 2003). Macadamia is one of the highest priced processed nuts available on the world market (Grimwood 1971, Duncan 2011). Currently, the snack market pays a premium for whole unblemished kernels compared to halves, pieces and commercial grade (blemished nuts). Clearly there is considerable potential for increasing profit with increasing the whole kernel percentage (Penter et al. 2008).

Macadamia is a medium sized, evergreen tree that forms part of the *Proteaceae* family. Only two of the five species, *M. integrifolia* Maiden and Betche and *M. tetraphylla* L.A.S. Johnson, are edible and due to their high value grown commercially (Trueman and Turnbull 1994b; Kaiser 2003). Although native to the Australian coastal rainforests of northern New South Wales and southern Queensland (25 to 29 ^{o}S) macadamias as an industry was first established in Hawaii in the 1930's. Australia quickly followed (Shigeura and Ooka 1984). Introduced to South Africa around 1935, the first commercial macadamia plantings in South Africa were established in the early 1960's (Allan 1996b). Hawaiian and Australian selections were planted in the sub-tropical areas of Levubu, the Lowveld (Nelspruit area) and KwaZulu Natal (Allan 1972a).

Macadamias require tropical or sub-tropical climatic regions with temperatures between 16 ^{o}C and 25 ^{o}C for maximum net photosynthesis (Allan and de Jager 1978). Regions must be frost free, as even light frost may damage young macadamia trees. The highest accumulation of dry matter in leaves occur between 20 ^{0}C and 25 ^{o}C, with no growth at 10 ^{o}C or lower (Trochoulias and Lahav 1983). In south east Queensland, macadamia flower initiation occurs under shortening day length in early May at night temperatures of 11 ^{o}C to 15 ^{o}C (Moncur et al. 1985). The kernel is marketable (mature) when it reaches an oil content of 72%. The kernel can be mature 190 days after flowering depending on the cultivar and growing conditions (McConchie et al. 1997).

Therefore the aim of this literature study was to investigate the factors influencing macadamia kernel recovery, whole kernel recovery and kernel discolouration. These quality parameters will be further discussed together with macadamia botany and phenology.

2. Morphology of the macadamia

2.1 Flowers

Macadamia trees flowers profusely, but only about 0.3% set as nuts. Approximately 100 to 300 flowers are borne on pendant racemes (Boyton and Hardner 2002). Racemes develop from axillary buds on mature stems, which can be several months (Wilkie et al. 2009) or several years old (Nagao et al. 1994). The flowers of *M. integrifolia* are white or cream compared to the pink of *M. tetraphylla.* Each flower comprises of four perianth lobes with interlocking margins and four stamens opposite and attached to the perianth lobes. The pistil consists of an ovary with two ovules and a 10 mm long style with a small area containing stigma papilla cells at the tip. The flowers are protandrous, the anthers releasing their pollen before the stigma of the same flower is receptive. Pollen will only start germinating two days after anthesis when the sigma is fully receptive (Sedgley et al. 1985). Some cultivars show self-incompatibility due to inhibition of the pollen tube growth in the style (Sedgley 1983). Cross pollination may increase the nut numbers and nut size (Trueman and Turnbull 1994a).

2.2 Fruit

The spherical macadamia seed, 1.2 to 2.5 cm in diameter, consist of an embryo (kernel), testa (shell) and a pericarp (husk) (Kaiser 2003). The embryo is connected to the pericarp by a micropyle and the pericarp is connected to the raceme by the pedicel. In macadamia the ovule, the embryo and the endosperm start to grow rapidly after fertilization. The embryo absorbs the endosperm completely as it develops and comes into contact with the inner integumentary membrane of the testa. The seed coat or testa is formed as the inner and outer integument cells differentiate into sclereids. The outer integument becomes lignified and turns brown when the seed matures. The testa is exceptionally hard and tough to remove (Kaiser 2003). The seed will abscise when mature and fall to the ground. This nut drop may be delayed in some cultivars (Trueman et al. 2000). The pericarp is removed (dehusked) after harvest. The seeds have 20 to 30% moisture, which is removed by curing (drying) the nut in the shell (NIS) under controlled atmosphere prior to cracking (Bungay 2001).

3. Phenology

3.1 Vegetative flush and carbohydrates

The growth and yield of macadamia trees are directly correlated to light interception. The radiant energy is converted into carbohydrates that are accumulated or used for growth and maintenance in the tree (O'Hare et al. 2004). The macadamia tree accumulates and stores carbohydrates in autumn and winter. During spring the tree draws on the stored carbohydrates, due to insufficient carbohydrate production through photosynthesis, to meet the high demands of nut growth and oil accumulation (Cormack and Bate 1976). Developing fruits are strong sinks, with high demand for energy, as macadamia kernels contain 72% or more oil (Stephenson et al. 1989). Therefore the tree requires sufficient reserves to meet the high energy demand. Insufficient reserves will lead to a decline in nut quality and yield. Carbohydrate accumulation during autumn and winter is important to replenish the reserves.

Macadamia trees need to balance vegetative and reproductive development for consistent optimum nut production (Stephenson et al. 1986). The new growth flush is needed for future bearing wood and the leaves as photosynthesizing source to sustain the crop. The macadamia leaves are most productive just after they reach full size and are hardened-off (mature). Consequently, for a macadamia tree to stay healthy and productive, it needs to grow new leaves (O'Hare et al. 2004). Maximum yields are obtained when trees in south east Queensland flush in late winter / early spring. The trees then become paradormant, after the spring flush hardens, during most of the oil accumulation period (O'Hare et al. 2004). The timing of vegetative flushing is important because immature leafy flushes during late autumn and early winter inhibit raceme production (Olesen 2005).

Vegetative flushing is influenced by temperature, water and nitrogen availability. Vegetative growth occurs through recurrent flushing (Olesen et al. 2006). A major late summer flush and minor spring flush occur when temperatures are relatively mild with mean minimum and maximum threshold temperatures between 10 ^{o}C and 30 ^{o}C. Low winter temperatures restrict vegetative growth as the spring flush only occurs when the monthly mean temperatures rise above 10 ^{o}C (Stephenson and Cull 1986). Trochoulias and Lahav (1983) reported that macadamia growth and dry matter production increased when temperature increased from 15 ^{o}C to 25 ^{o}C in a controlled-environment study. Flush development decreased as temperatures approach 30 ^{o}C (Wilkie 2009). Stephenson et al. (2003) reported that when water stress was imposed during the usual vegetative growth periods, the flush was delayed until after re-watering. Applications of nitrogen (N) prior to the usual vegetative growth periods had no effect on the timing of the flush, but it increased the length of the flush (Stephenson and Gallagher 1989).

3.2 Flower initiation to nut maturity

The potential yield of a macadamia tree is determined during floral initiation (Hancock 1991). Racemes develop from axillary buds on mature stems, which can be several months (Wilkie et al. 2009) or several years old (Nagao et al. 1994). Racemes are preferentially produced on short stems that consist of only a few vegetative flushes (Wilkie 2009). Macadamia flower initiation in south east Queensland occurs under shortening day length conditions in early May at night temperatures of 11 ^{o}C to 15 ^{o}C (Moncur et al. 1985). In Hawaii flower initiation occurs at higher temperatures (15 to 21 ^{o}C) (Stephenson and Gallagher 1986a), but flower initiation and raceme development is inhibited by high night temperatures (O'Hare et al. 2004).

Flower initiation is followed by a dormant bud phase which can last for 50 to 96 days (Moncur et al. 1985). Moncur et al. (1985) observed that bud dormancy was broken by a rise in temperature and light rain. The period from flower initiation to anthesis lasts 137 to 153 days, depending on the cultivar and the environmental conditions (Moncur et al. 1985). The first racemes are normally visible in mid-autumn under Australian conditions. Flowering usually starts in south east Australia in August (late winter), peaks in September (spring) and is completed by mid October (O'Hare et al. 2004).

Successful pollination is critical to achieve high yields. Once the flower is open it remains receptive for several days. Pollination is slow and Sedgley et al. (1985) reported that the stigma is only fully receptive for two days after anthesis. Macadamia flowers are self-incompatible to a degree (Sedgley 1983) and insects are necessary for efficient pollination (Penter et al. 2007b). The pollen tube needs up to seven days to reach the ovary. The ovary contains two ovules, but only one pollen tube reaches the ovary (Sedgley 1983). Pollination of the flower is completed when the ovary is fertilized and one ovule starts to develop.

During the first 90 days after flowering, the fruit structures are formed and the growth of the husk, shell and endosperm takes place (Jones and Shaw 1943). Two weeks after pollination, rapid nut development occurs and continues for 14 to 16 weeks until the shell hardens. No growth occurs after the shell hardens; only physiological changes occur within the shell. Growth occurs as a single sigmoidal pattern with a rapid increase in flesh weight about five to six weeks after anthesis and this continues until 15 to 18 weeks (Hancock 1991). Jones (1939) reported that by the time the shell starts to harden the fruit had already reached approximately 70 percent or more of its final fresh weight.

Rapid oil accumulation in the macadamia embryos occurs between 90 to 180 days after flowering (d.a.f.) in Hawaii (Stephenson and Gallagher 1986b). However, McConchie et al. (1996) reported that the rapid oil accumulation starts only two to three weeks later in Australia. These differences could be due to climatic differences between Hawaii and Australia, Hawaii having a more moderate climate. The kernel is marketable (mature) when it reaches 72% or more oil which can be achieved 190 d.a.f., depending on the cultivar and environmental conditions (McConchie et al. 1996). Warm, moderate climatic conditions hasten maturity while temperate conditions delay maturity (O'Hare et al. 2004). Cultivars differ in the time the nuts starts to drop after maturity.

Flower and fruit abscission continues from anthesis through to maturity in three distinct periods. The first period of abscission is due to the fall of unfertilized flowers during the first two weeks after anthesis, which could account for over 90% of the flowers. The second abscission period occurs three to eight weeks after anthesis and over 80% of the initial small immature nuts that set could drop. It is referred to as the immature nut drop period. The third period of abscission occurs when larger immature nuts drop gradually over a long period from nine weeks until maturity at 28 to 30 weeks (Hancock 1991).

4. Kernel recovery

4.1 Background

Kernel recovery refers to the amount of kernel recovered from the NIS after cracking (shell removal). Kernel recovery (KR) is expressed as a percentage weight of the nut that is kernel at 1.5% moisture content, the rest being shell. The term "sound kernel recovery" (SKR) means the entire weight of first grade kernel recovered from a weighted NIS and it is also usually expressed as a percentage (Hancock 1991).

Kernel recovery is determent by the nut size, shell thickness and therefore weight of kernel and shell. Large nuts will contain more kernel than small nuts if they have the same shell thickness (Hancock 1991). This means that with a higher kernel recovery, fewer nuts will be cracked for the same amount of kernel, reducing processing cost and more kernels are sellable per unit nut in shell (Hardner et al. 2009). Kernel recovery is influenced by cross-pollination, climate, soil moisture, carbohydrate availability and tree age. In the following section each factor and its relevance will be discussed.

4.2 Factors influencing kernel recovery

4.2.1 Cross pollination

Macadamia nut yield and fruit size improves with cross pollination. Trueman and Turnbull (1994a) observed that cross pollination increased the percentage of macadamia flowers with a pollen tube at the base of the style, and it resulted in an increase in initial fruit set and sometimes the mean NIS weight, kernel weight and kernel recovery. Wallace et al. (1996) confirmed these findings and found with cross pollination that final nut set in the cultivar 246 increased by 97% and kernel weight by 20%, respectively. Supplementary pollination increased NIS weight, kernel weight and kernel recovery in some cultivars e.g. A4, HAES 246 (Wallace et al. 1996).

In South Africa, Penter et al. (2007b) noted that in 'Beaumont', increased yield and kernel recovery occurred following cross-pollination by a number of different cultivars. Unfortunately 'Beaumont' flowers later than most of the commercial cultivars and this reduces the benefits derived from cross-pollination (Penter et al. 2007b).

Although macadamias can benefit from cross pollination, not all cultivars are compatible. McConchie et al. (1997) noted that significantly larger fruit were produced in 28 of 30 cross pollinator combinations, with different pollen sources but using the same maternal parents. This was not always the case as cultivar 246 fertilized by cultivar 814 produced significantly smaller fruit than self pollinated trees. Therefore McConchie et al. (1997) made a ranking of inter-genotype compatibilities. Suggestions were made to inter-plant compatible cultivars in commercial orchards to increase the frequency of cross-pollination and increase nut weight. McConchie et al. (1997) found that cross-pollinated fruit are significantly more likely to reach maturity compared to self pollinated fruit.

Even with compatible cultivars, inadequate cross-pollination could still be found. Macadamia trees require insects to transfer pollen from one flower to the next (Penter et al. 2007b). Therefore, low pollinator (insects) populations and/or pollinator activity in the macadamia orchard could result in insufficient transfer of pollen and directly cause inadequate cross-pollination. The insufficient supply of cross pollen in an orchard may also cause inadequate cross-pollination. The lower the number of cross pollinating cultivars in an orchard and the further the distance to the cross pollinator, the lower the supply of cross pollen to the flowers (Wallace et al. 1996; McConchie et al. 1997).

4.2.2 Climate and light interception

4.2.2.1 Temperature

Mature macadamia trees survived a 20-day heat wave in California with temperatures above 38 ^{0}C as they are adapted to short spells of high summer temperatures (Trochoulias and Lahav 1983). The macadamia has a relatively narrow temperature range for growth (Trochoulias and Lahav 1983) and photosynthesis (Allan and De Jager 1978) and it is sensitive to extremes beyond this range. Net photosynthesis of the macadamia is at maximum between 16 ^{o}C and 25 ^{o}C and decreases beyond 26 ^{o}C and would reach zero at 41 ^{o}C to 43 ^{o}C (Allan and De Jager, 1978). Trochoulias and Lahav (1983) reported that the highest accumulation of dry matter in leaves occurs between 20 ^{o}C and 25 ^{o}C, and no growth at 10 ^{o}C and lower.

High temperatures increase respiration rates and premature nut drop. Allan and De Jager (1978) noted that respiration rates are higher during warmer nights compared to cooler nights. CO_2 production was 75% faster at 29 ^{0}C compared to 18 to 19 ^{o}C. Hancock (1991) suggested that these high respiration rates are very important because oil accumulation occurs during the warmest months. High night temperatures may restrict the accumulation of oil by depleting assimilates and therefore influence the nut quality negatively. Stephenson and Gallagher (1987b) found that where water was not limited (leaf water potential above 0.5 MPa), temperatures of 30 0C and higher increased premature nut drop compared to lower temperatures.

Temperature influence kernel recovery. Stephenson and Gallagher (1986b) subjected trees to day temperatures of 15, 25, 30 and 35 ^{o}C and night temperature at 15 ^{o}C in a controlled-environment after rapid nut growth had largely been completed and oil accumulation already commenced. Kernel recovery was the highest at 30 ^{o}C, but the nut quality was low with 30.3% immature nuts (<72% oil in the kernels). The kernel recovery was lower at 25 ^{o}C than at 30 ^{o}C, but was still good compared to 15 and 35 ^{o}C. At 25 ^{o}C all kernels had good quality and contained 72% and more oil. Kernel recovery, kernel growth and oil content were low at 15 ^{o}C and 35 ^{o}C, the kernel recovery and weight actually declined at 35 ^{o}C and most kernels contained less than 72% oil. Stephenson and Gallagher (1986b) concluded that extreme temperatures of 35 ^{o}C during the later stages of nut development have adverse effects on oil accumulation and nut growth and resulted in poor kernel quality.

Moderate temperatures in February (Southern hemisphere) during the oil accumulation period are associated with high kernel recovery in Australia. Rain during this time seems to depress kernel filling, presumably due to reduced photosynthesis under cloudy conditions. This is in agreement with data from Hawaii where it was reported that the most important factor influencing kernel recovery was high temperatures during the early oil accumulation period (Stephenson and Gallagher 1990). High temperatures in the three months after flowering when the shell was formed resulted in early shell hardening and small nuts (Hancock 1991).

The high temperatures (>30 ^{0}C) that reduces macadamia kernel recovery could be regulated by evaporative cooling (Allan 1996a) and the use of reflecting substances e.g. kaolin clay (Alberts 2004). The average first grade kernel and kernel recovery increased on ‘Beaumont’ when evaporative cooling with overheads sprinklers was applied to trees in Pietermaritzburg (Allan 1996a). The overhead intermittent sprinklers switched on every time the air temperature exceeded 30 ^{o}C to lower the leaf temperature by 5 ^{0}C to 8 ^{0}C, resulting in more favourable temperatures for net photosynthesis.

Alberts (2004) proposed the use of reflecting substances e.g. kaolin to lessen the heat stress on macadamia trees. Kaolin and other particle film applications have been used on different crops to limit the impact of heat and water stress (Rosati et al. 2006). The reflective mineral-based (kaolin) particle film technology (PFT) reflects ultraviolet, photosynthetically active radiation (PAR) and infrared (IR) radiation, reducing canopy temperature (as much as 5 ^{0}C), transpiration and heat stress (Glenn 2012). Reduced water use efficiency (WUE), defined as unit of assimilated carbon per unit of transpiration, was found in apple (Glenn 2010), however the WUE increased in citrus (Jifon and Syvertsen 2003). Whole canopy photosynthesis can be increased with the reduction of canopy temperature and increased radiation into the inner canopy leaves, even though PAR is reduced by reflection at leaf level (Glenn 2012). While kaolin application on apple (Glenn et al. 2001) and grapefruit (Jifon and Syvertsen 2003) increased net assimilation, Lombardini et al. (2005) observed no effect on pecan trees.

Contradicting results were found with kaolin application in other crops. Applications at times resulted in no effect on total yield on e.g. pepper (Russo and Díaz-Pérez 2005), pecan (Lombardini et al. 2005) and tomato (Cantore et al. 2009), while increased yields was found in coffee (Steiman et al. 2007), apple (Glenn et al. 2001) and blueberry (Spiers et al. 2005). Steiman et al. (2007) found an increase in yield during the second season, suggesting it could be due to light reflection by kaolin into the inner canopy, which resulted in increased floral initiation. This in turn led to more fruit and possibly higher starch reserves due to increased photosynthesis. Applications of kaolin increased fruit weight, in apple (Glenn et al. 2001), tomato (Cantore et al. 2009) and pistachio (Azizi et al. 2013) while no effect or a reduction was found in coffee (Steiman et al. 2007), pecan (Lombardini et al. 2005) and blueberry (Spiers et al. 2005). However, regarding kernel recovery the only reference to kaolin applications found in literature described no effect on shell out (kernel recovery) of pecan (Lombardini et al. 2005).

Allan (1972a; 1972b) compared heat units of various regions to serve as a guide for climatic suitability for macadamias. A heat unit is the amount of heat that is available for plant growth by taking the sum of the number of degrees that the daily mean temperature is above the minimum growth temperature for each day (^{o}C days <12.8 ^{o}C). He found that the low number of heat units, especially during the shell development stage, in San Diego explained why smaller nuts are produced. Total number of heat units of 600 to 1000 during shell development and 1000 to 1350 during the oil accumulation period, are believed to be adequate which makes certain areas in South Africa acceptable for macadamia cultivation.

4.2.2.2 Altitude

High altitudes in Hawaii lead to thick shells and a reduction in yields (Hancock 1991). Increasing altitude results in reduction in temperature. In addition, higher altitudes are also associated with more cloud cover resulting in lower light intensity (Hancock 1991). It was reported that cloud cover and frequent rain at 700 to 830 meter above sea level (m.a.s.l.) range in Hawaii tends to slow down the tree development, thickens the shell of the nut and reduces the yield (Hancock 1991). It is suggested that macadamias are better suited to areas below 476 m.a.s.l. in Hawaii (Shigeura and Ooka 1984). Hancock (1991) mentioned that macadamias are successfully grown in Malawi at 550 to 1500, Guatemala between 550 and 1600 and Costa Rica at 700 m.a.s.l. Altitudes below 450 m.a.s.l. in the lower Ntchisi (Malawi) area are too hot and dry for good growth and tree health.

4.2.2.3 Row orientation and slope

The row orientation in an orchard has an effect on the solar radiation interception and the yield of trees. In a North-South row direction at latitude 43^{o} N the trees can receive up to 40% more radiation compared to the East-West row direction. The growth and yield of apple trees at latitude 55.3^{o} N is higher in North-South oriented rows compared to East-West oriented rows (Christensen 1979). Hadari (2004) revealed that intercepted radiation is at its optimum when rows are planted perpendicular to East and West slopes, and parallel to North and South slopes.

Huett (2004), using a linear regression model between yield and tree volume showed an increase in yield in macadamia as light interception increased up to 96%. It is in agreement with O'Brien and McConchie (1995) that observed bigger nuts and higher yields in the upper part of the tree canopy compared to the lower part with lower light interception. Boyton and Hardner (2002) found a higher nut set on the northern side of the tree in Australia. Stephenson and Cull (1986) reported that particularly during autumn and winter in Australia the trees produce more vegetative flushes on the northern side, which faces the sun, than on the southern side. Slope and row orientation of the orchard influences light interception and therefore important factors that will influence yield of macadamia.

4.2.3 Irrigation and soil moisture

Due to high annual rainfall irrigation is not a common practice when cultivating macadamia in Hawaii (1300 to 4800 mm) and northern New South Wales (1232 to 2283 mm) (Trochoulias and Johns 1992). However, according to Schoeman (2011) the average annual rainfall of 819 mm in the Nelspruit region in Mpumalanga, South Africa, is insufficient for macadamia production and an additional 700 mm of irrigated water is required for optimal yield. Water requirements for cultivars differ (Searle and Lu 2003). The cultivar HAES 741 required 40-55 L tree^{-1} day^{-1}, 10 to 30% more water than HAES 344 (35-40 L tree^{-1} day^{-1}) from end of flowering until nut maturity, while trees of both cultivars required 20-30 L tree^{-1} day^{-1} during the vegetative period, end of April to September (Southern Hemisphere). This additional water applied to the 'HAES 741' trees resulted in a significant increase in yield.

Trochoulias and Johns (1992) found no significance difference in kernel recovery between irrigation treatments, but during their eight-year study very high annual rainfall which ranged between 1232 and 2283 mm occurred and irrigation was only needed 9 to 24 times per year. Kernel recovery values did however fluctuate between 33.7 and 38.7%, during the eight-year study. NIS yield per unit trunk was reduced slightly however no consistent effect was found.

Most (~97%) of the water used by plants is lost by transpiration and only a small amount (~2%) absorbed by the roots is used for plant growth while the remaining water (~1%) is used in photosynthesis and other metabolic processes (Taiz and Zeiger 2010). Plants are seldom fully hydrated, due to transpirational water loss and during periods of drought, plants suffer from water deficit and this could lead to inhibition of plant growth and photosynthesis. The process most affected during drought is cell expansion (Taiz and Zeiger 2010). Stephenson et al. (2003) mentioned that the macadamia tree has several characteristics, such as xeromorphic leaves with sclerified bundle sheath tissues and dense clusters of proteoid roots, which enable them to endure extended periods of drought. Water stress at different stages of nut development will have different effects on the yield and nut quality (Stephenson et al. 2003). Water stress during the premature nut drop and early oil accumulation periods depress the yield. Higher kernel recovery was reported with water stress during the premature nut drop period, leading to increased splitting of these thinner shells (Stephenson et al. 2003). Water stress during the nut maturation period decreased the kernel recovery and nut quality which could probably be correlated with the reduction in photosynthesis in the water stressed trees in this critically high energy demanding period (Stephenson et al. 2003). Water stress during the critical oil accumulation (nut maturation stage) leads to a high percentage of immature kernel (Stephenson et al. 2003).

Goldhamer et al. (1985) found that shell enlargement in pistachio nuts is sensitive to water stress. They scheduled irrigation on crop evapotranspiration ((ETc), the sum of evaporation from the soil (E) and transpiration from leaves (T)) with full irrigation at 100% ETc. Nut size was reduced by severe water stress (0 and 25% ET_c), but little or no difference following mild water stress (50 and 70% ET_c). Water stress on almonds has a negative effects on kernel size (Girona et al. 1993) but a negligible effect on kernel dry weight (Goldhamer et al. 2006). Gregorio et al. (2009) found that the five irrigation treatments: full irrigation, regulated deficit irrigation (50% of ETc during the kernel-filling stage) and three partial root-zone drying treatments, irrigated at 70%, 50% and 30% ETc, respectively, during the whole growing season had no affect on kernel recovery. Kernel recovery fluctuations were seasonal and independent of their irrigation treatments.

Goldhamer et al. (1990) evaluated walnut tree recovery and performance in the second season, after returning to full irrigation following three years of sustained deficit irrigation and found that trees that were previously irrigated at 33 and 66% ET_c produced larger nuts and higher kernel percentage (kernel recovery) than trees previously irrigated at 100% ET_c. However, Goldhamer et al. (1988) found during the third year of sustained deficit irrigation at 66% ET_c that the walnut trees produced smaller nuts than control trees and Cohen et al. (1996) reported a decrease in walnut fruit size with the reduction in irrigation to 70% ET_c.

Stephenson and Gallagher (1987b) observed that fewer macadamia nuts abscise from trees during the premature nut drop period under high temperatures (30 ^{o}C) and low relative humidity (40%), when water was non-limiting compared to water stressed trees. Leaf water potential of -1.5 to -3MPa induced more nut drop at temperatures lower than 30 ^{o}C and high relative humidity. Severe levels of stress by restricting water supply reduced stomatal conductance. Thus severe nut drop from stressed trees was not only aggravated by the water deficit but also by the shortage of current assimilate for nut development (Stephenson and Gallagher 1987b).

4.2.4 Carbohydrates

Carbohydrate supply influence nut growth and nut drop (Turnbull et al. 1996). The macadamia tree accumulates and stores carbohydrates in autumn and winter. During spring the tree draws on the stored carbohydrates, due to insufficient carbohydrate production through photosynthesis, to meet the high energy demands of nut growth and oil accumulation (Cormack and Bate 1976). Thus the carbohydrate reserves are important for nut growth and development.

The need for carbohydrates for nut growth and development could be enhanced by treatments such as girdling and the application of growth regulators. Nagao and Sakai (1990) found that girdling, a treatment which often increases the levels of stored carbohydrates, increases the number of racemes when a 3.0 mm wide girdle was applied to the xylem around the trunk at 45 cm above ground level prior to flower initiation. Girdling, 10 mm wide seven days after anthesis on 9 to 15 mm wide branches, increased nut set but had no effect on nut weight (Trueman and Turnbull 1994b). Trueman and Turnbull (1994b) concluded that a macadamia tree requires 50 leaves on a girdled branch to support the development of one nut. The number of fruit set could be increased by girdling a branch with high leaf numbers but it does not increase the fruit diameter above those observed on the ungirdled branches. When assimilate availability is very low, the nut size was reduced on girdled branches with fewer than 300 leaves (Trueman and Turnbull 1994b).

Uniconazole and paclobutrazol are gibberellin biosynthesis inhibitors that are used commercially to restrict shoot elongation of fruit trees (Wilkie 2009). Stephenson and Gallagher (1986a; 1986b) reported that active vegetative growth in late spring depressed yield and the summer flush competes with nut development for carbohydrates resulting in lower kernel recovery. A foliar application of uniconazole (Sunny®) as a 3% solution (1.5 g L^{-1} uniconazole) after pruning in autumn or early winter reduced the length of re-growing shoots and increased kernel recovery (Wilkie 2009). Nagao et al. (1999) soil drenched uniconazole (0.2 g active ingredient (a.i.) per cm trunk diameter) in two-year-old potted macadamias and noted a significant increase in flowering the second year after the initial treatment. Tree height and trunk diameter were reduced significantly one year after the initial treatment, and shoot extension was suppressed for the duration of the four-year trial.

Hancock (1991) mentioned that paclobutrazol gave variable results and is not recommended commercially. This is in agreement with Phiri et al. (1992) who noted that when the growth regulator paclobutrazol was applied as a soil drench at 0.92 g per tree in February for two consecutive years it suppressed shoot growth in Malawi. Although the kernel recovery and yield were not significantly affected, it was higher in the first year of application. Swart (1993) reported the yield increased with paclobutrazol (Cultar©) application at 2 ml per tree as a soil drench in July or September in South Africa. With the same applications, Ferreira et al. (1995) reported no significant differences in yield and reduction in tree volume for two consecutive years.

High kernel recovery is associated with high carbohydrate levels which are influenced by crop load (Wilkie 2009), trunk girth and the application of nutrients like nitrogen and boron (Stephenson and Gallagher 1989a; 1989b). Kernel recovery tends to be high in the years with above average yields and tend to be lower in the years with poor yields (Stephenson et al. 2000). McFadyen et al. (2004) found a correlation between high yields and high kernel recovery. Trees compensate for low raceme densities by increasing the NIS weight and by increasing the number of fruit per raceme (Wilkie 2009). The NIS weight decreases as the fruit volume increases (Wilkie 2009) which is similar to the apple tree which bears small fruit when crop load is high (Robinson and Lakso 1995). In pecans kernel percentage and individual nut weight was improved by reducing yield with fruit thinning (Smith et al. 1993). Robinson and Lakso (1995) found in their study on apple that reducing crop load by thinning fruit, increased fruit size by allowing cell division to continue with less competition between fruit for carbohydrates. Unthinned trees had smaller fruits with fewer cells than larger fruit on thinned trees. McConchie et al. (1997) reported that following cross-pollination, the greater the number of nuts per raceme the greater the average size of nuts and the kernel recovery. There is also a correlation between high kernel recovery and large trunk girth (Stephenson and Gallagher 1989b).

The timing of fertilization influences the kernel recovery. High nitrogen (N) (690 g tree^{-1} annum^{-1}) application tend to cause a reduction in kernel recovery (Stephenson et al. 2002) and to a certain extent increases yield (Stephenson and Gallagher 1989b). Stephenson and Gallagher (1989b) noted that the application of N early in the reproductive cycle (June) tended to result in higher kernel recovery in Australia. During a six-year study high rates of N (690 and 1150 g tree^{-1}) increased kernel recovery by 1% in each of five years while only in one year did the timing of four or more split applications have an increase in kernel recovery (Stephenson et al. 2000). High N application did however resulted in a decrease in 1st grade kernel (Kruger 2000; Stephenson et al. 2000).

Stephenson and Gallagher (1987a) obtained higher yields and kernel recovery when foliar boron (B) was applied to macadamia trees after anthesis. By spraying at monthly intervals from early nut set to oil accumulation 0.002 ml L^{-1} B (Solubor) they increased the boron levels from ca. 30 to 65- 93 mg kg^{-1} in the leaves. Abnormal flower and fruit development is common in tree crops where boron is deficient (Stephenson et al. 1986). Wells et al. (2008) found kernel recovery and yield increased when foliar sprays in pecan were applied before pollination to meet the recommended optimum B leaf concentration range.

5. Whole kernel

5.1 Back ground

Macadamia kernels are sized into different styles, viz., whole, halves and chips or pieces (Weinert 1993). The weight of each style is expressed as a percentage of the total kernel weight. Premium prices are paid for whole kernel (Penter et al. 2008). There is potential for increasing profit by increasing the whole kernel percentage.

5.2 Physiology

Cultivars differ significantly on the percentage whole kernel recovery (Penter et al. 2008). According to Penter et al. (2008) a study of the ultrastructure of the adaxial surface between the cotyledons of several macadamia cultivars using transmission and light electron microscopy revealed that cultivars with more whole kernels had thinner cuticles and the surfaces of the two cotyledons were closely fused together compared to those with low whole kernel percentage where the contact was poor.

In the next section the effect of factors such as rough handling (nut drop), the dehusker and drying of NIS on the whole kernel percentage is discussed.

5.3 Rough handling (nut drop)

Wallace et al. (2000) examined the effect of impact on whole kernel recovery when NIS at different moisture contents was dropped on a hard surface. They noted that the whole kernels were reduced by 10% when dropped at 3% moisture and by 3 to 5% when dropped at 15% moisture content. Contrary to this Walton and Wallace (2008) reported that the dropping of nuts at different moisture content had no effect on kernel breakage. Penter et al. (2008) confirmed that NIS (at any moisture content) had no significant effect on whole kernel recovery. Although rough handling had no effect on whole kernel recovery it caused shoulder damage, surface damage, chipping and increased the extent of oily kernel which leads to reduced shelf life and quality of the kernel (Wallace et al. 2000; Walton and Wallace 2008).

5.4 Dehusker and cracker effects

Walton and Wallace (2005) reported that nuts dehusked at 10% and 22% moisture content showed no significant difference in whole kernel recovery. Penter et al. (2008) confirmed that there is no evidence that dehuskers reduce whole kernels if properly adjusted. The dehuskers are adjustable by adding or lessening the pressure applied to the nut-in-husk (NIH). Just enough pressure should be applied to the NIH to remove the husk and not break the nut shell.

Srichamnong (2012) mentioned that cracking force of NIS is influenced by nut size, cultivar and shell thickness. Srichamnong (2012) citing Liang et al. (1988) found that pre-treatment of NIS by freezing and notching NIS at 4 °C prior to cracking may be an alternative way to increase whole kernel recovery.

5.5 Drying of NIS

Penter et al. (2008) found that higher drying rates of NIS, removed moisture rapidly at 40 and 50 ºC, and increased the proportion of whole nuts recovered. Although it must be noted that high temperatures during drying have the potential to damage the kernel quality with spilling of oil and this leads to rancidity and shortens shelf life. Wallace and Walton (2003) found that wholes are reduced by 8 to 14% when nuts are allowed to dry slowly under field conditions. Frequent harvesting and rapid drying of NIS may prevent whole kernel losses (Wallace and Walton 2003). Bungay (2001) reported that whole kernel recovery at three different factories, decreased as the season progressed and storage time of NIS increased. Bungay (2001) explained that drier kernel will result in a loss of binding strength in the core at the interface between the two cotyledons and split easier into two halves.

6. Kernel discolouration

6.1 Back ground

Macadamia kernel discolouration is a disorder in which all or part of the basal portion of the kernel is stained brown to black (Penter et al. 2007a). In the processing industry the thin line of discolouration around the kernel equator is referred to as "onion ring". In more severe cases of discolouration, the stain is dark over the entire basal part of the kernel (distal-end-browning). It is mostly a superficial stain but could extend from the kernel surface down through 5 to 10 cell layers. The stain does not originate from cells in the kernel but from the shell (Penter et al. 2007a) due to a water soluble phenolic compound (Kaiser 2003).

Commercially kernels with discolouration fall in the second grade category (commercial grade) and are sold at lower prices. These discoloured kernels are chocolate coated or chipped (reworked) to smaller styles and sold at lower prices (Grimwood 1971). Sorting and production costs per unit acceptable kernel increase with the increase of commercial grade kernel (kernel discolouration, visual imperfections, damaged and defected kernels) (Hardner et al. 2009). In addition first-grade kernel yield is sensitive and dependent on the environment, particularly temperature, water availability and other management practices. Stephenson et al. (1995) found that cultivars with low overall percentage of first-grade kernel were more sensitive to these environmental variations. The next section will focus on the factors influencing kernel discolouration.

6.2 Maturity

Nut maturity influences the occurrence of discolouration (Penter et al. 2001). Penter et al. (2007a) investigated the discolouration in 'Beaumont' and found differences between regions and between seasons in South Africa and Malawi. The Limpopo and Malawi regions consistently have lower levels of discolouration than KwaZulu-Natal and Mpumalanga in 2003 to 2006. All

South African regions experienced more discolouration in 2006 compared to 2005. Discolouration was more prominent on hybrid cultivars. This disorder occurs more commonly in the early part of the harvesting season on 'Beaumont' and it generally declines as the season progresses (Penter et al. 2007a). Penter et al. (2001) however found that some late hanging (March) nuts in *M. integrifolia* cultivars in South Africa displayed discolouration. Discolouration increased in most cases during April to May, indicating that this disorder is related to kernel maturity and increases with age, even on the tree.

6.3 Water and nutrients

Soil moisture may play a role in the occurrence of discolouration. Non-irrigated orchards of 'Beaumont' displayed increased incidence of discolouration during dry spells and declined after rain. Discolouration in the Kiepersol area in South Africa, was low in 2006 which was a higher rainfall year compared to 2005 (Penter et al. 2007a). Stephenson et al. (2003) confirmed these findings by reporting that mild water stress resulted in low kernel quality i.e., more discoloured and shrivelled.

In contrast, kernels harvested from a wet orchard floor (wet soil) have more yellow colouring in addition to onion rings and distal-end-browning (Penter et al. 2001). Kruger et al. (2013) found that the incidence of kernel discolouration is higher during a wet cycle than during a dry cycle. In an ongoing study analysing historical data from a pack house in the Nelspruit region, from 2001 until 2013, Kruger et al. (2013) found a correlation between the elevated levels of immobile elements (Fe and Mn) and elevated soil moisture.

7. Conclusion

Stephenson and Gallagher (1989b) citing Radspinner (1971) concluded that a wide range of factors; cultivar, climatic conditions and tree age have the greatest effect on kernel recovery. The authors consider cross-pollination, carbohydrate levels and water as additional factors that influence kernel recovery. Whole kernel recovery is mostly determined by cultivar and can be influenced to a certain extend by the drying of the NIS (Penter et al. 2008). There is no clear evidence on which factors influence and determine kernel discolouration. Moisture and maturity could have an effect on discolouration but to what extent is still unknown. Although kernel recovery is cultivar related (McConchie et al. 1997), it can be managed through horticultural practices. Kernel recovery is determined by nut size and shell thickness (Hancock 1991). Horticultural interventions e.g. growth regulators, water management, evaporative cooling and nutrition can affect the nut size and/or shell thickness. To improve kernel recovery, future research in South Africa is needed on amongst others cross-pollination, soil moisture and using reflective substances to reduce heat stress.

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PAPER 1: POSSIBLE FACTORS THAT INFLUENCE MACADAMIA KERNEL RECOVERY, WHOLE KERNEL RECOVERY AND KERNEL DISCOLOURATION

Abstract

An increase in kernel recovery leads to higher value per nut in shell and lower production cost. Whole unblemished kernel returns a premium price compared to other styles like halves, pieces or commercial grade with kernel discolouration. In the Lowveld region, the same cultivar differs in yield in terms of kernel recovery, whole kernel recovery and kernel discolouration. This two-year study identified possible factors that can influence the above factors. Kernel recovery, whole kernel recovery and kernel discolouration differed between the six macadamia cultivation regions Barberton, Hazyview, Kiepersol, Nelspruit, Pietermaritzburg and White River and the 2010 and 2011 production seasons. Kernel recovery increased with an increase in orchard altitude. Cross-pollination resulted in significant increases in kernel recovery, but also increased kernel discolouration. High crop load was associated with high kernel recovery and low kernel discolouration. Irrigation type and efficacy influenced kernel recovery significantly with a high kernel recovery associated with lower irrigation efficacy on drip and micro sprinkler irrigation systems. Late nut-in-shell (NIS) delivery to the processing company, which could be due to late harvesting or storage, was associated with a decreased kernel recovery and lower whole kernel recovery. Curing of wet NIS on farm with ambient air was associated with lower whole kernel recovery compared to the Bungay system. High boron leaf levels were associated with high kernel recovery and high whole kernel recovery. High copper and low manganese leaf levels were associated with high whole kernel recovery. Low kernel discolouration was associated with high potassium and low nitrogen and zinc leaf levels. High vapour pressure deficit during the nut maturation period was associated with low whole kernel recovery. High daily maximum relative humidity during the nut growth stage

was associated with low kernel recovery. These results hold important implications for farming practices and the macadamia industry as a whole.

Introduction

Macadamia nuts are highly sought-after for their remarkable flavour, texture and health benefits (Grimwood 1971, Duncan 2011). It is the food source with the highest known level of mono-unsaturated fatty acids, which assists in decreasing low density lipoprotein cholesterol in humans and lowers the risk of heart disease (Garg et al. 2003). According to Duncan (2011) it is also one of the highest priced processed nuts on the world market. A premium is paid for whole, unblemished kernels compared to other styles like halves, pieces and commercial grade (blemished kernels) (Penter et al. 2008).

Kernel recovery influences the economic value of the macadamia crop. By increasing the kernel recovery, the kernel yield as a ratio of kernel to shell mass increases, leading to higher value per nut-in-shell (NIS) and lower production costs. Production costs are lower due to fewer nuts needed to be cracked for the same amount of usable kernel, which results in lower cost per unit kernel (Hardner et al. 2009). Kernel recovery is determined by the nut size and shell thickness, therefore, small nuts will contain less kernel than large nuts if they have the same shell thickness (Hancock 1991).

Kernel recovery is one of the easiest traits to assess and one of the most commonly reported (Hardner et al. 2009). However, kernel recovery is affect by a large number of factors. Stephenson and Gallagher (1989) quoting Radspinner (1971) found that cultivar, climatic conditions and tree age are some of the main factors that influence kernel recovery. Other studies have shown that kernel recovery is influenced by cross-pollination (Trueman and Turnbull 1994, Wallace et al. 1996), tree water relationships (Stephenson et al. 2003), carbohydrate levels in the tree (Wilkie 2009) and crop load or yield (McFadyen et al. 2004).

Whole kernel recovery differs significantly between cultivars and could be reduced by rough handling and different curing rates (Penter et al. 2008). According to Penter et al. (2008), a study using transmission and light electron microscopy revealed that cultivars with more whole kernels had thinner cuticles and the surfaces of the two cotyledons were closely fused together, compared to those with low whole kernel recovery where the contact was poor. Wallace et al. (2000) found that whole kernel recovery was reduced when nuts in their shells were dropped on hard surfaces at different moisture contents. To the contrary, Walton and Wallace (2008) and Penter et al. (2008) reported that the dropping of nuts at different moisture contents had no effect on kernel breakage. Penter et al. (2008) and Walton and Wallace (2005) found that nuts dehusked at either 10% or 22% moisture content showed no significant difference in the proportion of whole kernel recovered. Penter et al. (2008) however found that higher NIS curing rates (i.e. removing moisture rapidly at 40 and 50 ^{o}C) increased whole kernel recovery, which substantiates that slow drying under field conditions reduced whole kernel recovery by 8 to 14% (Wallace and Walton 2003).

As mentioned previously, commercial grade kernel (blemished kernels) does not achieve the same premium price as unblemished first grade kernel (Penter et al. 2008). In addition, the increase in commercial grade kernel (visual imperfection, damaged and defected kernel) on the sorting line, increases sorting and fixed costs of production per unit mass of acceptable kernel (Hardner et al. 2009). Kernel discolouration is classified as commercial grade and all affected kernel is removed, packed separately or reworked (chipped) and packed as smaller styles (Penter et al. 2007a). Macadamia kernel discolouration is a disorder in which all or part of the basal portion of the kernel is stained brown to black (Penter et al. 2007a). In the processing industry, the thin line of discolouration around the kernels equator is referred to as “onion ring”.

According to Penter et al. (2007a), soil moisture may play a role in the occurrence of kernel discolouration, as they observed increased kernel discolouration in a non-irrigated orchard of ‘Beaumont’ in Kiepersol during dry spells and a decrease after rain. In contrast, Kruger et al.

(2013) found that the incidence of kernel discolouration was higher during a wet cycle than during a dry cycle. In an ongoing study by Kruger et al. (2013) a link appeared between kernel discolouration, the elevated levels of immobile elements (Fe and Mn) and elevated soil moisture.

In the Lowveld region, orchards of the same cultivar differ in kernel recovery, whole kernel recovery and kernel discolouration. The opportunity to increase profit, clearly lies in increasing kernel recovery and whole unblemished kernel recovery. There is a need, therefore, to gain a better understanding of factors that possibly influence kernel recovery, whole kernel recovery and kernel discolouration in order to implement optimal management strategies to maximize productivity and profitability on commercial macadamia farms. This study addressed the orchard, cultural, environmental (climatic) and nutritional factors that influence kernel recovery, whole kernel recovery and kernel discolouration by analysing historical data.

Materials and Methods

Historical data from 99 orchards and 40 different farms in South Africa that deliver ‘Beaumont’ macadamia nuts to Golden Macadamias (Pty) Ltd (Alkmaar, Mpumalanga, South Africa) were used to determine which factors influence kernel recovery, whole kernel recovery and kernel discolouration. Golden Macadamias did batch processing during the 2010 and 2011 seasons and kept the respective batch data on individual orchards separately. Historical data included yield and nut quality, climatic conditions of the orchard, harvest date, post-harvest handling and orchard practices, including nutrition.

Nut quality determination:

Growers delivered the macadamia nut-in-shell (NIS) in 4 or 8 ton truck loads to the processing plant and a 20 kg representative sample was collected at delivery from each load. After the dry-in-shell (DIS) sample was cured to 1.5% kernel moisture content (under controlled atmosphere (Bungay 2001)), the DIS nuts were cracked with a mechanical Holiday cracker (WMC sheet metal works, Tzaneen, South Africa) to determine kernel recovery, style distribution (whole kernel recovery), kernel discolouration and other defects, which include immaturity, insect damage, mould and germination. Cracked shells and kernels and their fragments were separated with vibrating screens and blowers. Kernel recovery was determined by dividing the weight of kernel recovered through the weight of NIS and expressed as a percentage (kernel NIS^{-1} x 100). Style distribution was done by sizing the kernel into different styles, viz., whole, halves and chips or pieces (Weinert 1993). The weight of each style was expressed as a percentage of the total kernel weight. Kernel discolouration, including 'onion ring' and 'distal end browning' (Penter et al. 2007a), was determined through hand sorting according to commercial grade colour charts (Golden Macadamias (Pty) Ltd).

Climatic data:

The effect of the different seasons and regions on kernel recovery, whole kernel recovery and kernel discolouration was evaluated using the same historical data. The grouping of farms into regions was guided by the closest weather station to that farm. Of the 39 farms in the Lowveld (25° S) region, 7 farms were situated near Barberton, 1 near Hazyview, 3 near Kiepersol, 11 near White River and 17 near Nelspruit. Only 1 farm was situated in KwaZulu Natal near Pietermaritzburg (29° S). Daily climatic data were collected from the Agricultural Research Council - Institute of Soil, Climate and Water (ARC-ISCW) at: Barberton, Zenzelenzi (White River), Burgerhall (Kiepersol), Hazyview, Cedara PP (Pietermaritzburg) and Nelspruit; Institute for Tropical and Subtropical Crops (ITSC) weather stations (Table 1). The mean climatic variables were compiled over 4 fruit development stages, viz. premature nut drop (1 Oct. to 15 Nov.), shell hardening (16 Nov. to 15 Jan.), nut maturation (16 Jan. to 30 Apr.) and nut growth (1 Oct. to 15 Jan.).

Cross-pollination, tree age, yield, irrigation and nutrition

The effect of proximity of cross-pollinators (any cultivar except 'Beaumont') from the harvested orchard was evaluated. Cross-pollination options were inter-planted (cross-pollinator inter planted in orchard), adjacent orchard (cross-pollinator in neighbouring orchard), or absent (no cross-pollinator in immediate vicinity of the orchard). The effect of tree age and yield on kernel recovery, whole kernel recovery and kernel discolouration were evaluated. Tree age was calculated from the date of planting while yield data per orchard was collected and classified as high, medium or low. Crop load of young trees (4 to 9 years) was calculated per tree (Table 2). Trees of 10 years and older were classified as mature and crop load was calculated as follow: low $\leq$ 3500 kg ha^{-1}, medium between 3500 and 4900 kg ha^{-1} and high $\geq$ 4900 kg ha^{-1}. Irrigation types included dry-land (rain-fed), drip irrigation, micro-jet irrigation and drag-line irrigation. In addition, irrigation efficacy was rated in five categories from excellent (class 5) where a scheduling scheme was accurately followed, soil moisture was measured and the trees were not stressed to the opposite extreme, ineffective water application efficacy (class 1) used for dry-land orchards. Representative leaf samples were collected from 36 orchards at the beginning of summer (Nov.) (Huett and Vimpany 2007) and analysed at Labserve analytical services (Nelspruit, South Africa). Leave nutrient levels for Nov. 2009 were used for the 2010 season and the Nov. 2010 levels were used for the 2011 season. Nutrients included N (nitrogen), K (potassium), P (phosphorous), Ca (calcium) and Mg (magnesium) and were expressed as percentage dry weight (DW) and Cu (copper), Fe (iron), B (boron), Zn (zinc) and Mn (manganese) as mg kg^{-1} DW.

Orchard altitude, slope and row orientation

Orchard altitude, the direction of the slope and plant row orientation were recorded and evaluated. The highest and lowest altitude point per orchard was calculated from topographical maps (Department of Water Affairs and Forestry (DWAF), Nelspruit) and the average of the 2 points was used per orchard. The contours of each orchard indicated the slope: N (north), S (south), E (east), W (west), NE (northeast), NW (northwest), SW (southwest) and SE (southeast). Tree row orientation, i.e., N-S (north south), E-W (east west), NE-SW (northeast-southwest) and NW-SE (northwest- southeast), was recorded by using Google Earth (https://earth.google.com).

Harvest date, cold storage and curing of NIS

The date the batch of NIS was delivered to the processing plant (day of year) was used as indication of harvest date. NIS can be stored at 8-10% moisture content in a cold room (15 ^{0}C temp. and 54% RH) at the processing plant before curing, which was indicated as yes or no. Curing of NIS after dehusking varies and includes ambient (ambient air is blown over wet NIS), heat (constant hot air that ranges from 25 to 30 ^{0}C without regulating relative humidity (RH)) and Bungay (Bungay 2001, curing of wet NIS with only 2% moisture loss per day by regulating temp. and RH).

Statistical analyses

All statistical analyses were performed using SAS Enterprise Guide 5.1 (SAS Institute, Cary, N.C., 2012). All data analyses followed model assumption tests, which generally included tests for data distribution (normality, using the Shapiro-Wilk test) and residual deviance of the models (homoscedasticity, using the Bartlett test), that were always verified so that the model assumptions were not violated. The kernel recovery, whole kernel recovery and kernel discolouration data were normally distributed; however, the variance between the outcomes of the test factors were not equal (heteroscedastic). Therefore, the outcome of season (2010 vs. 2011) was undertaken using a Wilcoxon rank-sum test. Furthermore, a non-parametric generalized linear model (GLZ) approach with Gaussian (normal) distribution of errors and identity link function (Crawley 2007) was used to test the outcomes of orchard factors (categorical variables) and a step-wise general linear model was used to identify the most important and significant continuous variables of meteorological and leave nutrient factors likely to influence kernel recovery, whole kernel recovery and kernel discolouration. Each GLZ was tested for significance and the smallest Akaike's information criterion (AIC) was used to distinguish between model strengths. Least significant differences (LSD) were used to categorize the means of the factors when the GLZ indicated significant differences ($P < 0.05$).

Results

Kernel recovery

The kernel recovery of the 2010 season (30.05%) was lower than the 2011 season (33.27%). According to the Wilcoxon rank sum test, there was a significant difference between the log transformed kernel recovery for 2010 and 2011 ($P < 0.0001$). The different regions also showed a significant effect on kernel recovery ($P < 0.0001$), with Kiepersol (34.11%) the highest and Hazyview the lowest (29.30) (Table 3). Kernel recovery increased from 2010 to 2011 season in all the regions (Figure 1).

Significant contributions ($P < 0.0001$) to kernel recovery of macadamias are shown in the equations below:

(A) Orchard factors:

Y = 26.46 + A + B + C + D + 0.008 E - 0.005 F + G + H

AIC = 2823.77

Where Y = kernel recovery

A = season: 2010 = - 1.83, 2011 = 0

B = region: Barberton = -0.28, Hazyview = 0.79, Kiepersol = 2.07,

Pietermaritzburg = 0.95, Nelspruit = 1.14, White River = 0

C = crop load: high = 0.12, medium = 0, low = -1.05

D = cross-pollination: inter planted = 1.83, adjacent orchard = 0.72, absent = 0

E = average altitude

F = day of the year (delivery date)

G = irrigation type * irrigation efficacy: ineffective micro sprinkler = 0.40, ineffective drip = 0.55, ineffective dragline = 0.68, dry land = 0.53, medium micro sprinkler = - 0.10, medium drip = - 0.31, effective micro sprinkler = 0, excellent micro sprinkler = 0.61,

excellent drip = 0

H = slope * row orientation:

E	N-S =	0.84,	E	NE-SW =	0.33,
E	NW-SE =	- 0.04,	N	E-W =	2.28,
N	N-S =	1.40,	NE	E-W =	2.06,
NE	N-S =	1.22,	NE	NE-SW =	- 1.35,
NE	NW-SE =	0.18,	NW	E-W =	2.16,
NW	N-S =	1.01,	NW	NE-SW =	1.23,
S	E-W =	0.61,	S	N-S =	- 0.90,
SE	N-S =	1.13,	SE	NE-SW =	1.49,
SE	NW-SE =	0.61,	SW	N-S =	0.62,
SW	NW-SE =	0.71,	W	E-W =	0.78,
W	N-S =	0			

Although the mean kernel recovery of Hazyview region was the lowest, when adding all the factors in equation A, Barberton region shifted to the lowest region. Crop load of the trees had a significant influence on kernel recovery ($P < 0.0001$). Kernel recovery was lower with a low crop load (31.14%) compared to a medium (32.69%) and high (32.81%) crop load (Table 4). Cross-pollination made a significant contribution to kernel recovery ($P < 0.0001$). Kernel recovery was much higher when cross-pollinator trees were inter-planted (35.11%) compared to cross-pollinator trees in an adjacent orchard (32.94%) or when absent (31.77%) (Table 5).

Kernel recovery increased significantly with increasing orchard altitude ($P < 0.0001$). The lowest average orchard altitude was recorded as 541 meter above sea level (m.a.s.l.) and the highest at 998 m.a.s.l. (data not shown).The date of delivery to the processing plant had a significant effect on kernel recovery ($P < 0.04$) with kernel recovery decreasing the later in the season the NIS was delivered (data not shown). The interaction between irrigation type and efficacy had a significant effect on kernel recovery ($P < 0.03$), with kernel recovery at the highest (34.44%) on ineffective drip and at the lowest (31.60%) on medium drip (Table 6). However, in equation A, ineffective dragline and excellent micro sprinkler had the most positive and medium drip the most negative effect on kernel recovery.

The interaction between the orchard slope and tree row orientation had a significant effect on kernel recovery ($P < 0.0001$). Kernel recovery was at its lowest when the tree row orientation was parallel to the slope compared to row orientation that was perpendicular (across) the slope i.e. the NE slope with NE-SW (30.74%) row orientation compared to NW-SE (32.27%) row orientation (Figure 2). In equation A, a North facing slope with an E-W row orientation had the highest positive effect and a NE slope with NE-SW row orientation has the most negative effect on kernel recovery.

(B) Leaf nutrient levels:

$Y = 25.66 + 1.55\ L_N + 8.43\ L_K + 0.03\ L_B - 19.30\ L_P$

$R^2 = 0.2887$ ($P < 0.0001$)

Where Y = kernel recovery

L = leaf nutrient composition: N = nitrogen, K = potassium, B = boron,

P = phosphorous

High leaf N, K and B concentration in Nov. had a positive effect on kernel recovery while high leaf P concentration had a negative effect on kernel recovery.

(C) Meteorological data:

$Y = 180.02 - 11.49\ ETO\ (1) + 2.48\ Rs\ (1) + 1.29\ RH_{min}\ (2) – 1.07\ RH_{max}\ (3)$

$– 0.005\ Rain\ (3) – 1.27\ RH_{max}\ (4)$

$R^2 = 0.3884\ (P < 0.0001)$

Where Y = kernel recovery

ETO = total relative evapotranspiration

Rs = total radiation

RH = daily relative humidity: min = minimum, max = maximum

Rain = total rainfall

*numbers in parentheses refer to fruit development stage: 1 = premature nut drop, 2 = shell hardening, 3 = nut maturation, 4 = nut growth

High Rs had a positive and high ETO a negative effect on kernel recovery during the premature nut drop stage. High daily minimum RH during the shell hardening stage had a positive effect on kernel recovery. Low daily maximum RH during the nut maturation and nut growth stages including low total rainfall in the nut maturation stage increased kernel recovery.

(D) All recorded variables:

$Y = 165.59 + A + B + C + D + 0.01\ E - 0.007\ F + G + 0.009\ L_B – 1.55\ RH_{max}\ (4)$

AIC = 974.54

Where Y = kernel recovery

A = season: 2010 = - 1.19, 2011 = 0

B = region: Barberton = - 0.97, Hazyview = 2.03, Nelspruit = 2.85,

White River = 0

C = crop load: high = 0.39, medium = 0, low = - 0.53

D = cross-pollination: inter planted = 2.36, adjacent orchard = 1.27, absent = 0

E = average altitude

F = day of the year (delivery date)

G = irrigation type * irrigation efficacy: ineffective drip = 0.48, ineffective dragline = 0.65, medium micro sprinkler = - 0.44, medium drip = - 0.19, excellent micro sprinkler = 1.06, excellent drip = 0

L = leaf nutrient composition: B = boron

RH = daily relative humidity: max = maximum

*numbers in parentheses refer to fruit development stage: 4 = nut growth

The most important factors that affect kernel recovery are represented by equation D with a smaller AIC than equation A. Equation D includes all the factors from equation A, although it excludes Kiepersol and Pietermaritzburg regions, ineffective micro sprinkler, dry land, effective micro sprinkler and slope * row orientation. Leaf B concentration and average maximum RH during the nut growth stage were included from equation B and C. On irrigation efficacy and type, excellent micro sprinkler made the highest contribution to high kernel recovery, followed by ineffective drip and dragline. High B leaf concentration during Nov. was associated with high kernel recovery. High daily RH during the nut growth stage had a negative effect on kernel recovery.

Whole kernel recovery

The whole kernel recovery during the 2011 season (33.7%) was higher than the during the 2010 season (30.6%). According to the Wilcoxon rank sum test, there was a significant difference between the log transformed whole kernel recovery for 2010 and 2011 ($P < 0.0001$). The different regions also differed significantly in whole kernel recovery ($P < 0.0001$), with Nelspruit (33.88%) the highest and Hazyview the lowest (27.26%) (Table 3). Whole kernel recovery increased from 2010 to 2011 season in all the regions (Figure 3).

Significant contributors to whole kernel recovery of macadamias are shown in the equations below:

(E) <u>Orchard factors:</u>

Y = - 2.66 + A + B + 1.23 C – 0.04 D + E

AIC = 5052.69

Where Y = whole kernel recovery

A = region: Barberton = - 2.98, Hazyview = - 5.27, Kiepersol = - 5.36,

Pietermaritzburg = - 0.07, Nelspruit = - 0.53, White River = 0

B = curing: ambient = 5.23, heat = 0, Bungay = 8.34

C = kernel recovery

D = day of the year (delivery date)

E = crop load * cross-pollination: high * interplanted = 0.42, high * adjacent orchard = 0.68, high * absent = 1.15, low * interplanted = - 4.15, low * adjacent orchard = - 2.86, low * absent = - 1.92,

medium * adjacent orchard = - 3.18, medium * absent = 0

In equation D however, Kiepersol region had the lowest and White River region the highest whole kernel recovery. Different curing systems had a significant effect on whole kernel recovery ($P < 0.0001$). Whole kernel recovery was higher when a Bungay system (34.32%) compared to ambient (31.37%) and heat (28.82%) was used to cure NIS (Figure 4). Whole kernel recovery decreased the later in the season the NIS was delivered for processing ($P < 0.0001$). Whole kernel recovery increased significantly with the increase in kernel recovery ($P < 0.0001$). The interaction between crop load and cross-pollination had a significant effect on whole kernel recovery ($P < 0.0001$). High crop load and inter-planted cross-pollination was associated with high whole kernel recovery (38.04%) (Table 7). In equation D however, high crop load and absent cross-pollination were associated with the highest whole kernel recovery. Low crop load and inter-planted cross-pollination was associated with the lowest whole kernel recovery (28.59%) (Table 7).

(F) Leaf nutrient levels:

$Y = 28.49 + 0.41\ L_{Cu} + 0.07\ L_{B} – 0.005\ L_{Mn}$

$R^2 = 0.1719$ ($P < 0.0001$)

Where Y = whole kernel recovery

L = leaf nutrient composition: Cu = copper, B = boron, Mn = manganese

High leaf concentrations of Cu and B had a positive effect and high concentrations of Mn in the leaves a negative effect on whole kernel recovery.

(G) *Meteorological data:*

Y = 110.22 – 4.75 $Temp_{max}$ (3) + 69.79 VPD (3) + 0.006 Rain (4)

R^2 = 0.1140 ($P < 0.0001$)

Where Y = whole kernel recovery

Temp = daily temperature: max = maximum

VPD = vapour pressure deficit

Rain = total rainfall

*numbers in parentheses refer to fruit development stage: 1 = premature nut drop, 2 = shell hardening, 3 = nut maturation, 4 = nut growth

High daily maximum temperature during the nut maturation stage was associated with low whole kernel recovery. High VPD during the nut maturation stage increased whole kernel recovery. High total rainfall during the nut growth stage was associated with high whole kernel recovery.

(H) *All recorded variables:*

Y = 41.32 + A + B – 0.03 C + 1.59 D + 0.37 L_{Cu} + 0.03 L_B – 0.004 L_{Mn} - 74.76 VPD (3)

AIC = 1712.44

Where Y = whole kernel recovery

A = region: Barberton = - 1.12, Hazyview = 5.35, Pietermaritzburg = - 14.52,

Nelspruit = 8.63, White River = 0

B = drying: ambient = -3.05, Bungay = 0

C = day of the year (delivery date)

D = kernel recovery

L = leaf nutrient composition: Cu = copper, B = boron, Mn = manganese

VPD = vapour pressure deficit

*numbers in parentheses refer to fruit development stage: 1 = premature nut drop, 2 = shell hardening, 3 = nut maturation, 4 = nut growth

The most important factors that affected whole kernel recovery are indicated by equation H with a smaller AIC than equation E. The equation includes all the factors mentioned in equation E except the region Kiepersol and the interaction between crop load and cross-pollination. The equation also includes all the leaf nutrient concentrations from equation F and only VPD during the nut maturation stage from the meteorological data. VPD however did change from having a positive effect in equation G to a negative effect in equation H on whole kernel recovery.

Kernel discolouration

Kernel discolouration did not differ between the 2010 (6.39%) and the 2011 (7.01%) seasons. The different regions did show a significant difference in kernel discolouration ($P < 0.0001$). The incidence of kernel discolouration was the highest in Kiepersol (11.10%) and Pietermaritzburg (12.22%) and the lowest in Hazyview (3.79%) (Table 3). Hazyview, Kiepersol and Nelspruit showed an increase in kernel discolouration from the 2010 to the 2011 season (Figure 5).

Significant contributors to kernel discolouration of macadamias are shown in the equations below:

(I) *<u>Orchard factors:</u>*

$$Y = -5.76 + A + B + C + D + 0.02\,E + F + G$$

AIC = 4304.12

Where Y = kernel discolouration

A = season: 2010 = - 1.54, 2011 = 0

B = region: Barberton = 0.40, Hazyview = 5.51, Kiepersol = 5.44,

Pietermaritzburg = 5.10, Nelspruit = 2.44, White River = 0

C = crop load: high = - 1.26, medium = 0, low = 0.006

D = cross-pollination: inter planted = 0.006, adjacent orchard = 1.33, absent = 0

E = average altitude

F = irrigation type * irrigation efficacy: ineffective micro sprinkler = -0.39, ineffective drip = - 1.35, ineffective dragline = - 5.60, dry land = - 3.66, medium micro sprinkler = - 1.46, medium drip = - 2.96, effective micro sprinkler = 0, excellent micro sprinkler = - 2.48, excellent drip = 0

G = slope * row orientation:

E	N-S	1.50,	E	NE-SW	1.69,
E	NW-SE	- 1.58,	N	E-W	8.44,
N	N-S	- 0.24,	NE	E-W	17.20,
NE	N-S	0.98,	NE	NE-SW	- 1.70,
NE	NW-SE	- 0.83,	NW	E-W	- 1.19,
NW	N-S	3.58,	NW	NE-SW	- 0.19,
S	E-W	1.76,	S	N-S	- 0.94,
SE	N-S	- 0.28,	SE	NE-SW	1.15,
SE	NW-SE	0.77,	SW	N-S	- 1.63,

SW	NW-SE	3.32,	W	E-W	4.81,
W	N-S	0			

Although the Hazyview region showed the lowest incidence of kernel discolouration, in equation I it showed the highest effect on the increase of kernel discolouration. Although the seasons did not differ significantly as an individual factor, when included in the equation it differed significantly and resulted in lowering the AIC for orchard factors. Crop load had a significant influence on kernel discolouration ($P < 0.0001$). Kernel discolouration decreased as crop load increased (Table 4). Cross-pollination had a significant influence on kernel discolouration ($P < 0.002$). Kernel discolouration was much higher when cross-pollinator trees were inter-planted (8.61%) and planted in an adjacent orchard (8.44%) compared to absent (5.30%) (Table 5).

(J) Leaf nutrient levels:

$$Y = 9.04 + 2.53\ L_N - 6.14\ L_K - 6.57\ L_{Ca} + 6.20\ L_{Mg} - 19.95\ L_P + 0.13\ L_{Zn} + 0.006\ L_{Mn}$$

$R^2 = 0.3545$ ($P < 0.0001$)

Where Y = kernel discolouration

L = leaf nutrient composition: N = nitrogen, K = potassium, Ca = calsium,

Mg = magnesium, P = phosphorous, Zn = zinc,

Mn = manganese

High N, Mg, Zn and Mn leaf concentrations during Nov. were associated with high kernel discolouration while high K, Ca and P leaf concentrations were associated with low kernel discolouration.

(K) Meteorological data:

$Y = 78.41 + 1.73\ RH_{min}$ (4)

$R^2 = 0.1115$ ($P < 0.0001$)

Where Y = kernel discolouration

RH = daily relative humidity: min = minimum

*numbers in parentheses refer to fruit development stage: 1 = premature nut drop, 2 = shell hardening, 3 = nut maturation, 4 = nut growth

High minimum RH during the nut growth stage was associated with high kernel discolouration.

(L) All recorded variables:

$Y = 1.03 + A + B + C + 4.97\ L_N – 5.31\ L_K + 0.11\ L_{Zn}$

AIC = 1569.75

Where Y = kernel discolouration

A = region: Barberton = 1.55, Hazyview = 0.21, Pietermaritzburg = 4.70,

Nelspruit = - 1.22, White River = 0

B = crop load: high = -1.41, medium = 0, low = 1.04

C = cross-pollination: inter planted = 5.77, adjacent orchard = 1.98, absent = 0

L = leaf nutrient composition: : N = nitrogen, K = potassium, Zn = zinc

The most important factors that affect kernel discolouration are incorporated into equation L with a smaller AIC than equation I. The equation includes only region (excluding Kiepersol), crop load, cross-pollination and leaf nutrient concentrations of N, K and Zn. Pietermaritzburg region was associated, all the other factors included, with high kernel discolouration and Nelspruit region with low kernel discolouration.

Discussion

Kernel recovery

Kernel recovery differed significantly between seasons and regions. Hardner et al. (2009) also found variable results for kernel recovery for various cultivars at different sites in Australia. This is not surprising as regions differ in climatic conditions and Stephenson and Gallagher (1989) mentioned that Radspinner (1971) considers climatic conditions as one of the main factors that influence kernel recovery.

During the shell hardening stage, high kernel recovery was associated with high average daily minimum RH. High total relative evapotranspiration during the premature nut drop stage had a negative effect on kernel recovery. To the contrary, high daily maximum RH during the nut maturation and nut growth stages had a negative effect on kernel recovery. Considering that high relative evapotranspiration and low RH increase transpiration, close stomata and decrease CO_2 absorption, which in return reduce growth and photosynthesis (Hoffman et al. 1971), the assumption can be made that kernel recovery is sensitive to reduced photosynthate supply. High RH suppresses transpiration which negatively affects mineral uptake (Taiz and Zeiger 2010). These conditions together with high rainfall (also links with high max RH) can affect kernel recovery negatively during the nut maturation and growth stages. Stephenson et al. (2000) found that heavy rainfall (>200 mm/month) during summer–early autumn (nut maturation stage) was associated with low kernel recovery. The effect of evapotranspiration (premature nut drop), minimum RH (shell hardening) and maximum RH (nut maturation) were not significant when other factors were considered in equation D, only maximum RH during the nut growth stage remained significant indicating that is could be the more important climatic factor.

Crop load correlated positively with kernel recovery. Stephenson et al. (2000) also noted that in years with poor yields, kernel recovery was low while in years with above average yields, kernel recovery was higher. McFadyen et al. (2004) found similar results in their study and it was further confirmed by the positive correlation Wilkie (2009) found between kernel recovery and yield efficiency (kg NIS m^{-3}). Wilkie (2009) concluded that high kernel recovery is associated with decrease in NIS weight and increase in yield efficiency. Trees compensate for low raceme densities by increasing the number of fruit per raceme. The NIS weight decreases as the number of fruit increases (Wilkie, 2009), which is similar to the apple tree that produces small fruit when crop load is high (Robinson and Lakso 1995). Smith et al. (1993) found that fruit thinning in pecans reduced yield, but improved the kernel percentage (kernel recovery) and individual nut weight. Robinson and Lakso (1995) found in their study on apple that reducing crop load by thinning fruit, increased fruit size by allowing cell division to continue under less competition for carbohydrates. As previously mentioned, kernel recovery is determined by shell thickness and nut size; therefore if shells are thin, kernel recovery increases. We can assume that a high crop load in macadamia decreases cell division and therefore results in thinner shells.

Cross-pollination of ‘Beaumont’ increased kernel recovery and is at its highest when cross-pollinators were inter-planted in the orchard. This is consistent with the findings of Penter et al. (2007b) who showed in their study that kernel recovery increased in ‘Beaumont’ when cross-pollination was done by hand. Trueman and Turnbull (1994) and Wallace et al. (1996) observed that cross pollination increased the yield, kernel weight and kernel recovery in some cultivars e.g. A4, HAES 246. Timing of full bloom and compatibility between cultivars need to be considered to obtain the benefit of cross-pollination (McConchie et al. 1997), again boiling down to higher fruit set = thinner shells.

'Beaumont' trees grown in the Lowveld region at higher altitude gave higher kernel recovery compared to trees at lower altitude. In contrast, Hancock (1991) mentioned that increasing altitude in Hawaii (700 to 830 m.a.s.l.), resulted in a reduction in temperature, which lead to thicker shells, reduced yields and lower kernel recovery. Furthermore Koyuncu et al. (2004) found similar results in Turkey on walnuts, where high altitudes (1200 m.a.s.l.) produced smaller nuts with thick shells compared to bigger nuts at lower altitude (200 m.a.s.l). In addition, higher altitudes are also associated with more cloud cover (resulting in lower irradiance levels) and frequent rain that slows down tree development, thickens shells and reduces yields (Hancock 1991). Considering that macadamias are best suited to areas below 476 in Hawaii (Shigeura and Ooka 1984), between 550 and 1500 in Malawi, between 550 and 1600 in Guatemala and 700 m.a.s.l. in Costa Rica (Hancock 1991), the altitudes of between 540.5 and 997.5 m.a.s.l. in this study seems well within in the optimal range. Hancock (1991) mentions that altitudes below 450 m.a.s.l. in the lower Ntchisi (Malawi) area are too hot and dry for good growth and tree health. Therefore we can assume that temperatures in this study at the lower altitudes were higher than at higher altitude and that the altitude effect is probably a temperature effect. High temperatures in the three months after flowering result in small nuts due to early shell hardening (Hancock 1991). Furthermore Stephenson and Gallagher (1986) found kernel recovery, kernel growth and oil content were low at 15 and 35 ^{0}C, the kernel recovery and weight declining at temperature of 35 ^{0}C and most kernels contained less than 72% oil.

The interaction between orchard slope and row orientation contributed to kernel recovery but was no longer significant in the final equation D. The interaction between the type and efficacy of irrigation had a significant effect on kernel recovery, with higher values for the less effective drip and micro sprinkler irrigation. This is consistent with Stephenson et al. (2003) who found that water stress during the premature nut drop period (21 days during Nov.) increased kernel recovery; however water stress during the nut maturation period (mid-January until harvesting) decreased kernel recovery. Similarly Goldhamer et al. (1990) found higher kernel percentage in walnuts when they were evaluating hedgerow walnut tree recovery and performance in the second season, after returning to full irrigation following three years of sustained deficit irrigation at 33 and 66% ET_c compared to trees previously irrigated at 100% ET_c. In equation D excellent micro sprinkler irrigation showed the highest increase in kernel recovery, this was only associated with the other factors in the equation and not as a stand-alone factor, assuming the interaction between factors and effective micro sprinkler irrigation had an effect on kernel recovery.

High leaf B concentration was associated with high kernel recovery, which is consistent with the results Stephenson and Gallagher (1987) found when foliar B was applied to macadamias after anthesis. Stephenson et al. (1986) mentioned that B deficiency in tree crops commonly results in abnormal flower and fruit development. Wells et al. (2008) found an increase in kernel recovery in pecan when foliar B sprays were applied to meet the recommended optimal B range, although the timing of the foliar B application during the critical pre-pollination period appeared to be more critical for pecan production than the increase in B leaf concentration.

High kernel recovery is associated with high leaf N concentration. This is consistent with the results Stephenson et al. (2000) and Stephenson and Gallagher (1989) found. Leaf N was however not significant when other factors were also considered in equation D. Leaf K concentration was not significant when other factors were considered in equation D, but Zeng et al. (2001) found that K is in demand and critical during nut filling on pistachio trees.

Kernel recovery decreased the later NIS was delivered and processed during the season. According to Bungay (2001), NIS early in the season is cracked at a quicker rate due to low stoke and NIS is actually cracked at higher moisture content. Due to curing time that is shortened, kernels dry quicker in the outer layer, while the inner kernel is still wet. Later in the season the NIS is kept in storage and moisture has time to equalise throughout the kernel and it is in actual fact drier at cracking. Considering this, Hardner et al. (2009) mentioned that it is reported that kernel recovery assessed from wet NIS may be higher than when kernel recovery is assessed from drier NIS. Bungay (2001) also mentioned that lower kernel moisture content later in the season can lead to decreased whole kernel recovery and increased chips and kernel dust from the cracking may occur, and whether or not this is included in the assessment of kernel mass may affect how kernel recovery is calculated.

Whole kernel recovery

Whole kernel recovery increased from the 2010 to the 2011 season in all the regions, similar to the results found for kernel recovery. An increase in kernel recovery was associated with an increase in whole kernel recovery. Hardner et al. (2009) however found no correlation between kernel recovery and whole kernel recovery across cultivars. Considering that high kernel recovery is associated with thinner shells (Hardner et al. 2009) and that cracking force of NIS is influenced by nut size, cultivar and shell thickness (Srichamnong 2012), we can assume that by cracking NIS with high kernel recovery with thin shells uses less force and should result in higher whole kernel recovery.

Whole kernel recovery is influenced by the different methods of curing NIS. Curing using the Bungay system was associated with higher whole kernel recovery compared with the ambient air system (only ambient air is blown over the wet NIS). Bungay (2001) mentioned that ambient air curing has a dynamic humidity and temperature and changes as the climate changes. NIS that has already been cured to a low moisture content can be rewetted if the ambient air is more humid than the NIS, and thereby increasing curing time. Penter et al. (2008) found higher whole kernel recovery with curing NIS at 35 ^{0}C at a faster curing rate than NIS at room temperature and concluded that the higher whole kernel recovery is most likely due to increased drying rate rather than exposure to higher temperatures.

Whole kernel recovery decreased the later NIS was delivered and processed during the season, similar to kernel recovery, and as previously mentioned there is a correlation between kernel recovery and whole kernel recovery. Bungay (2001) reported a similar trend, with whole kernel recovery decreasing as the season progresses at three different factories, with the common denominator an increase in dry NIS storage time. As described earlier, NIS is wetter on the inside of the kernel early in the season and drier later in the season. Bungay (2001) explained that drier kernel will result in a loss of binding strength in the core at the interface between the two cotyledons and therefore a whole kernel will split easier into two halves.

High leaf B concentration was associated with high whole kernel recovery, similar to kernel recovery. Abnormal flower and fruit development are common in tree crops with B deficiencies (Stephenson et al. 1986). Harris and Brolmann (1966) found that B deficiency affected the inside of the cotyledons of peanuts and that B application reduced the “hollow-heart” defect.

High leaf Cu concentration was associated with high whole kernel recovery but the reason for this is not clear. Abercrombie (1998) reported shrivelled macadamia kernels when trees suffered from Cu deficiency. Abercrombie (1998) also referred to Sprague (1965) who described Cu deficiency symptoms on walnuts as: shells having a chalky appearance and kernels severely shrivelled. Kester et al. (1956) found similar results on almond kernels where Cu was deficient. Cu is an essential nutrient for normal plant growth and development and deficiency can have adverse effects on physiological process in plants, in particular a reduction in photosynthetic electron transport (Yruela 2005).

An increase in leaf Mn levels was associated with a decrease in whole kernel recovery. Cu reduces Mn absorption and toxicity in plants indicating a possible interaction between these two nutrients. Although Mn is an essential nutrient in plants and is involved in metabolic processes (photosynthesis and as an enzyme antioxidant-cofactor), an excess of Mn is toxic to plants (Millaleo et al. 2010). Mn phytotoxicity reduces biomass and photosynthesis, and increases oxidative stress. Stephenson et al. (1986) mentioned that high Mn is generally associated with poor yields in macadamia, but also found the opposite when high yields occurred on soil with high Mn.

The increase in VPD during the nut maturation stage was associated with a decrease in whole kernel recovery, this could not readily be explained. VPD is negatively correlated with RH and the higher the VPD value, the higher transpiration, which could result in stomatal closure, and a decrease in CO_2 conductance and photosynthesis (Turner et al. 1984).

Kernel discolouration

Kernel discolouration of the different regions differed significantly as Penter et al. (2007a) found and is probably climatically determined. Kruger et al. (2013) analysed 12 years of data and found that the incidence of discolouration is higher during a wet cycle than during a dry cycle. In contrast, Penter et al. (2007a) observed an increase in discolouration in a non-irrigated 'Beaumont' orchard during dry spells and a decrease after rain.

The incidence of kernel discolouration increased with a decrease in crop load and is possibly correlated to harvest time. In seasons with high crop loads, harvesting is prolonged and nuts hang for longer on the tree before being harvested, or nuts lay longer on the ground before being picked up. Penter et al. (2007a) found that kernel discolouration occurs more commonly in the early part of the harvesting season on 'Beaumont' and it generally declines as the season progresses. Penter et al. (2001) however also found that some late hanging (March) nuts of *M. integrifolia* cultivars displayed discolouration, indicating that this disorder might be related to kernel maturity and increases with age, even when still on the tree.

The negative correlation of kernel discolouration and cross-pollination is difficult to explain. It could be that if kernel maturity is correlated to kernel discolouration as Penter et al. (2001) mentioned and cross-pollinated fruit are more likely to reach maturity compared to self-pollinated fruit (McConchie et al. 1997), which could explain the effect on kernel discolouration.

It is difficult to explain the high kernel discolouration associated with high Zn leaf concentration. Research on kernel discolouration found that severely discoloured kernel had elevated Mn and Fe levels inside the kernel (Kruger et al. 2003). Although in equation J, kernel discolouration was associated with an increase in leaf Mn concentration, Mn concentration was not significant in the final equation L. Shahriaripour and Tajabadipour (2010) found in pistachios that Zn deficient trees had significantly higher concentrations of Fe. By applying Zn, Fe concentration decreased, with similar results in Mn.

It is difficult to explain the correlation of high leaf N and low leaf K levels with high kernel discolouration. However, Kruger (2000) and Stephenson et al. (2000) reported that high N fertilizer applications resulted in poor kernel quality. Generally high leaf K concentration is correlated with increased kernel quality (Zeng et al. 2001). Although excessive K may be associated with a significant reduction in Mg and Ca levels, we know from equation J, although not significant in equation L, that low leaf Ca and high leaf Mg levels were associated with high kernel discolouration. Therefore we can assume by increasing K levels, it automatically lowered the Mg level and therefore decreased kernel discolouration.

Conclusion

Kernel recovery, whole kernel recovery and kernel discolouration are influenced by many factors including environmental, cultural, and nutritional. Generally however it appeared that lower photosynthate levels in the tree could be responsible for lower kernel recovery, and whole kernel recovery. To optimize kernel recovery, whole kernel recovery and kernel discolouration, the location of the farm in a specific region in the Lowveld is important. High altitude, inter planting cross pollinators, high yield, early season harvesting and processing of NIS, high leaf B concentrations in Nov. and water management with deficit irrigation should all increase kernel recovery. Excellent managed and applied micro sprinkler irrigation had a positive correlation with high kernel recovery, assuming that the previously mentioned factors were applied. High whole kernel recovery can be achieved by increasing kernel recovery, hastening harvesting and delivery to the processing plant, correct curing of NIS, increase leaf B and Cu concentrations and decreasing Mn leaf concentrations. Low kernel discolouration was enhanced by high yield, no cross pollination, low leaf N and Zn concentrations and high leaf K concentration. Although these models gave a clearer indication of which factors influence kernel recovery, whole kernel recovery and kernel discolouration more in-depth studies are needed to confirm the appropriateness of these suggested strategies to alleviate the problems.

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Table 1: Cites of different weather stations in macadamia production regions

Region	Weather station	Latitude (degrees)	Longitude (degrees)	Altitude (m)
Nelspruit	Nelspruit: ITSG	-25.45472	30.97144	650
Kiepersol	Burgershall: AWS	-25.10925	31.08384	739
Hazyview	Hazyview	-25.04885	31.14449	484
Barberton	Barberton: Moodies Estate	-25.81098	31.00744	801
White River	Mbombela: Zenzelenzi	-25.32808	30.97066	858
Pietermaritzburg	Cedara: PP	-29.54192	30.26494	1066

Table 2: Crop load classification for young macadamia trees (4 to 9 years since planting)

Tree age	Crop load (kg)		
	Low	Medium	High
4	≤ 1.5	between 1.5 and 2.5	≥ 2.5
5	≤ 3.0	between 3.0 and 4.5	≥ 4.5
6	≤ 5.0	between 5.0 and 7.0	≥ 7.0
7	≤ 6.0	between 6.0 and 9.0	≥ 9.0
8	≤ 7.0	between 7.0 and 11.0	≥ 11.0
9	≤ 9.0	between 9.0 and 12.5	≥ 12.5

Table 3: Summary statistics including the sample size (N), mean, standard deviation (std. dev.), standard error of the mean (SE) and significance category ($P < 0.05$) for the regions analysed

Outcome	Region	N	Mean	Std. dev.	SE	Significance category
KR *	Hazyview	17	29.30	2.45	0.59	a
	Barberton	190	31.58	1.81	0.13	b
	Nelspruit	327	32.53	2.09	0.12	c
	Pietermaritzburg	25	32.59	2.89	0.58	d
	White River	204	32.77	2.17	0.15	e
	Kiepersol	47	34.11	1.66	0.24	f
WKR *	Hazyview	17	27.26	5.30	1.29	a
	Kiepersol	47	29.29	4.93	0.72	a
	Barberton	190	29.93	6.83	0.50	ab
	Pietermaritzburg	25	32.50	6.88	1.38	b
	White River	204	33.49	5.94	0.42	c
	Nelspruit	327	33.88	6.86	0.38	c
KD *	Hazyview	16	3.79	1.61	0.40	a
	Barberton	186	5.70	3.93	0.29	ab
	White River	204	6.00	3.34	0.23	b
	Nelspruit	322	6.93	5.94	0.33	b
	Kiepersol	47	11.10	5.77	0.84	c
	Pietermaritzburg	24	12.22	4.49	0.92	c

* KR = kernel recovery; WKR = Whole kernel recovery; KD = Kernel discolouration

Table 4: Summary statistics including the sample size (N), mean, standard deviation (std. dev.), standard error of the mean (SE) and significance category (P < 0.05) for crop load analysed

Outcome	Crop load	N	Mean	Std. dev.	SE	Significance category
KR *	Low	181	31.14	2.15	0.16	a
	Medium	281	32.69	1.81	0.11	b
	High	348	32.81	2.26	0.12	b
WKR *	Low	181	29.73	6.00	0.45	a
	Medium	281	33.18	6.60	0.39	b
	High	348	33.18	6.94	0.37	b
KD *	High	344	6.01	5.34	0.29	a
	Medium	278	6.69	4.40	0.26	b
	Low	177	8.28	5.34	0.39	c

* KR = kernel recovery; WKR = Whole kernel recovery; KD = Kernel discolouration

Table 5: Summary statistics including the sample size (N), mean, standard deviation (std. dev.), standard error of the mean (SE) and significance category ($P < 0.05$) for the cross pollination probability analysed

Outcome	Cross pollination	N	Mean	Std. dev.	SE	Significance category
KR *	Absent	440	31.77	1.91	0.09	a
	Adjacent orchard	336	32.94	2.19	0.12	b
	Inter-planted	34	35.11	2.18	0.38	c
WKR *	Adjacent orchard	336	31.93	6.68	0.36	a
	Absent	440	32.53	6.68	0.32	a
	Inter-planted	34	35.54	7.95	1.36	b
KD *	Absent	432	5.30	3.77	0.18	a
	Adjacent orchard	333	8.44	6.00	0.33	b
	Inter-planted	34	8.61	3.82	0.66	b

* KR = kernel recovery; WKR = Whole kernel recovery; KD = Kernel discolouration

Table 6: Summary results from the post-hoc test following a generalized linear model (Gaussian distribution of errors and identity link function) of the kernel recovery and kernel discolouration in response to irrigation type and efficacy. The sample size (N), mean and standard deviation (std. dev.) as well as the corresponding grouping codes are shown (similar letters indicates non-significant differences, $P < 0.05$)

Outcome	Irrigation efficacy*type	N	Mean	Std. dev.	Significance category
KR*	Medium drip	24	31.6	2.09	c
	Excellent drip	46	31.76	1.54	ce
	Medium micro sprinkler	404	32.24	2.32	b
	Excellent micro sprinkler	191	32.27	1.55	bc
	Effective micro sprinkler	25	32.59	2.89	abc
	Ineffective drag line	45	32.67	2.52	abe
	Dry land	24	32.99	2.25	abe
	Ineffective micro sprinkler	21	33.52	1.72	ad
	Ineffective drip	30	34.33	2.6	d
KD*	Ineffective drag line	45	4.78	2.27	cde
	Excellent micro sprinkler	191	5.13	3.49	c
	Dry land	24	5.32	4.7	ce
	Medium drip	24	5.72	4.11	bcde
	Excellent drip	46	5.9	2.41	e
	Medium micro sprinkler	395	7.05	5.27	be
	Ineffective drip	29	9.35	3.67	a
	Effective micro sprinkler	24	12.22	4.49	be
	Ineffective micro sprinkler	21	14.72	10.05	a

* KR = kernel recovery; KD = Kernel discolouration

Table 7: Summary results from the post-hoc test a generalized linear model (Gaussian distribution of errors and identity link function of whole kernel recovery (%) in response the inter action of crop load and cross-pollination. The sample size (N), mean and standard deviation (std. dev.) as well as the corresponding grouping codes are shown (similar letters indicates non-significant differences, P < 0.05)

Outcome	Crop load	Cross-pollination	N	Mean	Std. dev.	SE	Significance category
WKR *	Low	Inter-planted	9	28.59	3.59	2.15	cd
	Low	Absent	108	29.71	6.16	0.62	cd
	Low	Adjacent orchard	64	29.92	6.06	0.81	d
	Medium	Adjacent orchard	129	31.36	6.54	0.57	cd
	High	Absent	180	32.37	6.68	0.48	bc
	High	Adjacent orchard	143	33.34	6.82	0.54	bde
	Medium	Absent	152	34.73	6.27	0.52	e
	High	Inter-planted	25	38.04	7.61	1.29	a
KD *	High	Absent	176	4.52	3.15	0.36	d
	Medium	Absent	152	5.35	3.84	0.38	d
	Low	Absent	104	6.54	4.31	0.46	f
	High	Adjacent orchard	143	7.55	6.98	0.39	af
	High	Inter-planted	25	7.70	3.58	0.94	acef
	Medium	Adjacent orchard	126	8.30	4.51	0.42	ace
	Low	Adjacent orchard	64	10.70	5.71	0.59	b
	Low	Inter-planted	9	11.13	3.47	1.57	e

* WKR = whole kernel recovery; KD = Kernel discolouration

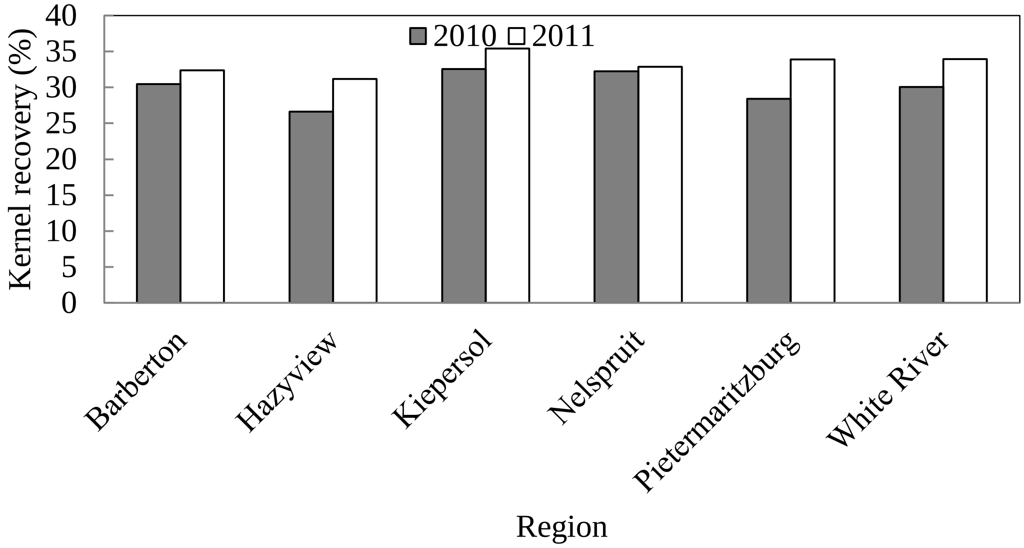

Figure 1: Mean kernel recovery of season 2010 and 2011 in 6 different macadamia producing regions

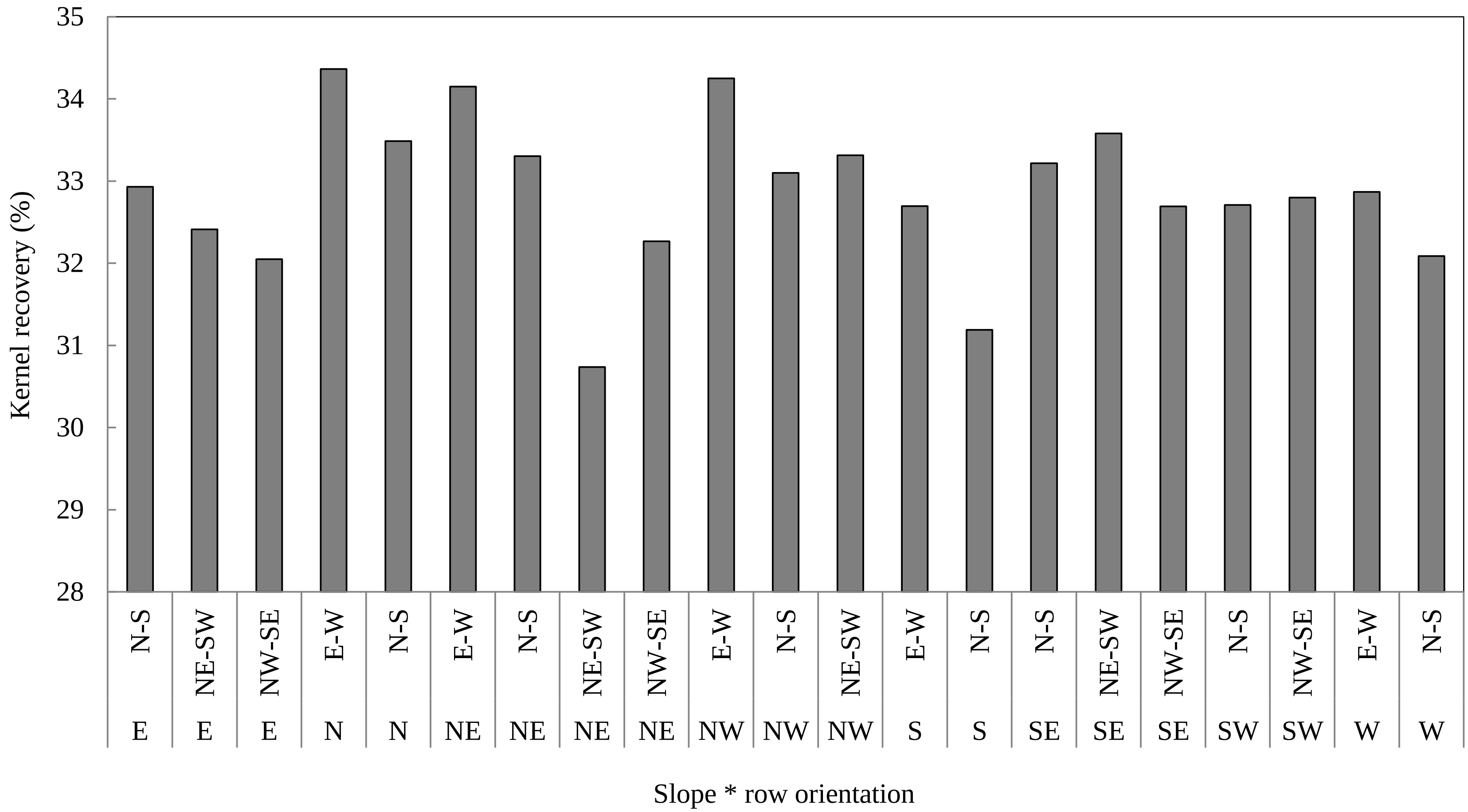

Figure 2: The effect of the interaction between slope and row orientation of a macadamia orchard on kernel recovery

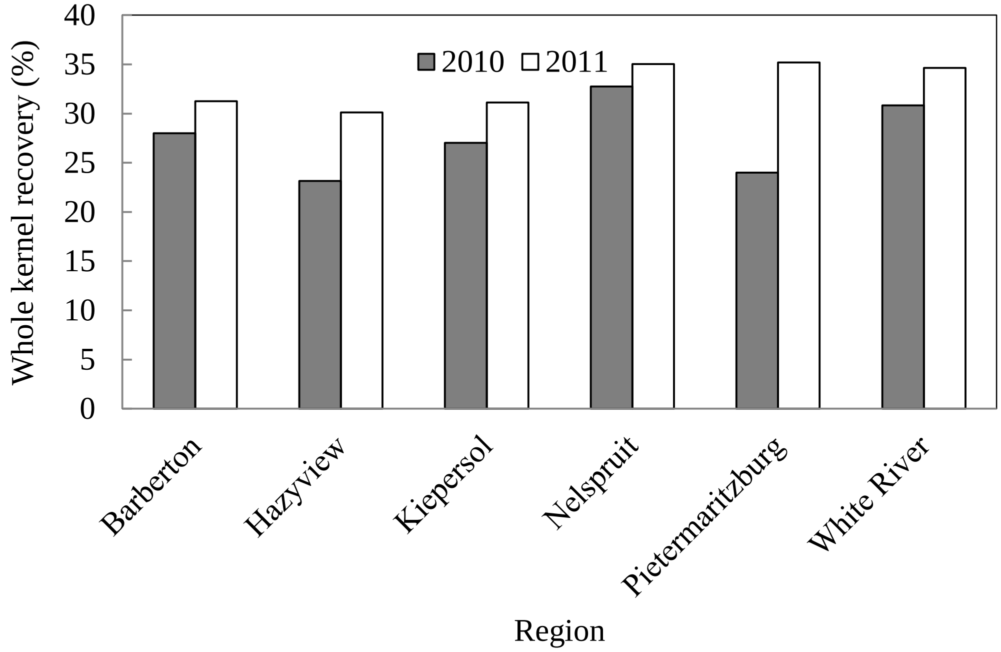

Figure 3: Mean whole kernel recovery of 2010 and 2011 in 6 different macadamia producing regions

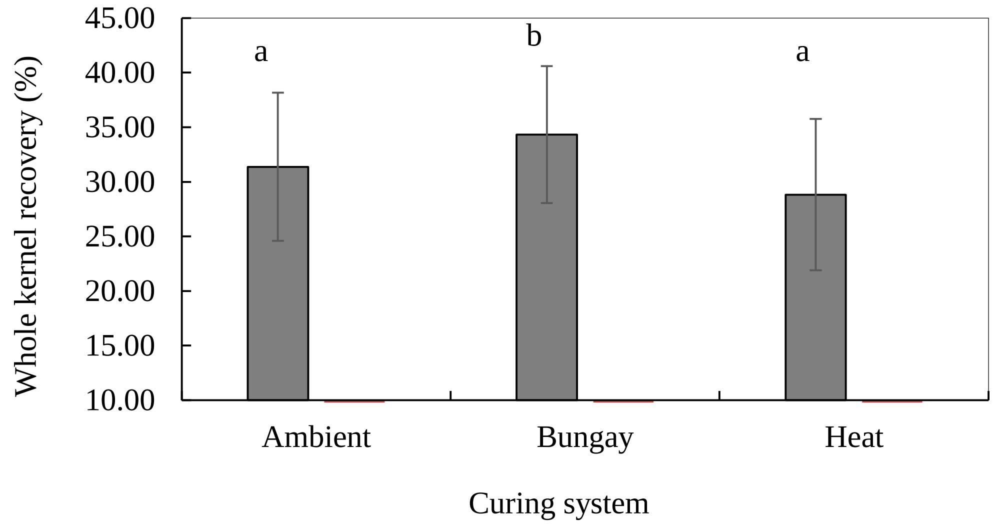

Figure 4: Effect of different curing systems on whole kernel recovery

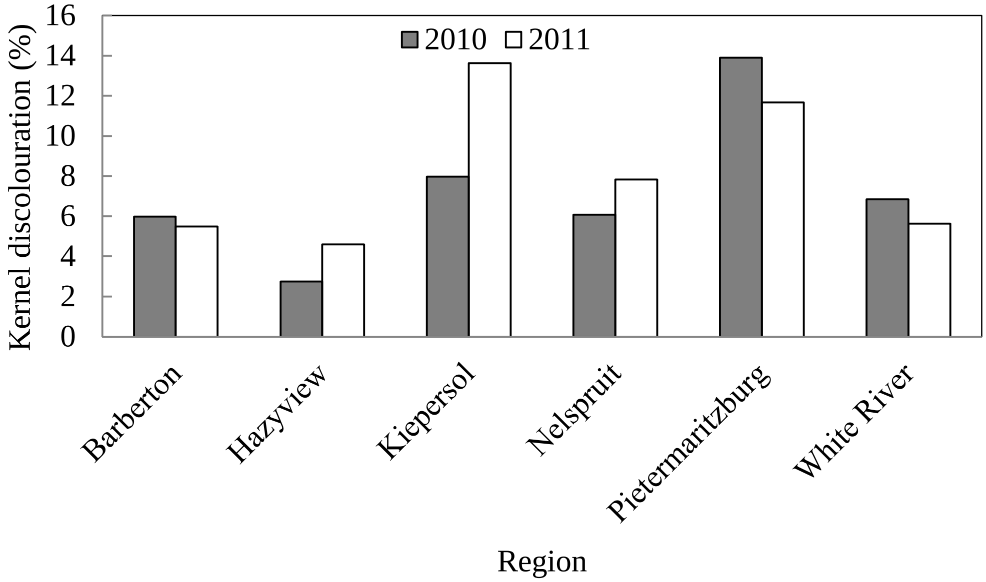

Figure 5: Mean kernel discolouration of 2010 and 2011 in 6 different macadamia producing regions

PAPER 2: THE EFFECT OF IRRIGATION LEVEL ON MACADAMIA KERNEL RECOVERY

Abstract

Macadamia trees can endure extended periods of drought, but water stress at different stages during fruit development could affect yield, kernel recovery and nut quality. Yield, nut quality and kernel recovery directly impact on the economic value of the crop. In this study water stress was induced in 'Beaumont' trees in a commercial orchard in the White River region by applying different levels of irrigation at different phenological stages, to determine if kernel recovery can be increased without decreasing the yield and nut quality. Two trials were conducted over two growing seasons (2011-2013) in the same orchard. In the first trial moderate water stress (66% irrigation) and over irrigation (198% irrigation) started 3 weeks after full bloom and ended after harvest. In the second trial moderate water stress (66% irrigation) was applied at different fruit development stages. Kernel recovery, yield and nut quality did not differ significantly between any of the treatments except that yield was increased during the 2011/12 season in the over irrigated plots, but not the following season.

Introduction

Macadamia is a genus in the family *Proteaceae*. Trees are evergreen and originate from the Australian coastal rainforests (Hardner et al. 2009). The edible species, *M. integrifolia* Maiden and Betche and *M. tetraphylla* L.A.S. Johnson are native to the rainforests of southern Queensland and northern New South Wales (Kaiser 2003). High annual rainfall occurs in Hawaii (1300 to 4800 mm) and northern New South Wales (1232 to 2283 mm) and therefore irrigation is not a common practice when cultivating macadamia in these regions (Trochoulias and Johns 1992). However, according to Schoeman (2011) the average annual rainfall of 819 mm in the Nelspruit region in Mpumalanga, South Africa, is insufficient for macadamia production and an additional 700 mm of irrigated water is required for optimal yield. Searle and Lu (2003) found that the cultivar HAES 741 required 40-55 L tree^{-1} day^{-1}, 10 to 30% more water than HAES 344 (35-40 L tree^{-1} day^{-1}) from end of flowering until nut maturity, while trees of both cultivars required 20-30 L tree^{-1} day^{-1} during the vegetative period, end of April to September (Southern Hemisphere). This additional water applied to the 'HAES 741' trees resulted in a significant increase in yield.

According to Stephenson et al. (2003), the macadamia tree has several characteristics, such as xeromorphic leaves with sclerified bundle sheath tissues and dense clusters of proteoid roots, which enable them to endure extended periods of drought. Stephenson et al. (2003) found that water stress at different stages of nut development will affect yield, kernel recovery and nut quality. Water stress during the premature nut drop period (21 days during November, Southern Hemisphere) increased kernel recovery; however it depressed the yield, while water stress during the nut maturation period decreased kernel recovery. On the other hand, Trochoulias and Johns (1992) reported that kernel recovery was not affected by irrigation treatments during their eight-year study, but annual rainfall was very high, ranging between 1232 and 2283 mm and irrigation was only applied 9 to 24 times per year.

Most (~97%) of the water used by plants is lost by transpiration and only a small amount (~2%) absorbed by the roots is used for plant growth while the remaining water (~1%) is used in photosynthesis and other metabolic processes (Taiz and Zeiger 2010). Plants are seldom fully hydrated, due to transpirational water loss and during periods of drought, plants suffer from water deficit and this could lead to inhibition of plant growth and photosynthesis. The process most affected during drought is cell expansion (Taiz and Zeiger 2010).

In almonds, water stress negatively affects the kernel size (Girona et al. 1993) but has a negligible effect on kernel dry weight (Goldhamer et al. 2006). Goldhamer et al. (1985) found that shell enlargement in pistachio nuts is sensitive to water stress. Irrigation was scheduled on crop evapotranspiration ((ETc) the sum of evaporation from the soil (E) and transpiration from leaves (T)) with full irrigation at 100% ETc. Nut size was reduced by severe water stress (0 and 25% ET_c), but little or no difference following mild water stress (50 and 70% ET_c). Goldhamer et al. (1990) evaluated walnut tree recovery and performance in the second season, after returning to full irrigation following three years of sustained deficit irrigation and found that trees that were previously irrigated at 33 and 66% ET_c produced larger nuts and higher kernel percentage (kernel recovery) than trees previously irrigated at 100% ET_c. However, Cohen et al. (1996) reported a decrease in walnut fruit size with the reduction of irrigation to 70% ET_c. Goldhamer et al. (1988) found that the walnut trees produced smaller nuts than control trees during the third year of sustained deficit irrigation at 66% ET_c.

The economic value of the macadamia crop is determined by the yield per tree, kernel recovery, and nut quality and nut style distribution. By increasing the kernel recovery, the kernel yield as a ratio of kernel to shell mass increases, leading to fewer nuts having to be cracked for the same amount of kernel (Hancock 1991). According to Hancock (1991), this is one of the reasons why growers are paid more for higher kernel recovery. The kernel recovery is determined by the nut size, shell thickness and therefore, weight of kernel and shell, and large nuts contain more kernel than small nuts if they have the same shell thickness.

According to Jones and Shaw (1943) the fruit structures are formed and the growth of the husk, shell and endosperm takes place during the first 90 days after flowering. Growth in fruit size continues until 12 to 15 weeks after anthesis until the shell hardens (Jones 1939; Trueman and Turnbull 1994). Growth occurs as a single sigmoidal curve with a rapid increase in flesh weight from 5 to 6 weeks after anthesis until 15 to 18 weeks when the shell hardens, there after no further increase in size occurs (Hancock 1991). Jones (1939) reported that by the time the shell starts to harden the fruit had already reached approximately 70 percent or more of its final fresh weight.

Other factors that impact on the economic value of macadamia are nut quality and style distribution. After cracking the nuts, kernels are sized into different styles, viz., whole, halves and chips or pieces (Weinert 1993). Increases in visual imperfections, and damaged and defected kernels result in increased sorting costs and increased fixed costs of production per unit mass of acceptable kernel and therefore decreased income per kg (Hardner et al. 2009). In addition first-grade kernel yield is sensitive and dependent on the environment, particularly temperature, water availability and other management practices. Stephenson et al. (1995) found that cultivars with low overall percentage of first-grade kernel were more sensitive to these environmental variations.

The objective of this study was to determine whether water stress during different fruit development stages of ‘Beaumont’ macadamia affects kernel recovery, yield or quality in macadamia.

Materials and Methods

Plant material and site

The study was conducted on the same ‘Beaumont’ trees over two seasons, 2011/2012 and 2012/2013, in a commercial orchard near White River (sub tropical; lat. 25°18′S, long. 30°56′E, 834 m.a.s.l.) in Mpumalanga, South Africa. The trees, on own roots, were planted in 2001 at a spacing of 6 x 3 m. The soil was classified as a Hutton soil (MacVicar 1991) with an orthic A and red apedal B horizon, ± 35% clay, a deep moderately drained (no permanent high water table) soil with no compaction or obstruction layers visible in the top 80 cm of soil volume. The infiltration rate of the soil is moderate due to a moderate-fine to moderate-coarse texture. Trees were irrigated with 40 L hr^{-1} micro sprinklers with a wetting radius of 1.5 m at 1.75 bar pressure. Irrigation scheduling was based on the capacitance probe (Aquacheck (Pty) Ltd, Durbanville, South Africa) readings and continuous data were logged of soil moisture content by an automated system. The probe was installed one month (September 2011) prior to the start of the trial in the control block. The probe had capacitance sensors at 10, 20, 30, 40, 60 and 80 cm. The maximum root activity was identified and the top 40 cm were classified as the root zone. The 60 and 80 cm sensors were classified as below root zone. Irrigation was applied when volumetric soil moisture content of the root zone in control plots reached 24%, calibrated according to soil type, texture and crop (Aquacheck (Pty) Ltd). An additional probe was installed in the 66% irrigation treatment but due to technical problems after a lightning storm all data was lost.

Treatments and trial design

Two trials were conducted with both designed in randomized complete blocks with 10 single tree plot replicates. Guard trees were left between plots. In the first trial two irrigation treatments were compared to the standard commercial irrigation scheduling (40 L hr^{-1}). These treatments were achieved using different nozzles sizes, 26.5 and 79 L hr^{-1} micro sprinklers, respectively (Table 1). Water applications in the moderate stress treatment (26.5 L hr^{-1} sprinkler) represent a 66% of standard irrigation in the hourly water application while the over irrigation treatment was achieved by increasing the application rate to 198% of standard application (79 L hr^{-1} sprinkler). Application started 3 weeks after full bloom (7 Oct. 2011 and 3 Oct. 2012, respectively) and ended after harvesting (14 April 2012 and 10 April 2013, respectively). Before and after the treatments irrigation was set at the normal standard (control) application rate as based on probe readings as discussed above.

In the second trial three treatments were applied (Table 2). Trees were moderately stressed (66% of standard irrigation) at different fruit development stages; 3 weeks after full bloom until end of premature nut drop, after premature nut drop until end of shell hardening and 3 weeks after full bloom until end of shell hardening as described in Table 2. Before and after the treatments irrigation was set at the normal standard (control) application rate.

Due to rainy weather plant water potential, stomatal conductance and photosynthesis readings could not be performed at the time that equipment was available from Stellenbosch University.

Data collection on field trial

Yield per tree, and average nut-in-shell (NIS) size, kernel recovery, style distribution and kernel discolouration per tree were determined. To determine yield per tree, nuts were stripped per tree (harvested), dehusked (husk removed) and weighed as wet-in-shell (WIS). WIS refers to freshly harvested nuts after removal of the husks and with a moisture content of 20 to 30% (Bungay, 2001). Samples of 5 kg WIS per tree were cured (dried) to 1.5% kernel moisture content under controlled relative humidity and temperature (Bungay, 2001). Dried nuts at 1.5% kernel moisture content are called dry-in-shell (DIS). Sampling equipment and procedures were facilitated by the Golden Macadamias (Pty) Ltd (Alkmaar, Mpumalanga, South Africa) processing plant. To determine the percentage NIS bigger than 20 mm in diameter, sizing was done by a size grader tumbler.

Samples were cracked with a mechanical Holiday cracker (WMC sheet metal works, Tzaneen, South Africa) to determine kernel recovery, style distribution, kernel discolouration and immaturity. Cracked shells and kernels or their fragments were separated with vibrating screens and blowers. Kernel recovery was determined by weight of kernel recovered from total NIS and expressed as a percentage (kernel NIS^{-1} x 100). Style distribution was done by sizing the kernel into different styles, viz., whole, halves and chips or pieces (Weinert 1993). The weight of each style was expressed as a percentage of the total kernel weight. Discolouration was hand sorted according to commercial grade colour charts (Golden Macadamias (Pty) Ltd). 'Distal-end browning' and 'onion ring' (Penter et al. 2007) were both classified as discolouration. Immature nuts were separated with the floatation test in brine solution (water) at specific gravity (SG) 1.025 (Grimwood 1971).

Hourly climatic data were collected electronically by the Agricultural Research Council - Institute of Soil, Climate and Water (ARC-ISCW) at Mbombela weather station: Zenzelenzi (lat. 25^{0}19´S, long. 30^{0}58´E, altitude 858 m.a.s.l.). The weather station is situated ± 4.4 km from the trial block.

Data analysis

The general linear models (GLM) procedure of the Statistical Analysis System (SAS Enterprise Guide 5.1) (SAS Institute, Cary, N.C., 2012) was used to analyse the data. Least significant differences (LSD) were used to compare treatment means when the ANOVA indicated significant differences ($P < 0.05$) between treatments.

Results and discussion

Rainfall and irrigation

The total rainfall during the trial period for the two seasons differed by 125 mm, with the total rainfall during the 2011/12 season the highest at 1065 mm compared to 940 mm during the 2012/13 season (Table 3). Although the 2011/12 season had the higher total rainfall, most (724 mm) fell during the shell hardening stage compared to a more even distribution over the fruit development stages during the 2012/13 season (Table 3). The total rainfall of 76 mm during the 2011/12 season during the premature nut drop stage was much lower than the 271 mm during the 2012/13 season (Table 3; Figure 1).

During the 2012/13 season only 11 irrigation applications were made during the trial period (3 Oct. 2012 to 10 Apr. 2013) and 14 applications during the 2011/12 season (7 Oct. 2011 to 14 Apr. 2012) (Table 4). These applications were made when volumetric soil moisture content in the root zone of the control plots reached 24%. Of the three extra applications during the 2011/12 season, two were during the premature nut drop stage and one during the shell hardening stage.

The probe data indicated a lower volumetric soil moisture content below the root zone during the premature nut drop stage (7 Oct. to 15 Nov. 2011) during the 2011/12 season and a steady increase during Sept. prior to the premature nut drop stage (3 Oct. 2012) during the 2012/13 season which corresponded with high and regular rainfall (Figure 2). The volumetric soil moisture content below the root zone during the premature nut drop stage was lower in 2011/12 compared to 2012/13 (Figure 2). Unfortunately the data between 11 and 15 Oct. 2011 and 1 to 23 Jan. 2013 were lost due to technical problems with the probe.

Considering the relatively high and evenly spread rainfall and therefore few irrigation applications, we conclude that although tree water stress was not measured (midday stem xylem water potential or pre-dawn water potential) that moderate water stress (66% irrigation) was difficult to achieve. Also the over irrigated plots were probably not always much wetter than the control and therefore irrigation treatments could not be achieved as envisaged.

The total relative evapotranspiration for the 2011/12 season was 735 mm compared to the 705 mm of the 2012/13 season. This difference between the two seasons came about during the nut maturation stage when 27 mm more total relative evapotranspiration was recorded during the 2011/12 season (Table 5). The 74.3% average hourly relative humidity during the nut maturation stage of the 2012/13 season was higher than the 71.2% during the 2011/12 season (Figure 3). Considering the data above it is concluded that the nut maturation stage in 2012/13 was wetter than during 2011/12.

Kernel recovery and nut size

No significant differences in kernel recovery were found between the different levels of irrigation during the 2011/12 (Table 6) and 2012/13 seasons (Table 7). Moderate water stress at different fruit development stages also did not result in significant differences in kernel recovery during the 2011/12 (Table 8) and 2012/13 seasons (Table 9). As mentioned above the actual treatments could not be successfully applied due to high and continued rainfall. Trochoulias and Johns (1992) found similar results with high annual rainfall ranging between 1232 and 2283 mm compared to the 940 and 1065 mm in our study. They had to use supplementary irrigation when evapotranspiration exceeded rainfall only 9 to 24 times per year during their 8-year study. Gregorio et al. (2009) also found no differences in kernel fraction (kernel recovery) in almond between five irrigation treatments: full irrigation, regulated deficit irrigation (50% of ETc during the kernel-filling stage) and three partial root zone drying treatments, irrigated at 70%, 50% and 30% ETc, respectively, during the whole growth season with Mediterranean semi-arid weather (±364 mm rainfall). Stephenson et al. (2003) however recorded an increase in macadamia kernel recovery with water stress during the premature nut drop stage, while water stress during the nut maturation period decreased kernel recovery. Their trial was conducted in a lysimeter facility with controlled mild water stress (xylem water potential of -1.5 to 2.0 MPa) at various phenological stages and was therefore more reliable than our field trials. As previously mentioned kernel recovery is determined by the nut size, shell thickness and therefore, weight of kernel and shell, and large nuts contain more kernel than small nuts if they have the same shell thickness. Possibly due to the lack of differences in soil moisture induced by our irrigation treatments no significant differences in average size of NIS bigger than 20 mm were found (Table 6, 7, 8 and 9). No significant differences were found in nut size between the two seasons (Table 10 and 11). Goldhamer et al. (1990) found that walnut trees produced larger nuts when deficit irrigation (33 and 66% $ET_{c)}$ was applied and followed up with two years of full irrigation. Goldhamer et al. (1990) suggested that the size may be affected by the stress levels and crop load.

An overall increase in kernel recovery of 3.1 and 2.7% was found from the 2011/12 to the 2012/13 season, respectively (Table 10 and 11). Trochoulias and Johns (1992) also found that kernel recovery fluctuated between 33.7 and 38.7% in their eight-year study on different irrigation schedules in Australia. In Paper 1 we reported that kernel recovery can be affect by a wide range of factors: altitude, cross-pollination, yield, time of harvesting, water and boron nutrient levels.

Whole kernel recovery

Whole kernel recovery was not significantly influenced by irrigation treatments (Table 6, 7, 8 and 9) or season (Table 10 and 11). This could either be because we could not induce differences in moisture content as planned or that, as stated in Paper 1 only harvesting time, curing procedures, tree nutrition and according to literature cultivar differences and rough handling have an effect on whole kernel recovery. Rough handling included dropping the NIS at 3% (cracking moisture) and 15% (harvesting moisture) moisture content on hard surfaces and dehusker damage (Penter et al. 2008). In Paper 1 however we found a positive correlation between whole kernel recovery and kernel recovery but as kernel recovery was not influenced by our irrigation treatments this could not be confirmed in this study.

Discolouration

Irrigation treatments had no significant effect on the kernel discolouration (Table 6, 7, 8 and 9). Kernel discolouration was however higher in 2011/12 than in 2012/13 (Table 10 and 11). According to Paper 1, low kernel discolouration is correlated to high yield.

Yield in this study increased from 2011/2012 to 2012/2013 as discussed below. Kruger et al. (2013) found that the incidence of discolouration is higher during a wet season than during a dry season. They analysed data on kernel discolouration for 2001 to 2013 in the Nelspruit area, and correlated it to climatic data. They concluded that, as literature indicated elevated levels of immobile elements (Fe and Mn) in discoloured kernels, these immobile elements would require wet conditions for uptake. As mentioned earlier the 2012/13 nut maturation stage was wetter than in the corresponding stage in 2011/12 season possibly explaining this increase in kernel discolouration. In contrast, Penter et al. (2007) observed an increase in discolouration during dry spells and a decrease after rainfall in a non-irrigated 'Beaumont' orchard.

Yield

The 198% irrigation treatment significantly increased the total DIS yield per tree by 43% compared to the untreated control during the 2011/12 season (Table 6), however this was not the case in 2012/13 (Table 7). No other significant effects were found on yield during 2011/12 and 2012/13 season in trial 1 or 2 (Table 6, 7, 8 and 9). Stephenson et al. (2003) found that yield in water stressed trees during the premature nut drop stage tended to be lower than well watered trees, therefore the higher yield on the 198% irrigated plots during a drier season confirms this and indicates that the 100% irrigation treatment could not have been enough during this season. Water stress on other nut types also affected yield negatively; almond (Goldhamer and Smith 1995), pistachio (Kanber et al. 1993) and pecan (Garrot et al. 1993). However, Trochoulias and Johns (1992) found that all 5 irrigation treatments (sprinkler rates of 30, 78, 108, 180 and 234 L h^{-1}) according to evapotranspiration needs on macadamia, reduced NIS yield per unit trunk slightly, but it failed to show any consistent effect. According to Huett (2004) with the variable and cyclical yield of macadamia, a minimum of five years is needed to demonstrate yield responses, in a well-designed field trial.

The overall total DIS yield per tree increased from 2012 to 2013 season by 128% in trial 1 (Table 10) and 90% in trial 2 (Table 11). Hail storms were recorded on 16 Oct. 2011 and early Feb. 2013 (Du Toit, 2013). The hail storm in 2011 did knock off some of the newly formed fruit per tree; unfortunately it is very difficult to determine the actual loss at this very early stage of fruit development, due to the small (needle) size of the fruit.

Kernel immaturity

Irrigation treatments had no significant effect on the percentage immature kernel (Table 6, 7, 8 and 9). As mentioned earlier, the incidence of immature kernel decreased from 2011/12 to 2012/13 (Table 10 and 11). Although the hail storm in early February 2013 was not very severe (Du Toit, 2013) hail damage to husks before maturity would have increased the incidence of immature kernel (Gallagher et al. 2003; Jones 1994) in the 2013 season, rather than decreasing it. The decrease in immature kernel could have been influenced by the wetter 2012/13 nut maturation stage compared to the 2011/12 season.

Average kernel mass is used to describe kernel size and Hardner et al. (2009) reported that Mason and Wills (1983) recorded a significant relationship between kernel size and oil content, therefore kernel mass is reduced if immature kernels are present in the NIS sample. As mentioned earlier, kernel recovery is determined by weight of kernel recovered relative to NIS weight and it could therefore be assumed that kernel recovery could be influenced by the percentage immature kernels. The percentage immature kernel was less in 2012/13 (Table 11) compared to 2011/12 (Table 10) and this could have resulted in the higher kernel recovery observed in 2012/13. The yield increase from the 2011/12 to 2012/13 season (Table 10 and 11) could also be correlated to the higher kernel recovery as mentioned by McFadyen et al. (2004). This is substantiated by the correlation Wilkie (2009) found between kernel recovery and yield efficiency (kg NIS m^{-3}), when he presented yield on a canopy volume basis. Stephenson et al. (2000) also noted that in years with poor yields, kernel recovery tended to be low and in years with above average yields, kernel recovery tended to be higher. The kernel recovery was not affected by the different water stress treatments during the two seasons, but the increase from 2012 to 2013 season was influenced by the yield increase, decrease of immature kernel and other unknown factors such as climatic conditions and tree age as mentioned earlier.

Conclusion

Although water stress at different levels and fruit development stages did not show any effect on kernel recovery and quality, one has to consider that irrigation deficit trails in the Lowveld during the summer rainfall period is challenging. Yield was increased by the 198% irrigation treatment during a drier pre mature nut drop stage in 2012 season, but not when a wetter corresponding period during 2013 was experienced. Moderate water stress throughout the season and at different fruit development stages did not influence yield but one has to bear in mind that actual water stress probably did not occur and could not be confirmed using plant water measurements. Future trials could consider rain covers although Stephenson et al. (2003) found some inconsistent results due to the lack of evaporation and the effect of buffering soil moisture. More severe water stress could be considered to increase kernel recovery, but yields and growth could then be affected. Variation in soil and rainfall will hamper the effectiveness of on-farm water stress and more practical and effective methods to increase kernel recovery should be investigated.

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Table 1: Different irrigation treatments applied in first trial

Treatment	Sprinkler type L hr $^{-1}$	Percentage irrigation relative to standard control %
Control	40	100%
Moderate stress	26.5	66%
Over irrigated	79	198%

Table 2: Irrigation treatments used in trial 2 indicating at which fruit development stage moderate water stress was applied

Treatment	Season	Fruit development stages		
		Premature nut drop	Shell hardening	Nut maturation
	2011/12	7 Oct. - 15 Nov.	16 Nov. – 18 Jan.	19 Jan. – 14 Apr.
	2012/13	3 Oct. - 11 Nov.	12 Nov. – 14 Jan.	15 Jan. – 10 Apr.
Control		100%	100%	100%
Stage 1		66%	100%	100%
Stage 2		100%	66%	100%
Stage 3		66%	66%	100%

Table 3: Total rainfall for two separate seasons during the different fruit development stages at Mbombela weather station: Zenzelenzi

Season	Total rainfall (mm)			
	Premature nut drop	Shell hardening	Nut maturation	Total
2011/12	76	724	265	1065
2012/13	271	278	391	940

Table 4: Number of irrigation applications for the 2011/12 and 2012/ 2013 season during the different fruit development stages

Season	Irrigation applications			
	Premature nut drop	Shell hardening	Nut maturation	Total
2011/12	4	3	7	14
2012/13	2	2	7	11

Table 5: Total relative evapotranspiration for two separate seasons during the different fruit development stages at Mbombela weather station: Zenzelenzi

Season	Total relative evapotranspiration (mm)			
	Premature nut drop	Shell hardening	Nut maturation	Total
2011/12	133	241	361	735
2012/13	134	237	334	705

Table 6: Effect of irrigation treatments on kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield per tree and immature kernel of 'Beaumont' macadamia nuts in the White River region during 2011/12

Treatment	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
Control *	29.58	ns	92.69	ns	26.23	ns	8.58	ns	3.08	b	4.53	ns
Moderate stress **	29.80		91.78		25.56		10.60		2.84	b	4.43	
Over water ***	30.00		92.24		24.71		8.85		4.41	a	4.27	
Pr > F	*0.3730*		*0.5907*		*0.6053*		*0.2303*		*0.0408*		*0.9646*	

ns Not significant
* Irrigate with 40 L hr^{-1} micro sprinkler according to probe readings and scheduling.
** Irrigate with 26.5 L hr^{-1} micro sprinkler per tree.
***Irrigate with 79 L hr^{-1} micro sprinkler per tree.

Table 7: Effect of irrigation treatments on kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield per tree and immature kernel of 'Beaumont' macadamia nuts in the White River region during 2012/13

Treatment	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
Control *	33.01	ns	93.07	ns	27.30	ns	25.03	ns	7.97	ns	1.45	ns
Moderate stress **	32.77		93.14		27.30		24.23		7.88		1.39	
Over water ***	32.92		94.00		25.70		25.22		7.66		1.45	
Pr > F	*0.8247*		*0.4599*		*0.3035*		*0.9220*		*0.8914*		*0.9521*	

ns Not significant
* Irrigate with 40 L hr^{-1} micro sprinkler according to probe readings and scheduling.
** Irrigate with 26.5 L hr^{-1} micro sprinkler per tree.
***Irrigate with 79 L hr^{-1} micro sprinkler per tree.

Table 8: Kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield and immature kernel of 'Beaumont' macadamia nuts in the White River region following moderate stress treatments during different fruit development stages in 2011/12

Treatment	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
Control *	29.65	ns	94.74	ns	24.19	ns	10.35	ns	4.64	ns	4.02	ns
Moderate stress during nut set **	29.73		92.08		25.32		9.21		3.76		3.57	
Moderate stress during shell hardening **	29.83		94.05		25.86		9.61		4.27		4.05	
Moderate stress during nut set and shell hardening **	30.45		93.10		25.71		8.36		4.29		3.03	
Pr > F	*0.0690*		*0.1909*		*0.5613*		*0.6486*		*0.5751*		*0.7191*	

ns Not significant

* Irrigate with 40 L hr^{-1} micro sprinkler according to probe readings and scheduling.

** Irrigate with 26.5 L hr^{-1} micro sprinkler per tree.

Table 9: Kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield and immature kernel of 'Beaumont' macadamia nuts in the White River region following moderate stress treatments during different fruit development stages in 2012/13

Treatment	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
Control *	32.15	ns	93.13	ns	27.38	ns	25.02	ns	8.39	ns	1.29	ns
Moderate stress during nut set **	32.73		93.82		27.06		26.91		7.99		1.51	
Moderate stress during shell hardening **	32.84		93.23		27.86		25.20		7.95		1.48	
Moderate stress during nut set and shell hardening **	32.57		92.77		26.43		26.54		7.95		1.53	
Pr > F	*0.1573*		*0.4779*		*0.8609*		*0.9036*		*0.8349*		*0.8510*	

ns Not significant
* Irrigate with 40 L hr^{-1} micro sprinkler according to probe readings and scheduling.
** Irrigate with 26.5 L hr^{-1} micro sprinkler per tree.

Table 10: Mean of kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield per tree and immature kernel of 'Beaumont' macadamia nuts in the White River region during 2011/12 and 2012/13, trial 1

Season	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
2011/12	29.79	b	92.24	ns	25.50	ns	9.34	b	3.44	b	4.41	a
2012/13	32.90	a	93.40		26.77		24.83	a	7.83	a	1.43	b
Pr > F	*<.0001*		*0.0837*		*0.1083*		*<.0001*		*<.0001*		*<.0001*	

ns Not significant

Table 11: Mean of kernel recovery, sizing, whole kernel recovery, kernel discolouration, total DIS yield per tree and immature kernel of 'Beaumont' macadamia nuts in the White River region during 2011/12 and 2012/13, trial 2

Season	Kernel recovery (%)		Sizing (>20mm) (%)		Whole kernel recovery (%)		Kernel discolouration (%)		Total DIS yield (Kg tree^{-1})		Immature kernel (%)	
2011/12	29.91	b	93.49	ns	25.27	b	9.38	b	4.24	b	3.67	a
2012/13	32.57	a	93.24		27.18	a	25.92	a	8.07	a	1.45	b
Pr > F	<.0001		0.6302		0.0181		<.0001		<.0001		<.0001	

ns Not significant

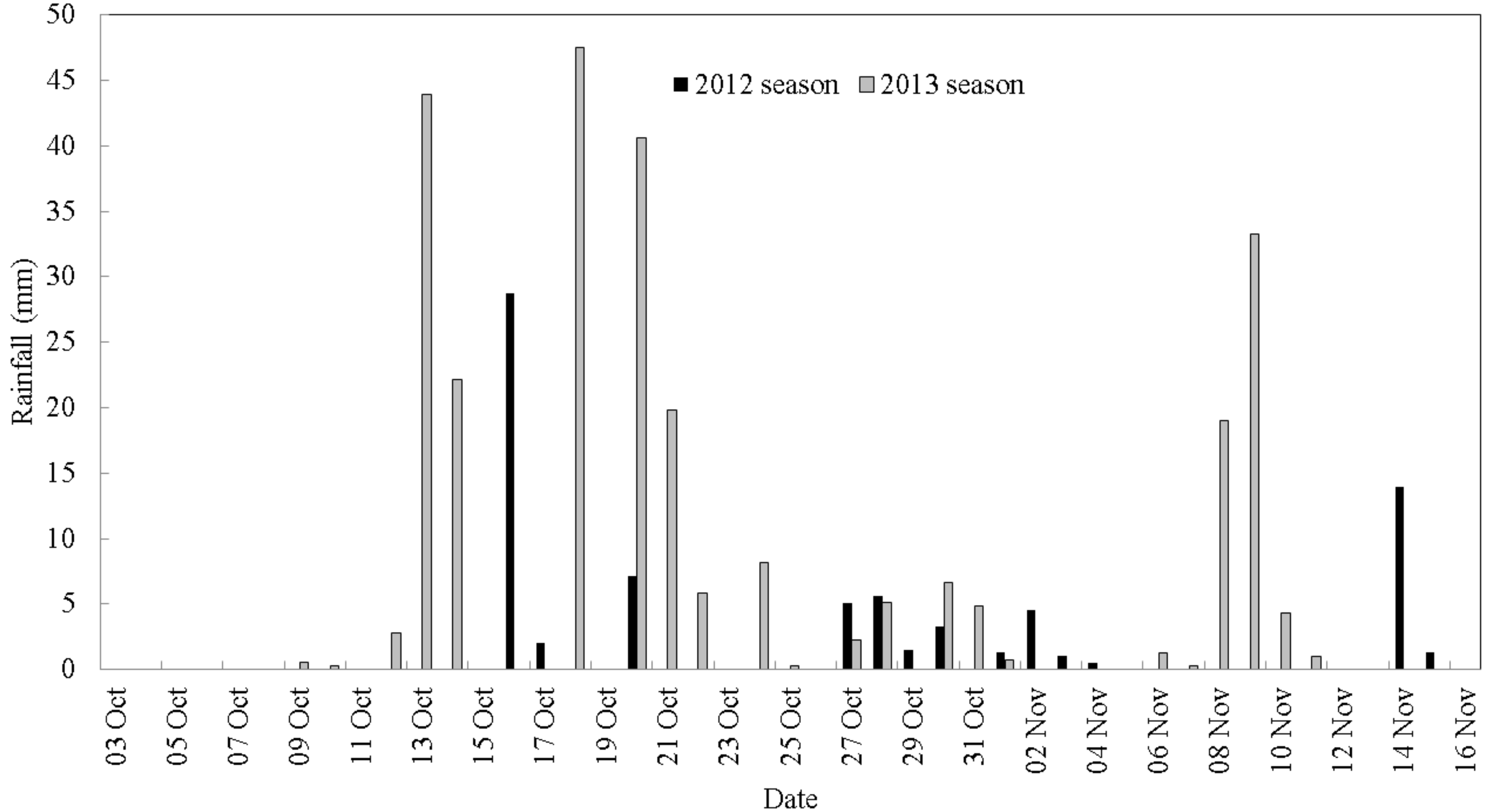

Figure 1: Total rainfall per day for two separate seasons during the premature nut drop stage at Mbombela weather station: Zenzelenzi

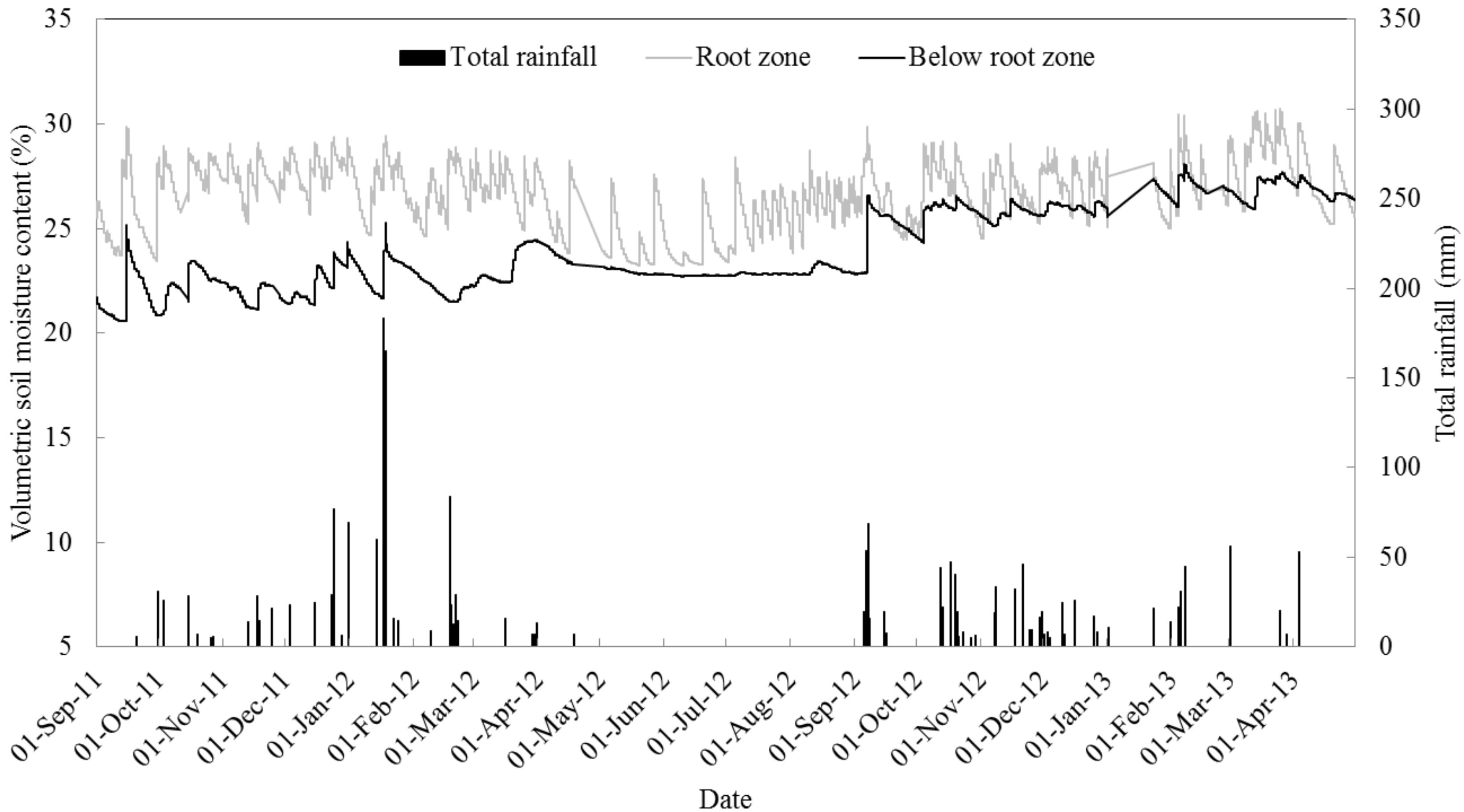

Figure 2: Volumetric soil moisture content (%) measured in trial plot in White River region and total rainfall (mm) measured at Mbombela weather station: Zenzelenzi from 1 Sept. 2011 until 1 Apr. 2013

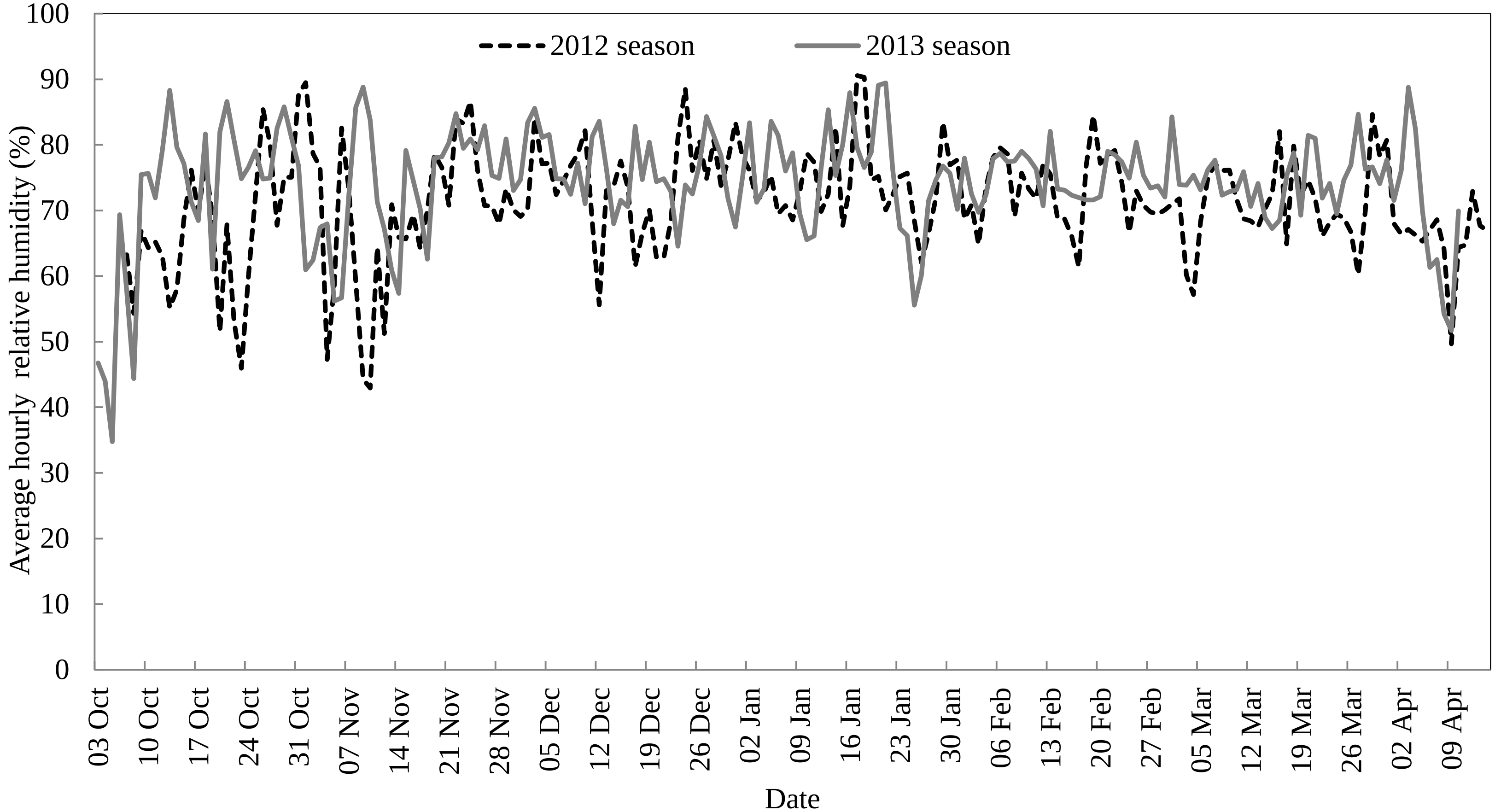

Figure 3: Average hourly relative humidity per day of year for two separate seasons as determined at Mbombela weather station: Zenzelenzi

PAPER 3: THE EFFECT OF KAOLIN FOLIAR APPLICATION ON KERNEL RECOVERY AND PHOTOSYNTHESIS OF MACADAMIA CV. BEAUMONT TREES

Abstract

Macadamia trees have a narrow temperature range for optimal photosynthesis and growth, and beyond this range they are sensitive to high temperatures. High temperatures (>30 ^{o}C) reduce kernel recovery. Kernel recovery is determined by shell thickness and nut size, i.e. large nuts will contain more kernel than small nuts, if shell thickness is the same. Increase in kernel recovery leads to fewer nuts to be cracked for the same amount of kernel, which results in lower cost per unit kernel and higher returns. In this study, kaolin foliar application was evaluated for heat stress reduction, which in return should increase kernel recovery without reducing yield, nut quality and tree photosynthesis. Two experiments were conducted, the first experiment near Barberton in Mpumalanga, during the 2011-2012 season in a six-year-old 'Beaumont' commercial orchard. Three kaolin foliar treatments were applied, viz. 12.5 g L^{-1} applied twice (10 and 31 October 2011), 25.0 g L^{-1} applied on 10 October 2011, and 12.5 g L^{-1} applied on three dates (10, 31 October and 21 November 2011). Kaolin applications did not significantly affect kernel recovery, nut yield or quality. Temperature during the study was not continuously high (>30 ^{o}C), thus heat stress could not be mitigated. In the second experiment the rate of photosynthesis was determined at different light levels following the application of kaolin on one-year-old 'Beaumont' nursery trees. Photosynthesis was not reduced by applications of 1, 3 and 5 layers of kaolin at irradiation of 200, 800 and 1800 µmol $m^{-2}s^{-1}$.

Introduction

Macadamia is a medium sized, evergreen tree that belongs to the *Proteaceae* family and is grown commercially in frost free tropical or subtropical regions (Hancock 1991). Mature macadamia trees can adapt to short spells of high summer temperatures, as it survived the 20-day heat wave in California with temperatures above 38 ^{0}C (Trochoulias and Lahav 1983). However, it has a relatively narrow temperature range for optimal growth (Trochoulias and Lahav 1983) and photosynthesis between 16 and 25 ^{0}C and photosynthesis decreases beyond 26 ^{0}C and reaches zero at 41 to 43 ^{0}C (Allan and De Jager 1978). Trochoulias and Lahav (1983) reported that new leaf growth contributed most to total dry matter between 20 and 25 ^{0}C, while temperatures above 30 ^{0}C were detrimental to dry mass accumulation.

World production of macadamia kernels was estimated at 27 639 metric ton in 2009 and although this represents only 1% of the world nut kernel market (INC 2010), it is one of the highest priced processed nuts available (Grimwood 1971, Duncan 2011). Growers therefore cultivate macadamias in climatic regions that are not really suitable. In most of the South African growing regions, primarily the Lowveld, the temperature regularly exceeds 30 ^{0}C (Alberts 2004). High temperatures like these increase respiration rate and induces premature nut drop. Allan and De Jager (1978) measured the respiration rate at night and found that CO_2 production rate was 75% higher at 29 ^{0}C compared to 18 to 19 ^{0}C. Stephenson and Gallagher (1987) found that where water was not limited (leaf water potential above 0.5 MPa), temperatures of 30 ^{0}C and higher increased premature nut drop compared to lower temperatures.

Temperatures also influence kernel recovery. High temperatures in the three months after flowering result in early shell hardening and small nuts (Hancock 1991). Stephenson and Gallagher (1986) found that kernel recovery was high at a day temperature of 30 ^{0}C, compared to day temperatures of 15, 25 and 35 ^{0}C, but the nut quality was low with 30.3% immature nuts (<72% oil in the kernels). Kernel recovery, kernel growth and oil content were low at 15 and 35 ^{0}C, the kernel recovery and weight declined at temperature of 35 ^{0}C and most kernels contained less than 72% oil.

Heat stress in macadamia might not be relieved by abundant soil moisture at temperatures above 30 ^{0}C, due to slow absorption of moisture by the roots and the high transpiration rate (Alberts 2004). Evaporative cooling can however reduce the stress of high temperatures (>30 ^{0}C) that reduces macadamia kernel recovery, and the percentage first grade kernels in 'Beaumont' (Allan 1996).

Application of reflecting substances e.g. kaolin clay, could be more practical to apply than evaporative cooling to reduce high temperatures (>30 ^{0}C) (Alberts 2004). According to Rosati et al. (2006), particle film applications, including kaolin, have been used on different crops to limit the impact of heat and water stress. The reflective mineral-based (kaolin) particle film technology (PFT) reflects ultraviolet, photosynthetically active radiation (PAR) and infrared (IR) radiation (Glenn 2012). Glenn (2012) concluded that canopy temperature could be reduced, as much as 5 ^{0}C by the reflection of IR radiation, which would reduce transpiration and heat stress. The reduction of canopy temperature and heat stress resulted in reduced water use efficiency (WUE), defined as unit of assimilated carbon per unit of transpiration, in apple (Glenn 2010), however the WUE increased in citrus (Jifon and Syvertsen 2003). Although PAR is reduced by the reflection at leaf level, it compensates with increasing incident radiation on the inner canopy leaves and combined with reduced canopy temperature it can increase the whole canopy photosynthesis (Glenn 2012).

Contradicting results have been found with kaolin application in other crops. Applications at times resulted in increased yields, e.g. apple (Glenn et al. 2001), blueberry (Spiers et al. 2005) and coffee (Steiman et al. 2007) while no effect on total yield was found in pecan (Lombardini et al. 2005), tomato (Cantore et al. 2009) and pepper (Russo and Díaz-Pérez 2005). Applications of kaolin increased fruit weight in apple (Glenn et al. 2001), tomato (Cantore et al. 2009) and pistachio (Azizi et al. 2013) while no effect or a reduction was found in coffee (Steiman et al. 2007), pecan (Lombardini et al. 2005) and blueberry (Spiers et al. 2005). Steiman et al. (2007) suggested that this inconsistency may be linked to variation in application techniques and kaolin coverage, which subsequently affects the leaf temperature, light reflection and photosynthesis.

Nut size (nut weight) and shell thickness determine kernel recovery; therefore large nuts contain more kernel than small nuts with the same shell thickness (Hancock 1991). Higher kernel recovery means that more kernels is sellable per unit nut-in-shell (NIS), and also directly reduces processing cost (Hardner et al. 2009).

The objective of this study was to determine whether foliar kaolin application would reduce heat stress under hot growing conditions in a commercial 'Beaumont' macadamia orchard to such an extent that kernel recovery is improved, without negatively affecting the quality and yield. In addition leaf photosynthesis was measured.

Materials and Methods

Plant material and site

A commercial six-year-old 'Beaumont' orchard near Barberton (subtropical; lat. 25°48′S, long. 31°00′E, altitude 801 m.a.s.l.) in Mpumalanga was used. The orchard has a gentle West-Northwest facing slope (gradient ± 5-10%). The trees, on own roots, were planted in 2005 on a soil ridge, 2 m wide and 0.8 m high, at a spacing of 6 x 3 m in a North-South row direction. The ridge is well-drained with ± 30% clay with no obstruction layer visible and covered with 2 cm wood chip mulch. Trees were irrigated with 40 L hr^{-1} micro sprinklers with a wetting radius of 1.5 m at 1.75 bar pressure. Irrigation scheduling was based on capacitance probe (DFM software solutions, Stellenbosch, South Africa) readings, with sensors at 10, 20, 30, 40, 60 and 80 cm. The maximum root activity was identified and the top 40 cm classified as the root zone. Continuous monitoring of soil moisture content within and below the rooting zone facilitated optimal irrigation scheduling. The orchard received routine horticultural practices including fertilization, irrigation, and weed and pest control.

Treatments and trial design

Kaolin (Screen Duo™) (Crop Microclimate Management, North Carolina, U.S.A.) was applied at 2500 L ha^{-1} as a light-cover foliar spray to just before runoff with a handheld spray gun, targeting the outer leaf canopy. Screen Duo™ is a combination of refined kaolin and salicylate. A non-ionic surfactant, Biodew®, (a.i. alcohol alkoxylate; Plaaskem (Pty) Ltd, Lilianton, Boksburg, South Africa) was added at a rate of 15 g L^{-1} to all kaolin applications. Three kaolin treatments were applied, viz. 12.5 g L^{-1} applied twice (10 and 31 October 2011), 25.0 g L^{-1} applied on 10 October 2011, and 12.5 g L^{-1} applied three times (10 , 31 October and 21 November 2011) (Table 1). The experimental design was a randomized complete block design consisting of ten single-tree replicates. Guard trees were left between plots.

Due to rainy weather at the time when photosynthesis was supposed to be measured in the field trial, a second trial was performed. In this trial kaolin, at a concentration of 12.5 g L^{-1}, was applied to the leaves of five one-year-old 'Beaumont' nursery trees and photosynthetic rate determined using the LI-6400XT photosynthesis system (LiCor, Nebrasca, U.S.A.). One, three and five layers of kaolin were applied to two leaves per tree. One leaf per tree was covered during kaolin application to serve as untreated control. Photosynthesis was measured before the application of kaolin to serve as a baseline indicator of photosynthetic rates of the trees. Subsequent photosynthesis was measured on the one untreated and two treated leaves per tree, after kaolin layers had dried completely. Measurements were done at three light levels (200, 800 and 1800 µmol m^{-2} s^{-1}), a block temperature of 25°C, air flow rate of 400 µmol.s^{-1} and CO_2 concentration of 380 µmol mol^{-1}. All measurements were recorded between 09h30 and 17h30 on 10 October 2014.

Data collection on field trial

Hourly climatic data were collected electronically by the Agricultural Research Council - Institute of Soil, Climate and Water (ARC-ISCW) at Barberton weather station: Moodies Estate (lat. 25°48′S, long. 31°00′E, altitude 801 m). The weather station is situated ± 100 m from the trial block.

Nuts were harvested on 30 April 2012 by strip-picking all nuts from a tree. Nuts were dehusked and weighed as Wet-in-Shell (WIS). Samples of 5 kg per tree were cured (dried) to 1.5% kernel moisture content, under controlled atmosphere (controlled relative humidity and temperature) (Bungay, 2001). Yield per tree, nut-in-shell (NIS) size, kernel recovery, style distribution and kernel discolouration were determined. The NIS were size graded, 18 mm, 18-20 mm and >20 mm in diameter. Sampling equipment and procedures were facilitated by Golden Macadamias (Pty) Ltd (Alkmaar, Mpumalanga, South Africa) processing plant. Samples were cracked with a mechanical Holiday cracker (WMC sheet metal works, Tzaneen, South Africa) to determine kernel recovery, style distribution, kernel discolouration and immaturity. Cracked shells and kernels and their fragments were separated with vibrating screens and blowers. Kernel recovery was determined by the weight of kernel recovered from a weighed NIS and expressed as a percentage (kernel NIS^{-1} x 100). Style distribution was done by sizing the kernel into different styles, viz., whole, halves and chips or pieces (Weinert 1993). The weight of each style was expressed as a percentage of the total kernel weight.

Discolouration (all or part of basal portion of kernel is stained brown / black) was hand sorted according to commercial grade colour charts (Golden Macadamias (Pty) Ltd). ‘Onion ring’ and ‘distal end browning’ (Penter et al. 2007) were both classified as discolouration. Immaturity was tested by using the floatation test in a brine solution at a specific gravity of 1.025 (Grimwood 1971). First-grade kernels had an oil content of 72% or more while for second-grade kernels oil content was between 67% and 72%.

The general linear models (GLM) procedure of the Statistical Analysis System (SAS Enterprise Guide 5.1) (SAS Institute, Cary, N.C., 2012) was used to analyse the data. Least significant differences (LSD) were used to compare treatment means when the ANOVA indicated significant differences ($P < 0.05$) between treatments.

Results and Discussion

Yield, kernel recovery and quality

Maximum air temperature was higher during the premature nut drop stage (10 Oct. to 18 Nov. 2011) with a mean temperatures of 28.7 ^{0}C compared to the slightly lower 27.8 and 27.7 ^{0}C experienced during the shell hardening (19 Nov. to 21 Jan.) and nut maturation (22 Jan. to 29 Apr.) stages, respectively (Table 2). According to Stephenson and Trochoulias (1994), temperatures of 30 ^{0}C and above increase premature nut drop, hastens nut development and therefore leads to smaller nuts. During the 2011 spring and summer, 54 days of the 203 days of nut development, reached daily maximum temperatures above 30 ^{0}C, of these 15 of the 54 days were during the premature nut drop stage and 17 of the 54 days during the shell hardening stage (Figure 1). None of the kaolin applications significantly affected yield per tree, indicating that premature nut drop was not reduced by the kaolin applications (Table 3). This was notwithstanding the fact that maximum air temperature on 15 of 40 days was above 30 ^{0}C.

No significant differences were found in nut size and kernel recovery, although 17 of 64 days during the shell hardening stage maximum temperatures were above 30 ^{0}C. Fruit structures; husk, shell and endosperm are formed during the first 90 days after flowering (Jones and Shaw 1943) and growth in fruit size continues until shell hardening, 12 to 15 weeks after anthesis (Trueman and Turnbull 1994; Jones 1939). Although for 32 days of the 104 days (30.8%) the maximum temperatures were above 30 ^{0}C during the fruit development and growth stage before the shell hardened (premature fruit drop plus shell hardening stage), these days did not occur continuously and warm spells were always followed by cooler days, resulting in the mean maximum temperatures during the premature nut drop and shell hardening stage being 28.7 and 27.8 ^{0}C, respectively. The maximum number of days when the maximum daily temperature exceeded 30 ^{0}C was 5 days which occurred from 8 to 12 Nov., 11 to 15 Dec. and 18 to 22 Dec. Every plant has an optimum temperature range where maximum growth occurs and where the rate of cell division and therefore fruit growth is proportional to temperatures (Allan and De Jager 1978). Stephenson and

Gallagher (1986) found that when macadamia trees were grown in a controlled-environment glasshouse, under continuous day temperature of 30 ^{0}C for eleven weeks, higher kernel recovery (values not mentioned) were found compared to day temperatures of 15, 25 or 35 ^{0}C, with kernel recovery at the highest temperature of 35 ^{0}C lower than at 25 ^{0}C. These high temperatures of 30 and 35 ^{0}C were not reached continuously in the current study in the Barberton region, with only 6 days registering above 35 ^{0}C in total (Figure 1) and therefore the potential impact of kaolin on heat stress reduction and consequently on kernel recovery and yield could not be fully evaluated.

No significant differences were found in percentage immature kernel between kaolin treated trees and untreated controls, but levels were low (1.24 to 2.31%) (Table 3). As trees in our trial experienced a mean maximum temperature of 27.7 ^{0}C (Table 2) during the nut maturation stage, this is in accordance with Stephenson and Gallagher (1986) who found enhanced oil accumulation at 25 °C compared to higher temperatures of 30 and 35 ^{0}C. Also the quality parameters, whole kernel recovery and kernel discolouration were not significantly influenced by kaolin applications (Table 3). These findings concur with the literature that only rough handling by dropping the NIS at 3% (cracking moisture) and 15% (harvesting moisture) moisture content on hard surfaces and dehusker damage, drying at high temperature (40 to 50 ^{0}C) and differences between cultivar are factors that have an affect on whole kernel recovery (Penter et al. 2008). According to Penter et al. (2007), rainfall decrease kernel discolouration in a non-irrigated orchard, but no study to date has identified orchard temperature as a factor influencing kernel discolouration.

In our trial the application of kaolin particle film to mature macadamia tree canopies had no significant effect on kernel recovery, yield and quality. Lombardini et al. (2004) found similar results in pecan and Steiman et al. (2007) in coffee, although the coffee plants showed an increase in yield during the second season. Steiman et al. (2007) suggested this increase in yield in the second season could be due to the kaolin increasing the light reflected into the inner canopy, which resulted in increased floral initiation. This in turn led to more fruit and possibly higher starch reserves due to increased photosynthesis.

Photosynthesis

Photosynthesis of control leaves was highest at 12.34 µmol m^{-2} s^{-1} in the morning (10h26) and lowest at 1.13 µmol m^{-2} s^{-1} late afternoon (17h21). Similar to walnuts (Rosati et al. 2006), photosynthesis was higher in the morning (between 9h30 and 11h00) and decreased throughout the day. Therefore to determine the effect of kaolin applications on photosynthesis, the difference between the control leaves and kaolin treated leaves were determined. Kaolin applications, one three or five layers, did not significantly reduce photosynthesis, even when measured at 200, 800 and 1800 µmol m^{-2} s^{-1} irradiance (Table 4).

Kaolin increases whole tree canopy photosynthesis by reducing the temperature and increasing the interior canopy light due to the reflection of light by the kaolin covered leaves (Glenn 2012). While kaolin application on apple (Glenn et al. 2001) and grapefruit (Jifon and Syvertsen 2003) increased net assimilation, Lombardini et al. (2005) observed no effect on pecan trees. In our study photosynthesis was measured on individual leaves on nursery trees. The photosynthesis was not significantly reduced in these leaves even at low light intensity, indicating that should kaolin prove effective in reducing high temperature stress in subsequent trials, it will probably not be to the detriment of net carbon assimilation.

Conclusion

Foliar kaolin application could potentially be a practical and economical way of regulating heat stress on macadamia trees, but due to the season in which our study was conducted not reaching long periods with maximum daily temperatures exceeding 30 ^{0}C, the potential impact of kaolin on heat stress reduction and consequently on kernel recovery and yield could not be fully evaluated. We did however establish that up to five layers of foliar applied kaolin did not significantly reduce individual leaf photosynthesis. With the macadamia industry expanding at a phenomenal rate in South Africa, more producers will plant in marginal areas where heat stress is a more limiting factor than in the Barberton region where this study was conducted. Further studies on foliar application of kaolin in such regions should be considered.

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Table 1: Kaolin treatments with rates and date of applications

Treatment	Rate (g L^{-1} kaolin)	Application
1	12.5	3 weeks after full bloom (10 Oct. 2011)
		21 days after first application (31 Oct. 2011)
2	25.0	3 weeks after full bloom (10 Oct. 2011)
3	12.5	3 weeks after full bloom (10 Oct. 2011)
		21 days after first application (31 Oct. 2011)
		21 days after second application (21 Nov. 2011)

Table 2: Mean maximum, minimum and average temperature, total heat units and total rainfall as measured during the fruit development stages at Barberton (2011/2012)

Fruit development stage	Temperature (˚C)			Heat units	Rainfall (mm)
	T_{max}	T_{min}	T_{avg}		
Premature nut drop*	28.67	16.21	21.70	468	107
Shell hardening**	27.78	18.22	22.30	787	332
Nut maturation***	27.66	16.56	21.23	1112	299
Total				2367	738

* 10 October to 18 November 2011

** 19 November 2011 to 21 January 2012

*** 22 January to 29 April 2012

Table 3: Effect of kaolin applications on kernel recovery, yield Dry-in-Shell (DIS) per tree, whole kernel recovery, kernel discolouration, immature kernel and sizing of 'Beaumont' macadamia nuts in the Barberton region during 2011/2012.

Treatment	Yield (DIS) Kg tree^{-1}		Sizing (>20mm) (%)		Kernel recovery (%)		Immature kernel (%)		Whole kernel recovery (%)		Kernel discolouration (%)	
Untreated control	10.77	ns	88.81	ns	32.24	ns	1.38	ns	24.97	ns	19.34	ns
12.5 g L^{-1} kaolin x2 *	10.48		90.81		31.77		1.24		27.93		15.11	
25.0 g L^{-1} kaolin x1 **	10.68		90.52		32.21		2.31		26.62		15.85	
12.5 g L^{-1} kaolin x3 ***	10.79		89.18		32.61		1.95		25.73		16.55	
Pr > F	*0.9745*		*0.5416*		*0.1472*		*0.3336*		*0.2766*		*0.4757*	

* Kaolin applied on 10 and 31 Oct. 2011
** Kaolin applied on 10 Oct. 2011
***Kaolin applied on 10 and 31 Oct. And 21 Nov. 2011

Table 4: Differences in photosynthetic rate of 'Beaumont' nursery trees leaves at different light levels (photosynthetic active radiation (PAR)) between control leaves and leaves covered with 1, 3 or 5 layers of kaolin applied at 12.5 g L^{-1}

Number of Kaolin layers	Irradiance level (PAR) (µmol m^{-2} s^{-1})	Difference in photosynthesis (µmol CO_2 m^{-2} s^{-1})	Standard deviation
1	200	-0.29	0.79
1	800	-1.00	1.15
1	1800	-1.38	1.72
3	200	0.20	0.50
3	800	-0.68	0.30
3	1800	0.27	2.51
5	200	-1.07	1.20
5	800	-1.36	1.64
5	1800	-1.32	1.42
Pr > F			
Layers		*0.2710*	
Light level		*0.4073*	
*Layers*light level*		*0.7715*	

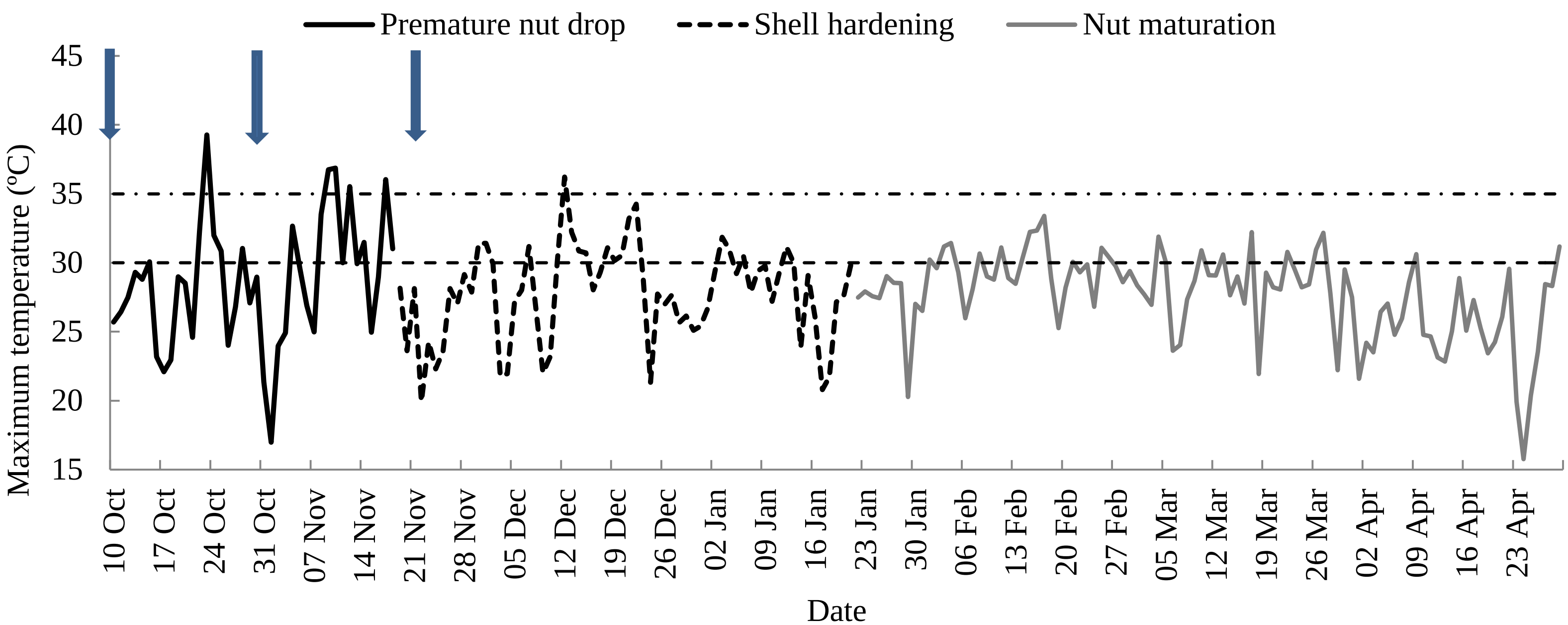

Figure 1: Daily maximum temperature during the different fruit development stages in Barberton (2011/2012). Date of kaolin applications are indicated by arrow

General Discussion and Conclusions

South Africa is one of the leading producers of macadamia nuts in the world. Macadamia nuts are one of the highest priced processed nuts available and the cultivation of the crop is highly profitable. Growers therefore also cultivate macadamias in climatic regions that are not really suitable. In the Lowveld region, it was found that orchards of the same cultivar differ in kernel recovery, whole kernel recovery and kernel discolouration. Growers receive higher pay-outs for nuts that yield high kernel recovery and unblemished (no discolouration) whole kernels. New orchards are currently being planted and the question was raised what influences kernel recovery, whole kernel recovery and kernel discolouration. To further increase profitability, the factors that influence these parameters needed to be investigated and optimal management strategies need to be developed.

Kernel recovery, whole kernel recovery and kernel discolouration vary over seasons and regions, therefore to optimize these parameters the location of the farm in a specific region is important. Kernel recovery was the highest in the Kiepersol region, but also kernel discolouration, while kernel recovery and discolouration were much lower in the Hazyview region. We therefore assume that climate plays a role although it was not very clear from the models we fitted. Relative humidity and vapour pressure deficit however had an influence on both kernel recovery and whole kernel recovery. The meteorological data was from one weather station that was central to a region, the micro climate of a farm or orchard may vary from this. Future studies should focus more on climatic factors by having dedicated weather stations at the trial sites, to exclude these variances.

Cross-pollination, high yield, soil moisture stress and high leaf boron (B) concentration were all factors that were identified from the literature to influence whole kernel recovery (Trueman and Turnbull 1994, Stephenson et al. 2003, McFadyen et al. 2004, Wilkie 2009) and these factors were reconfirmed as being important in Paper 1. High altitude, early season harvesting and processing of NIS were identified as new possible factors that could increase kernel recovery. Whole kernel recovery was associated with method of curing of NIS, improved by faster delivery and harvesting time, which also concur with the literature (Bungay 2001, Penter et al. 2008). We established that whole kernel recovery correlated with kernel recovery. Growers can therefore benefit with increased prices and lower production cost by increasing kernel recovery and whole kernel recovery at the same time. Increased B and copper and decreased manganese leaf concentration in Nov. were associated with high whole kernel recovery. Low kernel discolouration was influenced by high yield, no cross pollination, low nitrogen and zinc and high leaf potassium concentration in Nov. Although our models gave a clearer indication of which factors influence kernel recovery, whole kernel recovery and kernel discolouration more in-depth studies are needed to confirm the appropriateness of these suggested strategies and to correlate it with yield.

In the literature study moisture and heat stress were identified as possible factors that could be investigated to increase kernel recovery, whole kernel recovery and decrease kernel discolouration.

Irrigation deficit trials in the Lowveld during the summer rainfall period was very challenging and we concluded that although tree water stress was not measured (midday stem xylem water potential or pre-dawn water potential) that moderate water stress (66% irrigation) was difficult to achieve. Therefore the result that water stress at different levels and fruit development stages did not show any effect on kernel recovery and quality was not surprising. Although yield was increased by the 198% irrigation treatment in one season, it was probably not always much wetter than the control and therefore irrigation treatments could not be achieved as envisaged. Further trials could consider rain covers although Stephenson et al. (2003) found some inconsistent results due to the lack of evaporation and the effect of buffering soil moisture. Variation in soil and rainfall will hamper the effectiveness of on-farm water stress and more practical and effective methods to increase kernel recovery should be investigated.

Application of kaolin could potentially be a practical and economical way of regulating heat stress of macadamia trees (Alberts 2004), but due to the season in which our study was conducted not reaching long periods with maximum daily temperatures exceeding 30 °C, the potential impact of kaolin on heat stress reduction and consequently on kernel recovery and yield could not be fully evaluated. We did however establish that up to five layers of foliar applied kaolin did not significantly reduce individual leaf photosynthesis, therefore future studies on kaolin could be considered. With the macadamia industry expanding into Southern Africa and suitable land for macadamia production less available and more restricted, heat stress will become a more limiting factor. Future studies on kaolin application could be considered in drier and consistently hotter regions.

Future research on the factors that influence kernel recovery, whole kernel recovery and kernel discolouration – most notably, nutrition and climate – is needed. Nutrition can be manipulated by foliar applications or fertigation, it might be worthwhile to evaluate horticultural interventions e.g. growth regulators. An alternative option would be to compare different cultivars under different climatic conditions of macadamia production regions in South Africa, to establish which cultivar produces the optimum yield, kernel recovery, whole kernel recovery and less kernel discolouration under which climatic conditions.

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