Microclimate modification to improve productivity of ‘Carmen®-Hass’ avocado orchards using shadenet under subtropical conditions of Limpopo province, South Africa

by

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submitted in fulfilment of the academic requirements of

Master of Science in Agriculture

in Agrometeorology

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Pietermaritzburg

South Africa

July 2016

PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Agrometeorology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the South African Avocado Growers' Association, Hans Merensky Foundation and Department of Agriculture, Forestry and Fisheries.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Professor M.J. Savage

Date: 12 July 2016

DECLARATION 1: PLAGIARISM

I, Clarance Kgethego Malapana, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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DECLARATION 2: PUBLICATION

My role in each paper and presentation is indicated.

Blakey, R.J., Tesfay, S.Z., Savage, M.J., Malapana, C.K., Mazhawu, E. 2014. Reducing environmental stress to increase avocado yield and fruit quality. Progress report – Year 1. Paper presentation to the South African Avocado Growers' Association Symposium 2014, 18th Feb 2014, Tzaneen, South Africa.

Blakey, R.J., Van Rooyen, Z., Köhne, J.S., Malapana, C.K., Mazhawu, E., Tesfay, S.Z., Savage, M.J. 2015. Growing avocados under shadetting. Progress report – Year 2. Paper presentation to the South African Avocado Growers' Association Symposium 2015, 17th Feb 2015, Tzaneen, South Africa.

Blakey, R.J., Van Rooyen, Z., Köhne, J.S., Malapana, C.K., Mazhawu, E., Tesfay, S.Z., Savage, M.J. 2015. Growing avocados under shadenetting in South Africa. Paper presentation to VIII World Avocado Congress 2015, 13th to 18 Sept, 2015, Lima, Peru.

Malapana, C.K., Savage, M.J. 2016. Enhancing microclimate and productivity of subtropical avocado 'Carmen®-Hass' in protected cultivation. Paper presentation to 2016 Combined Congress for Soil and Plant Sciences, 18th to 21 Jan, 2016, Bloemfontein, South Africa.

These papers were presented based on the current project.

ABSTRACT

The agricultural environment is a complex and dynamic system. Microclimate, the crop, biosphere, and management practices interact to determine the best yield production. South Africa is a water-scarce country, with high variability in annual rainfall. Thus, water quality and quantity are major limiting factors in agriculture. Hence, shadenetting can be used to modify the orchard microclimate to make the environment more conducive for fruit production.

The South African avocado industry is export-oriented, so there is a commercial need to optimise the exportable percentage of avocado fruit. Sunburn, wind and hail damage and small fruit size as a result of water stress are the major cull factors for the industry. It is believed that shadenetting, with changes in management practices, can counter these limiting factors. There is no literature on growing avocado fruit under shadenetting. Therefore, the aim of the research was to determine the effects of a 20% white shadenet on 'Carmen®-Hass' avocado orchards and productivity. The long term objective is to improve avocado fruit quality and profitability in the Mooketsi Valley, Limpopo province, South Africa, a subtropical environment by reducing abiotic stress, particularly, solar irradiance, heat and wind.

The trial was conducted at Goedgelegen Estate in the Mooketsi Valley on 'Carmen®-Hass' trees planted in 2007/8 season. A 1-ha shadenet structure (6 m high) was used, with 20% white shadenet over the roof and 40% green shadenet on the sides. Air and canopy temperature, relative humidity, wind speed, solar irradiance and leaf wetness duration (LWD) and sap flow were monitored at a sub-hourly rate. Evapotranspiration was calculated from the above mentioned parameters. Irrigation was monitored five times per week using tensiometers at 300- and 600-mm soil depths. The comparison between open and shadenet leaf areas showed that leaves in the open treatment were reduced as a result of the abiotic stress. Fruit water content under the shadenet compared to the open was greater, such enabled fruit under the shadenet to reach maturity two weeks earlier when compared with open treatment.

Air and canopy temperature and relative humidity were slightly reduced under the shadenet, with the greatest difference occurring during the flowering period in mid-winter. The modification in air temperature and relative humidity was beneficial for bee activity and pollination in 2015 compared to the 2014 season. 'Carmen®-Hass' flowers in mid-winter when temperature conditions are not conducive for pollination. Canopy temperature was also reduced under shadenetting compared to the open treatment. The reduction was due to differences in tree density and the role that shadenetting plays. The infrared thermometer measurements were uniform with dense canopies compared to sparse tree canopies.

The midday incoming solar irradiance was reduced by 18% under the shadenet compared to the open treatment. Calm conditions were experienced under the shadenet. Hence, windspeed was reduced to negligible levels. Also, the shadenet resist air flow to a certain height compared to the open treatment. LWD was extended by 12% under shadenet. An infestation of the insect pest citrus leaf roller (*Archips occidentalis*) caused severe damage to the fruit during the 2014/15 season due to the high plant density used. Significant results were that evapotranspiration was reduced by 14 and 29% less water was applied under the shadenet to maintain an adequate soil water content compared to the open treatment.

Fruit reached minimum maturity two weeks earlier under shadenet compared to the open treatment. Fruit quality and pack-out were improved under the shadenet due to reduction in sunburn, wind damage and small fruit. But poor yields were experienced during the 2014 season due to poor bee activity, pollination and fruit size distribution were reduced under the shadenet compared to the open treatment. But following the improved bee activity in 2015, the 2016 normal season yield is likely to be improved under the shadenet than in the open treatment. Data collected in the Mooketsi Valley showed that 20% white shadenet has modified the microclimate and improved fruit quality. The water use under the shadenet was improved compared to the open treatment. But a thorough investigation on bee management under shadenet is required to optimise pollination in order to obtain greater yields under the shadenet.

ACKNOWLEDGMENTS

I would like to acknowledge the following people for their contributions and support:

To the God of Engenas, Edward and Barnabas Lekganyane, thank you Father for the guidance, knowledge and wisdom you bestowed on me. The protection and strength you provided during the course of the study.

My supervisor, Professor Michael J. Savage, for the supervision and direction you have provided towards my research. You have always been at the forefront of my academics from 2010 and inspired me to pursue my studies in Agrometeorological research.

My co-supervisor, Dr. Robert J. Blakey, for the mentorship you provided in avocado research. You made a long inspired dream of working for Westfalia Fruit Estate come true for having introduced and guided me into the avocado industry.

I would like to thank the South African Avocado Growers' Association (SAAGA), Westfalia Fruit Estates, University of KwaZulu-Natal, Hans Merensky Foundation and Department of Agriculture, Forestry and Fisheries (DAFF) for funding the research and infrastructural support.

Mrs Meryl A. Savage, Dr. Samson Z. Tesfay, Dr. Alistair D. Clulow and Mr. Vivek Naiken for the administration, support and motivation towards my research is well acknowledged.

Westfalia Technological Services, Mr. Jan van Eyk and Mrs Nastassia Botha for all the hospitality and assistance they provided at Westfalia Farm Estate and Goedgelegen Farm.

Evidence Mazhawu, Patrick Malatjie, Quintin Hatté, Ntanga Netshilema, Jonathan Pasi, Nicolas Moyo, Gontse Matshoge, Thobeka Manyathi, Sabelo Shezi, Sheldon Strydom and Sthandiwe Luthuli for their assistance, support and inputs.

My family and girlfriend, Lebogang L.R. Mphahlele for their support towards my academic career. Lebogang I know my research started when you were experiencing quite a number of hardships, yet you never stopped living life to the fullest. I am grateful to God for having restored your strength and health and the support and prayers from my supervisors, friends and our families when days were dark.

Proverbs 3: 5-6 [5]Trust in the Lord with all your heart and lean not on your own understanding. [6]In all your ways submit to Him, and He will make your path straight.

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CHAPTER 1: INTRODUCTION

1.1 Avocado production in South Africa

Avocado (*Persea americana* Mill.) is originally from central Mexico and was discovered in 1499 (Popenoe, 1926, Bergh and Ellstrand, 1986). According to Schaffer *et al*. (2013b), avocado originated mostly within geographically tropical latitudes of (23.5ºN to 23.5ºS) and is often listed as a subtropical fruit. Avocado belongs to the family Lauraceae and is classified into three subspecies of economic and cultural importance, i.e. West Indian, Guatemalan and Mexican (Popenoe, 1927, Bijzet, 2001, Schaffer *et al.*, 2013b).

In South Africa, avocado production is concentrated in the warm and cool subtropical areas of Limpopo, Mpumalanga and KwaZulu-Natal provinces. The South African avocado season extends from mid-March to November. Hence, the climatic variability allows the major cultivars (‘Hass’, ‘Fuerte’, ‘Pinkerton’, etc.) to be available over an extended period during the season. Approximately 70% of the trees produced by South African avocado nurseries are ‘Hass’ and the remaining 30% is comprised mostly of ‘Fuerte’, ‘Ryan’ and ‘Pinkerton’ (Blakey and Wolstenholme, 2014).

The South African avocado industry is export-oriented. The production area has expanded from approximately 2 000 hectares in the 1970s to over 12 000 hectares in recent years. Recently, over 12 million cartons were exported compared to 370 000 cartons in 1970 (William, 1984, Blakey and Wolstenholme, 2014).

The United Kingdom and Western Europe absorb at least 90% of the exported crop with the remainder feeding Eastern Europe and the Middle East. The South African market also plays a significant role with demand having grown considerably over the past few years. The major competitor of the South African avocado industry is Peru, which produces large volumes at the same time as South Africa. Other countries such as Mexico, USA, Chile, Israel, Spain, Brazil, Australia, New Zealand and Kenya are counter seasonal or do not export to Europe (Mogala, 2012).

1.2 Use of shadenets in horticulture

Shadenets are used to shelter agriculturally important crops from extreme climatic conditions such as low and high temperature, solar irradiance, etc. (Savage, 1978, 2014). Shadenets differ from greenhouses and tunnel-houses in the level of protection against excessive solar irradiance, rainfall and insects, type of material and colour of material (Mthembu, 2001; Smit, 2006; Tinyane, 2013). The use of shadenets in the South African horticultural industry is becoming popular due to economic and agronomic benefits and protection against adverse weather they offer.

1.2.1 Cost and availability of shadenet material

The economic feasibility of growing fruit trees under shadenet is not known. The cost of building a shadenet may depend on the desired area, type of material etc. (Al-Helal and Abdel-Gjany, 2010). Shadenets are available in a variety of colours, e.g. white, pearl, grey, clear, black, red, and blue. Shadenets vary in shading intensity against solar irradiance including, near infrared radiation (NIR), infrared radiation (IR), ultra-violet (UV) and photosynthetic active radiation (PAR) (Stamps, 2009).

1.2.2 Effect of shadenet on plant production

Studies on the use of shadenets have been conducted on apples, berries, citrus, tomatoes, peppers, peaches, table grapes, mangos etc. (Mthembu, 2001, Smit, 2006, Illic *et al.*, 2012, Milenkovic *et al.*, 2012, Sauphanor *et al.*, 2012, Kong *et al.*, 2013, Savikin *et al.*, 2013, Tinyane *et al.*, 2013). However, there is no literature on growing avocados under shadenet.

Shahak *et al*. (2004) found that 30% grey shadenet had an effect on apple and peach flowering intensity, fruit set and growth compared to blue, pearl, red and yellow and the control. The study also found that a combination of 30% red and white shadenet reduced PPFD (photosynthetic photon flux density) by 18% but increased fruit set compared to the control. Furthermore, Smit (2006) found 20% black shadenet to have resulted in reduced sunburn severity and/or intensity, fruit firmness and total soluble solids but increased fruit mass of ‘Fuji’ and ‘Braeburn’ apples. However, the study showed no consistency in fruit firmness between cultivars grown under the shadenet and the open treatment.

Abouatallah *et al*. (2012) reported that their shadenets reduced citrus fruit drop and maintained high leaf water content but had no effect on fruit size. However, the study did not specify the type of shadenet, i.e. colour and shading percentage used .

1.3 Motivation for the study

In South Africa, the majority of the avocado is produced in the warm and water scarce subtropical parts of South Africa (Limpopo province). Heat stress and excessive winds at flowering and fruit set results in reduced yields and pack-out percentages. However, growers within the province have raised concerns about the need to improve fruit quality, productivity and profitability.

Also, growers depend on limited irrigation water but if drought occurs, the industry is set to lose millions of rands since South African avocados are export-oriented. In other words, avocado growers can tolerate having phytophthora root rot disease but cannot tolerate limited water for irrigation. ‘Carmen®-Hass’ is a newly discovered ‘Hass-like’ avocado cultivar that bears fruit twice a year (normal and out-of-season fruit). ‘Carmen®-Hass’, also known as ‘Mendez 1’, was selected by Carlos Mendez Vega. The cultivar is protected by the U.S. Patent and Plant Breeders Rights are managed by Westfalia Fruit Estate in Africa and the Middle East. The fruit matures earlier than ‘Hass’ with consistent bearing and excellent postharvest quality. The cultivar flowers 1-7 months earlier than ‘Hass’. Thus growers can supply avocados when the demand is high and still export the out-of-season fruit when Chilean ‘Hass’ fade out of the European markets.

In Limpopo province, solar irradiance is excessive for optimal avocado growth and development, reaching a maximum of 500 to 1000 W m^{-2} at mid-day on cloudless days in winter and summer, respectively. This results in sunburn and loss of normal- and out-of-season marketable fruits. It was proposed that commercial shadenet structures can alter the microclimate within the orchards to a level adequate for tree growth and development. This will also provide protection against insects and birds thus increasing profitability. The shadenetting may also reduce evapotranspiration and the need for frequent irrigation. Shadenet has been used for decades in South Africa but no work has been reported for avocado under shadenetting.

1.4 Aims and objectives

1.4.1 General aim

The aim of the study was to determine the effects of a 20% white shadenet on ‘Carmen®-Hass’ microclimate, avocado tree phenology, fruit quality, water use and yield under the subtropical conditions in the Mooketsi valley near Tzaneen in the Limpopo province, South Africa.

1.4.2 Objectives

1. To determine the effect of a 20% white shadenet on ‘Carmen®-Hass’ so as to reduce abiotic stress and in particular heat, solar irradiance and wind speed.

2. To investigate and monitor the ‘Carmen®-Hass’ tree phenological responses under the shadenet in order to optimise bee activity and pollination.

3. To monitor the bee activity and pollination so as to increase long-term yield and profitability of ‘Carmen®-Hass’ avocados in the Mooketsi valley.

1.5 Dissertation structure

The dissertation is structured in the traditional format. The present Chapter, chapter 1, introduces the study, giving a background on the South African avocado production and the use of shadenets in horticultural production. The motivation for the study, aims and objectives are also included in the present chapter. Chapter 2 is the literature review of the study. However, there is no literature on growing avocados under shadenetting. Thus the literature is based on other fruit crops grown under shadenetting.

Chapter 3 is the material and methods of the study, giving details on methods used during the study. The results and discussion of the study is provided in Chapter 4. The results and discussion are detailed in subsections of microclimate, soil-plant water relations, tree phenology and yield and postharvest studies. Chapter 5 is the conclusion and recommendations for the study.

CHAPTER 2: LITERATURE REVIEW

2.1 Avocado tree phenology

Avocado trees have rounded canopies with dense foliage. However growth form varies from upright (‘Edranol’), rounded (‘Hass’) to spreading (‘Fuerte’) (Schaffer *et al*., 2013b). Shoot growth is made up of flushes with varying vigour, duration and extent. Individual flushes consist of small spaced leaves at the base, followed by large well-spaced alternate leaves and ends up with a rosette of closely spaced leaves (Verheij, 1986, Robbertse, 2011). Avocado tree branches produce different flushes two to three time a year except shaded and bearing shoots. The different flushes on a particular branch are easily recognisable, as the approach of a period of quiescence is marked by shorter internodes and then a ring of closely spaced buds (Davenport, 1982, 1990).

2.1.1 Cultivars

‘Hass’ is the major exported cultivar globally with an export trade of 90% compared to other cultivars (Crane *et al*., 2013). Other important cultivars for export and local markets include ‘Fuerte’, ‘Pinkerton’, ‘Ryan’, ‘Carmen®-Hass’, ‘Gem’, and ‘Maluma’ (Bijzet, 2001, Mogala, 2012, Blakey and Wolstenholme, 2014).

2.1.1.1 ‘Hass’

‘Hass’ is grown in cool subtropical areas and at high elevation in tropical areas. It is a medium to large tree with a semi-upright growth. ‘Hass’ is a flower Group A cultivar, i.e. the flower functions as a female on the first day of opening and a male in the afternoon of the following day. ‘Hass’ fruit are ovate, dark green on the tree and purplish to black when ripe. Fruit set is less sensitive to cold temperatures than ‘Fuerte’ and ‘Ettinger’ but the leaves are more cold sensitive (Crane *et al*., 2013).

Fruit size problems are noticeable in orchards situated in warmer and drier climates and become more pronounced with tree age (Cameron *et al.*, 1952, Lahav and Zamet, 1975, Slabbert, 1981, Kremer-Köhne and Köhne, 1995, Garner and Lovatt, 2008). ‘Hass’ requires more energy to grow but growth is suppressed under extreme heat and low humidity. Köhne and Kremer-Köhne (1990) recommend that ‘Hass’ requires more water and have a high nitrogen fertilizer requirement for improved fruit size.

A long-term solution to ‘Hass’s size problem was to breed new black skinned cultivars with large average fruit size (Bijzet, 2001). This led to the ‘Hass-like’ selections such as: ‘Lamb-Hass’, ‘Harvest’, and ‘Carmen®-Hass’. ‘Carmen®-Hass’ is the only ‘Hass-like’ cultivar that is commercialised but plantations per hectare are still small. ‘Lamb-Hass’ was not successful and ‘Harvest’ is the only semi-commercialised cultivar (Kremer-Köhne, 1999, 2000, Arpaia, 2004, Bruwer, 2006, Dixion *et al.*, 2008).

Soil water is conserved through mulching which reduces avocado seed coat degeneration and pedicel ring-neck associated with water stress (Moore-Gordon and Wolstenholme, 1996). However, the study was based on the cool subtropical climate with adequate rainfall. Thus mulching depends on the C:N ratio, availability, and decomposition rate. Whilst nitrogen needs to be applied at the right time and rates to avoid increased vegetative growth or fruit drop (Cutting, 1993).

'Hass' trees do not follow a regular alternate bearing pattern (Mickelbart *et al*., 2012). Alternate bearing patterns can be disturbed by environmental events such as; air temperature, photoperiod, water availability, etc. Low fruit set is also attributed to excessive flower abscission even in healthy, well-managed orchards (Garner *et al.*, 2011). Moore-Gordon *et al*. (1998) concluded that the percentage of small fruits harvested each year varies from 20 to 60%, depending on climate, tree health, cultivation practices and crop load. The small fruit size is also related to the genetic make-up of the seed coat, location and environmental conditions.

2.1.1.2 'Carmen®-Hass'

'Carmen®-Hass' is an early flowering cultivar with normal- and out-of-season flower sets which can be marketed when 'Hass' supply is low. Depending on the environment grown in, it may bloom 1 to 7 months earlier than 'Hass' (Van Rooyen, 2011). Fruit reach minimum maturity earlier than 'Hass'. Unlike 'Hass', it is consistent in bearing with excellent postharvest quality (van Rooyen, 2011, Crane *et al.*, 2013).

In the subtropical climate of South Africa, the cultivar has an optimum and consistent off-season production. In California, i.e. a Mediterranean climate, the cultivar is partially suppressed during off-season production due to colder and extreme weather conditions. But it still appears to have higher flowering intensity than 'Hass'. Advantages of this cultivar include; out-of-season fruit availability, increased overall productivity and fruit that are indistinguishable from 'Hass' to the consumer. 'Carmen®-Hass' may have an alternate crop, smaller fruit sizes and off-season fruits may be smooth and round (Illsley-Granich *et al.*, 2011).

The cultivar is protected by the U.S. Patent and Plant Breeders Rights and it is managed by Westfalia Fruit Estate in Africa and the Middle East. Trees are vigorous and cold tolerant but fruit are slightly smaller than 'Hass' (Crane *et al*., 2013).

2.1.2 Vegetative growth

Avocado trees grown in the moist summer rainfall subtropics have a spring growth flush which is followed by a summer and early autumn growth flush. In the southern parts of California, coastal Israel and Chile, the spring flush concludes early allowing an early summer and autumn flush. However, avocados grown in the warm subtropical climates have one winter flush and three summer flushes

(Salazar-Garcia *et al*., 2006). The summer flush is vital for normal functioning of the tree. They survive winter and are more photosynthetically efficient than spring flush.

Spring and summer flushes intercept more radiation as they shade spring flushes and contribute most of the carbon budget of the tree (Wolstenholme, 2011b). Avocado leaves expand to full size in about 30 days. Schaffer *et al*. (1991) found a net carbon loss in 'Booth 8' leaves until they reached 72% of full size. There are about 350-510 stomates per mm^2 on the abaxial surface whilst stomatal activity is reduced in older leaves by dense epicuticular wax (Blanke and Lovatt, 1993).

2.1.3 Reproductive growth

The transition from vegetative to reproductive growth takes place in the primary axis meristem. In 'Hass', the transition phase occurs early in the process of shoot development (Salazar-Garcia and Lovatt, 1998, Salazar-Garcia *et al.*, 1999, Salazar-Garcia *et al.*, 2006). Floral induction is when an environmental stimulus (temperature or photoperiod) leads to floral induction.

2.1.3.1 Flowering

Floral buds are mixed buds with reproductive and vegetative primordia. Each floral bud develops into a compound inflorescence that can be determinate (floral bud) or indeterminate (vegetative bud) (Salazar-Garcia *et al.*, 2013). Indeterminate buds are produced in abundance and shade fruit against sunburn, whilst determinate buds are common on stressed trees (Schroeder, 1944).

Avocado flowers are bisexual with functional male and female organs controlled by a time mechanism called synchronous protogynous dichogamy (Alcaraz *et al.*, 2013). Avocado cultivars are therefore classified in two groups (A or B) based upon their flowering behaviour. In the type A cultivars such as; 'Hass' and 'Carmen®-Hass', flowers open in the morning as females, close at midday and reopen in the afternoon of the following day in the male stage. In the type B cultivars 'Fuerte', the flowers open in the afternoon in the female stage, close in the evening and reopen the following morning in the male stage. However, the cycle may be disrupted by environmental conditions (Alcaraz and Hormaza, 2009a, Salazar-Garcia *et al.*, 2013).

During the first opening, both self- and cross-pollen can adhere, hydrate and germinate successfully on avocado stigmas but only one pollen tube reaches the stigma (Sedgley, 1976). Robbertse *et al*. (1997) found that 'Ettinger' (Type B) pollen outperforms 'Hass' (Type A) in terms of germination and pollen tube growth. Davenport (2000) demonstrated that pollen tubes can reach the egg apparatus within 24 hours of pollination of male stage flowers but could not demonstrate fertilisation viability after an extended period.

In ‘Fuerte’ avocado, flowering is induced by low air temperature (less than 20 ˚C) and photoperiod (Buttrose and Alexander, 1978). However, the same does not hold for ‘Hass’ avocado (Schaffer *et al*., 2013b). Sledgley (1981) and Sedgley and Grant (1983) found that under controlled environmental conditions, floral development in ‘Hass’ and ‘Fuerte’ was inhibited at high air temperatures (33/23 ºC day/night).

2.1.3.2 Pollination and fruit development

Pollination occurs due to temporal overlap between the male and female flowers. However air temperature plays a key role in this process, air temperatures below 18 ºC delay flower opening in the female stage. Low air temperatures in Type B cultivars result in female stage to be omitted, thereby, reducing pollination. Thus, changes in air temperature can result in irregular blooming and overlap of female and male stages within the same flowering type. Alcaraz and Hormaza (2009, 2013) found that the female and male floral stages overlap by 2 hours. But prolonged overlap is not required for pollen transfer to occur, as bees or other insects could carry pollen for extended periods.

Pollination is affected by movement of pollen through the orchard. Thus, efficient avocado pollinators include: stingless bees (*Apidae meliponinae*), Mexican honey wasp (*Brachygastra mellifica*) and honey bees (*Apis mellifera* L.) (Ish-Am and Eisikowitch, 1998, Ish-Am *et al*., 1999, Can-Alonzo *et al.*, 2005). Honey bees are considered the primary pollinator of avocado in major parts of the avocado producing states. However, the avocado flower is not very attractive to bees. Seemingly, bees prefer more fragrant flowers such as citrus and wild flowers than avocado. The avocado nectar is unattractive and contains high levels of potassium and phosphorus content (Ish-Am and Eisikowitch, 1993, Eardley and Mansell, 1996, Visscher, 1997, Afik *et al*., 2006a, Afik *et al*., 2006b).

Ish-Am and Lahav (2011) found that the rate of bee visitations to avocado trees was positively correlated with pollination rate. Other studies found that avocado pollination and/or fruit set were greatly reduced when pollinators were prevented from accessing inflorescences (Vithanage, 1990, Johannsmeier and Morudu, 1999, Can-Alonzo *et al.*, 2005). This indicates that honeybees are essential for commercial avocado production and result in optimum fruit development.

Fruit development rate is dependent on cultivar and environmental conditions (Salazar-Garcia *et al*., 2013). As the seed matures, the embryo is surrounded by large cotyledons. The seed coat connects the seed and mesocarp. During fruit growth, the mesocarp water content decreases as oil content and dry matter increases concomitantly with fruit water decrease.

2.2 Avocado microclimate

Determining the impact of environmental stress factors on crop production is necessary as crop production expands. The impact of these stress factors can be reduced by understanding the physiological and growth responses of fruit crops under different environments (Schaffer and Anderson, 1994). This section focuses on environmental stress factors that play a role in anatomical, soil water, physiological and phenological stress of avocado.

In natural woody plant communities, solar irradiance and water stress limits plant growth and development more than other environmental stress factors (Savage, 1988; Whiley and Schaffer, 1994; Schaffer *et al*., 2013a). Savage *et al*. (1996) stated that accurate knowledge of soil water availability is important for efficient water management and simulated crop performance.

2.2.1 Solar irradiance

Solar irradiance enters the earth's atmosphere as short wave radiation. Clouds reflect, absorb and transmit solar energy. The direct and diffuse components of solar irradiance arriving at the earth's surface heat the surface. The surface reflects some of the solar irradiance and also emits infrared irradiance into the atmosphere (Savage, 1980a, b).

Solar irradiance consists of wavelengths between 250 and 2500 nm. This includes PAR (photosynthetic active radiation) with wavelengths of 400 to 700 nm and ultraviolet (UV). PAR wavelengths are photosynthetically active and essential in plant production. Infrared wavelengths between 700 and 2500 nm result in a heating effect on plants. Short-wave radiation with a wavelength greater than 700 nm but less than 1100 nm are important for flowering, fruiting, photoperiodism, colouration of fruit, and seed germination (Kubin, 1971, McCree, 1972, Campbell, 1981, Sheehy, 1985). Thus, solar irradiance impacts on photosynthesis, CO_2 assimilation, and water loss (Savage, 1979, Jackson, 1980).

Savage (1988) found that not more than 50% of the incoming solar irradiance is actually photosynthetically active and that it is not the radiation which is photosynthetically active but the leaf chloroplasts. The plant canopy can only absorb 70% of the incoming solar irradiance and only 10% is transmitted by the leaf chloroplasts (Wolstenholme, 2013). The leaf is the principal photosynthetic functional unit. Therefore it is the efficiency of capture and use of solar energy that determines the vegetative production of the plant. Leaf area and arrangement change during the life of a crop by leaf movement can occur even during the course of a single day (Loomis and Connor, 2002). The productivity of a crop depends on the ability of plant cover to intercept the incident solar irradiance, which is a function of leaf area availability, the architecture of vegetation cover and conversion efficiency of the energy captured by the plant into biomass (Abraha and Savage, 2010). Water and nutrient deficiencies may reduce rate of leaf growth, and yield below optimum levels due to insufficient energy capture (Mariscal *et al*., 2000).

Radiation quantity intercepted by plant cover is influenced by a series of factors such as leaf angle, leaf surface properties affecting light reflection, the thickness and chlorophyll concentration, the size and shape of the leaf phyllotaxis and vertical stratification, and the elevation of the sun and distribution of direct and diffuse solar radiation (Abraha and Savage, 2010; Campillo *et al*., 2012).

Shadenets are designed to transmit only part of the solar irradiance and convert it from direct to diffuse irradiance. This is significant for photosynthesis of mature plants where leaves at lower levels are shaded. The amount of photosynthesis received on both shaded and unshaded leaves will be a result of the diffuse irradiance. Hence, leaf expansion will be insignificant (Healey *et al*., 1998). Desmarais *et al*. (1999) found that transmitted solar irradiance was lower for amber than white shadenets, and increased with shadenet hole size. Bastias *et al*. (2012), found that coloured shadenets reduced photosynthetic photon flux density (PPFD in μmol s^{-1} m^{-2}) by 27% compared to white shadenets. Smit (2006) found that at low transmission rates, leaf photosynthesis is reduced by 39% for grey shadenet and 31% for black shadenet. However, the author concluded that low PPFD levels had no effect on apple fruit maturity.

Waggoner *et al*. (1959) found that shadenets without plants had a 20 and 33% reduction in the ultraviolet radiation, on a cloudy and a clear day, respectively. The study also found that the returned infrared radiation was greater than in an openfield, by 4 and 25% on cloudy and clear days, respectively. Allen (1975) showed that diffuse solar irradiance under shadenet was 38% greater than that outside the shadenet.

In a sweet pepper study, Moller and Assouline (2007) demonstrated that 30% black shadenets transmit 56% of the solar irradiance. Solar irradiance transmission under the shadenet may decrease with time due to dust and algae accumulation. Smit (2006) found that 20% black shadenet reduced PPFD by 22, 29 and 31% measured on different dates and concluded that reduction in PPFD was not detrimental to the photosynthetic capacity of the leaves.

In a tomato study, Kitta *et al*. (2012) measured solar irradiance below four different shadenets, and concluded that the transmission was roughly correlated with the initial shading intensity. Shadenets with 34 and 49% shade factors have the largest and lowest transmissions, respectively, for both PAR and short-wave radiation. However, Smit (2006) and Kitta *et al*. (2012) did not show a link between shading properties and transmission percentages as different shading material have different transmission percentages for different environmental conditions. The transmission properties provided by manufacturers are based on simulated laboratory conditions instead of environmental conditions (Tanny, 2013).

2.2.2 Wind speed and direction

Shadenet structures are designed to prevent excessive wind and decrease the internal mean wind speed (Teitel, 2007; Tanny, 2013). Waggoner *et al*. (1959) measured wind speed at a height of 1 m under and outside an empty shadenet. The study concluded that wind speed reduction within the shadenet is due to the resistance induced by shadenet.

Tanny (2013) defined a non-dimensional wind speed measurement height as: $Zs = (\frac{(Z-hc)}{(Hs-hc)})$ where z is wind speed measurement, height, H_s is shadenet height, and h_c is the canopy height (Tanny *et al.*, 2006). However, the formula is applicable to vegetables and cereal crops and not tree crops. Desmarais *et al*. (1999) measured wind speed at a 3.2-m height inside and outside the shadenet, but did not provide a specific relationship between inside and outside measurements. Siqueira *et al.* (2012) reported that wind speed increased with height from the top of the tree canopy to the roof top of the shadenet.

Air movement and direction under shadenet is important for the identification of microclimate heterogeneity and spotting regions prone to low ventilation (Tanny, 2013). Moller *et al.* (2003) demonstrated that over the windward half of the shadenet, air flow direction was opposite to the external wind and inside and outside of the shadenet, air flow was in the same direction. Shadenets are designed to reduce the pressure drop which resist air flow under the shadenet (Teitel, 2007, Savage, 2014).

2.2.3 Temperature and relative humidity

Air temperature is a combined product of several real-time energy transfer processes which include radiation exchange, convection (ventilation) and evapotranspiration (Kimball *et al.*, 1997). The shading effect of shadenets reduces the amount of incoming radiant energy, and has the potential to reduce air temperature (Kimball *et al*., 1997; Savage, 2013; Tanny, 2013).

Canopy temperature, i.e. leaf and fruit temperature measurements, is a crucial component of energy transfer. Accurate measurements of the leaf-to-air temperature gradient is essential in determining transpiration rate. Leaf temperature range for maximum net CO_2 assimilation is between 20 and 30 ^{o}C and anything outside this range, reduces CO_2 assimilation (Bower *et al*., 1978).

Avocados are grown under a wide range of temperatures. The South African avocados are grown in subtropical areas (warm to cool climates) with temperature extremes. Furthermore, the area is divided into warm and cool subtropical based on the mean annual temperature (MAT). Mooketsi has a MAT of 21 ˚C and the area is frost free but other parts of Tzaneen may experience light frost due to cool clear skies. Air temperatures above 35 ˚C lead to greater fruit drop in September-October and January-February (Wolstenholme, 2011a).

Shadenets also emit infrared radiation to the sky and cool the adjacent air layer. Therefore, at 1 m above the ground, air under shadenets is cooler than that outside. This is due to the sinking of cool air from the shadenet (Waggoner *et al*., 1959; Savage *et al*., 1996; Tanny, 2013). Tanny *et al*. (2009) observed that air temperature in an apple orchard with different levels of shading was lower by 1.4 ^{o}C than the open treatments. The study also found that during night-time, air temperature under shadenets was about 0.3 ^{o}C greater than the open treatment. This was due to reduced net infrared radiative loss under the shadenet.

Moller and Assouline (2007) showed air temperature under the shadenet to be lower than that outside the shadenet, and the maximum greenhouse effect inside the shadenet did not exceed 1.0 ^{o}C. Kittas *et al*. (2012) showed that air temperature under different shading treatments was similar to that outside the shadenet. Rossel and Ferguson (1979) studied a small shadenet house covered with ultraviolet stable fine-mesh polyethylene shadenet which reduced PPFD by 40% and was insect-proof.

Desmarais *et al*. (1999) showed that during the daytime, for a 50% shadenet, air temperature was about 3 ^{o}C higher under the shadenet than outside. Spraying water on the 32% shadenet resulted in differences of about 1 to 2 ^{o}C between inside and outside the shadenet. Tanny *et al*. (2008) investigated the effect of roof height on air temperature and humidity in a 60% shadenet. These authors concluded that net irradiance is identical under shadenet. Air temperature near the plants, as well as leaf temperature was greater in the lower shadenet than in the higher one.

Air temperature influences avocado tree flowering, synchrony and fruit set (Sedgley and Annells, 1981). Mickelbart *et al*. (2012) observed that there is no clear relationship between air temperature prior to and during flowering. Sedgley and Grant (1983) postulated that air temperature may affect fruit set and yield by alternating the timing of male and female flowering. Wolstenholme (2011b) stated that Type A cultivars, e.g. 'Hass', are more cold tolerant during flowering compared to Type B cultivars and that Type A flower early in warm subtropical areas of South African flower.

However, Ish-Am (2008) found that there is a significant negative linear correlation between avocado flowering times and the average daily air temperature at 20 ^{o}C. On a warmer day (>25 ^{o}C), flower opening follows a normal opening sequence for Type A or B cultivars. But during cooler days (14 ^{o}C), flower opening is delayed or postponed into the night, or even the next morning.

In Israel, over-head irrigation reduced air temperature, thereby increased relative humidity (RH) during heat waves. RH affects photosynthesis either because of changes in stomatal conductance or because of non-stomatal response. RH is the ratio of the quantity of water vapour in air at a given temperature relative to the water vapour pressure deficit (VPD) (maximum quantity of water vapour the air can hold at that temperature relative to the water vapour pressure) (Bower, 1978).

Siqueira *et al*. (2012) reported an increase of about 35% in the VPD under shadenet (at 5-m height) compared to the value at the same height above an open banana orchard. Tanny *et al*. (2008) found that RH in a 3.2-m high insect proof shadenet used for pepper was greater within the foliage layer and decreased towards the shadenet roof. The authors concluded that this vertical gradient in humidity resulted from the upper region of the shadenet interacting strongly with the lower air atmosphere. There is less air movement and a reduced evopotranspiration gradient inside than outside the shadenet.

2.3 Soil-plant water relations

Enlargement of the wetted soil volume and root growth of an avocado orchard improves water uptake. This allows increased transpiration rate under high climatic conditions, preventing canopy water stress (Cantuarias, 1995).

2.3.1 Soil water stress

Plants experience water stress either when root water supply becomes limiting or when the transpiration rate becomes greater than available water. Water stress is caused by water deficit, i.e. drought or high soil salinity. Drought limits plant productivity in many parts of the earth under agriculture or forestry production (Chartzoulakis *et al*., 2002).

Photosynthesis is also affected by water stress and decreases with a decrease in leaf water potential. This results in metabolic changes with functional and structural re-arrangements of photosynthesising apparatus (Lisar *et al*., 2012). Chernyard’ev (2005) found that the photosynthetic rate in leaves for C_3 (avocados) and C_4 plants decrease under water stress. The study also indicated that C_4 plants photosynthesis is more sensitive to water stress. Water stress reduces the supply of CO_2 from the environment due to stomata closure of stomata (Furini and Bernacchia, 2004, Ghannoum, 2009).

Nunes *et al*. (1989) stated that maintaining photosynthetic capability during periods of water stress is important in plant adaptation to drought environments. Root-to-shoot ratio increases under water stress in order to facilitates water absorption. This also helps maintain osmotic pressure, although the root dry mass and length decreases.

Kamel and Loser (1995) showed that plant growth is directly proportional to the soil water availability. Water stress creates an imbalance between PPFD interception and its utilization. In summer, avocado water stress in summer disrupts physiological processes and limits productivity (Chartzoulakis *et al.*, 2002, Ferreyra *et al.*, 2007). Schaffer *et al*. (2013a) postulated that water stress also limit root expansion and likely to reduce stem water potential and biomass production (Moore-Gordon *et al.*, 1996, Dixion *et al.*, 2007).

Sterne *et al*. (1978) and Whiley *et al*. (1988) demonstrated that phytophthora root rot also limits plant water potential under severe water stress conditions. Water stress during early fruit development is also linked with fruit physiological and pathological disorders. Thus water stress can lead to poor fruit set, reduced yield and increased fruit drop. It is essential that avocado orchards be irrigated so that water needs are adequately met, i.e. deficit irrigation (Blanke and Lovatt, 1993; Mickelbart *et al*., 2000).

2.3.2 Water use efficiency (WUE)

One-third of the earth's surface area is occupied by water, but only 2.5% of the total water on earth is fresh water. However, most of the fresh water is locked up in glaciers and ice caps and a meager 0.3% of the earth's freshwater resources constitute lake and river storage (Shiklomanov, 1993). Human use contributes 26% of total terrestrial evapotranspiration and 54% of runoff that is geographically accessible (Nair *et al*., 2013). The agricultural sector uses about 80% of the freshwater supply of the world for its food supply (Shiklomanov, 1993, Clothier and Green, 1994, Seckler, 1996, Nair *et al.*, 2013).

The term water use efficiency (WUE) evaluates the efficiency of water use focusing on the beneficial use of water, crop performance, irrigation systems and movement of water in and out of definite areas such as a field, service area of a basin, or area overlying an aquifer (Nair *et al*., 2013). WUE may be measured in terms of crop output per unit of water, e.g. tons per kL used in contrast to the standard efficiency measure of dimensionless output to input ratio. Jones (2004) argued that the term WUE is a misnomer owing to the fact that only an insignificant portion of the water used for crop transpiration is assimilated by the crop and is not a true efficiency measure.

WUE is used in multiple contexts within different disciplines, i.e. physiologists, agronomists, irrigation scientists and agricultural economists. However, physiologists and agronomists perceive water use as technical efficiency (yield per unit of water used), economists consider the economic efficiency the economically optimal resource use, and where the marginal benefit is equal to the marginal cost (Jones, 2004).

The physiologist's definition of water use efficiency can vary depending on where the water is located relative to the plant, the time scale of measurement and the relationship of the measure of efficiency with carbon gain (Kremer, 1983, Kremer and Boyer, 1995). Physiologists measure the carbon gain in relation to biomass accumulation (Bacon, 2004; Nair *et al*., 2013).

Irrigation scientists strive to provide water for crop transpiration from a source with minimal losses in between. The term efficiency is most commonly used by the irrigation scientists to describe the ratio of the water used by the crop to the water diverted from the source (Burt *et al.*, 1997). Hence, it is expressed as a volume per volume of water basis (Pierce and Nowak, 1999, Whelan and McBratney, 2000). This concept differs from that of physiologists, who perceive efficiency as the mass of photosynthates produced per volume of water used in kg m^{-3}.

Agronomists are mainly concerned with maximising biomass production or crop yield per unit of water used. The major difference in the efficiency concept between physiologists and agronomists is that, the different possible water losses during crop production are not considered (Bos, 1980, Howell, 2001). One major source of loss is the evaporation loss from the soil, especially during the early stages of crop growth when the ground covered by the crop canopy is very small. Agronomists take into account soil evaporation and perceive water use efficiency as the ratio of the dry matter produced or the economic yield of a crop plant to the evapotranspiration (Nair *et al.*, 2013).

The economic efficiency is generally expressed in net profit per unit of irrigation water applied. The efficient level of irrigation application is the profit maximising level of irrigation taking into account all costs and crop yield response to irrigation (Beattie *et al.*, 2009). Efficient use of irrigation water occurs when marginal revenue (price of the crop produce in a perfectly competitive market) is equal to the price of water (Seckler, 1996; Nair *et al.*, 2013).

Jiao *et al*. (2004) showed that irrigation and rainfall affects fertilisation and nutrients. Efficient irrigation methods such as irrigating based on crop evapotranspiration (ET) or soil water sensors minimize over-irrigation while not affecting yields (Silva *et al.*, 2009, Migliaccio *et al.*, 2010); and subsequently reduce nutrient leaching (Kiggundu *et al*., 2012). However, over irrigation in avocado orchards makes the roots prone to phythophtora root rot diseases (Lahav and Whiley, 2002).

Patridge (1997) postulated that micro-sprkinklers should be used for irrigation as these allow for optimal root hydration. The study also found that mulching during dry periods reduces soil temperature and evaporation. Wolstenholme *et al*. (1997) and Wolstenholme (2013) stated that mulching is beneficial against stressful climatic conditions. They also found that mulching reduces tree water stress and leaf canopy temperature which significantly reduces rate of transpiration as stomata cells only close under high carbon dioxide conditions and under darkness.

2.3.3 Evapotranspiration (ET$_o$)

Evaporation is the loss of water vapour from living tissues and influenced by the physiology of the plant. Evapotranspiration is an estimate of water loss from the soil by evaporation and transpiration by vegetation. Transpiration is the loss of water through plant stomata or leave cuticle (Salisbury and Ross, 1992). It is an integrated measure of the meteorological variables (solar radiation, air temperature, RH and wind speed), along with other crop attributes (Tanny, 2013).

Evapotranspiration is a key parameter in irrigation management. Canopy ET$_o$ changes under shadenet does not depend on meteorological modifications alone, but on the crop as well. In a pepper study, Moller *et al*. (2004) found that the main factors contributing to reduced ET$_o$ in shadenet were solar irradiance and air temperature, VPD and wind speed. In avocado, evaporation is associated with increased transpiration (Whiley *et al.*, 1988). Growers increase irrigation from flowering to fruit set to reduce water stress and high air temperatures.

Avocado stoma respond to temperature variations faster than they do to changes in air humidity. Trees respond to high evaporative demand, as air temperature increases (Bower *et al.*, 1977). High air temperature will increase the saturation water vapour pressure (Whiley *et al*., 1988). During avocado flowering, increased transpiration in response to greater potential transpiration levels is restricted to 10 mm day^{-1} (Cantuarias, 1995, Nicolas *et al.*, 2008).

However, non-restricted soil water availability improves the response of avocado transpiration to variations in evaporative demands. Cantuarias (1995) concluded that during periods of high evaporative demand, drip-line irrigated trees showed greater transpiration rates than micro-sprinklers. In most cases, drip-lines do not wet the entire root zone. Micro-sprinklers are more efficient at wetting the root zone particularly at the surface since avocados have shallow spreading roots.

2.3.4 Sap flow

Sap flow refers the rate at which water moves up the xylem and is lost to the surrounding atmosphere. In plant stems sap flows from the xylem cells or sapwood as a result of rising temperature and pressure. The sapwood consists of actively growing cells that conduct water and nutrients from the roots to the branches of the tree (Biddulph, 1959, Denmead, 1984). This is known as ascent of sap process due to simultaneous occurrence of transpiration, capillary rise and bulk flow (Levitt, 1974).

In tree plant, sap flow delays transpiration by 15 to 45 minutes (Hinckley, 1971, Steinberg *et al.*, 1989). The pressure causes the sap to flow out of the tree through a wound or tap hole. But under cool environments, suction is developed and draws water into the tree through roots. Sap flow meters are used to measure the rate of transpiration in plants (Dynamax, 1997).

There are various techniques for measuring sap flow. For the purposes of this review only, three methods will be discussed, namely; the stem steady state heat energy balance technique (SSSHEB), heat pulse velocity (HPV) and Granier's thermal dissipation. These techniques use heat to measure sap flow. The SSSHEB and HPV techniques are the most frequently applied methods for sap flow. They are empirical and critically dependent on assumptions. Assumptions depend upon circumstances may depart from reality to varying degrees (Bloodworth *et al.*, 1955, Closs, 1958, Daum, 1967, Landsberg *et al.*, 1976, Kucera *et al.*, 1977, Baker and van Bavel, 1987, Steinberg *et al.*, 1990).

The SSSHEB technique requires measurement of heat flux conducted through plant trunk or branch. But other stem steady state techniques use multiple instead of single dynamic output heaters, which potentially, eliminate a need for dynamic measurements of conducted heat flux, i.e. sap flow is measured directly. The technique also reduces transient errors due to changes in heat flux to and from storage with plant tissue temperature changes (Baker and Nieber, 1989).

The SSSHEB technique requires two empirical constants, i.e. $Kstem$ and $Kgauge$. $Kstem$ varies in and between plants with differences in plant stem anatomy. $Kgauge$ is approximated *in situ* under zero sap flow conditions but is prone to error introduced from limited equipment precision, sampling procedure and model-error residuals (van Bavel, 1992, Savage *et al.*, 2000).

The HPV technique also has a number of varying techniques. They differ in placement distance and arrangement of sensors, heater output, the method of calculating HPV and determining the ratio of the specific heat capacity of conducting xylem wood to that of sap. The HPV technique is made around the assumption that the stem is an infinite homogeneous, porous material with constant thermal conductivity (Savage, 2000). But the heater and temperature probes are of finite size and have different thermal properties to the surrounding three dimensional stem tissue. The HPV method only measures the sap velocity whilst sap flux requires knowledge of the conducting area of the xylem (Miller *et al.*, 1980, Cohen *et al.*, 1981, Steinberg *et al.*, 1989).

The TDP or Granier heat dissipation method is an empirical method for determining sap flow in trees with diameters greater than 40 mm. Two cylindrical probes are inserted radially into the stem about 100 mm apart. The upper probe contains the sensing thermocouple and a heater and the lower probes contain a thermocouple. Constant power is supplied to the heater and the temperature difference is empirically related to sap flow. Temperature difference is measured under flow and no sap flow conditions and using values of the sap density and the area of the sap wood, thereafterthe mass flow rate of sap can be computed (Granier, 1985, 1987, Dynamax, 1997).

Measham *et al.* (2014) monitored sap flow in cherry fruit pedicels using the heat pulse technique. The study found that sap flow in cherry fruit is linked to ambient VPD (water vapour pressure deficit) even under non water stress conditions. Livellara *et al*. (2011) found that VPD is linked to sap flow in apples. However, both studies where based on leaf-fruit sap flow instead of entire tree sap flow.

Savage *et al*. (2000) found that when a portion of the tree is shaded from the incident solar irradiance, there is an immediate decrease in sap flow rate implying a rapid response to physiological events. But when the shading was removed, sap flow immediately increased. Thus, tree water capacitance does not affect measurements of sap flow at high water potential (Nicolas *et al.*, 2004, 2005).

Ansley *et al*. (1994) found sap flow and transpiration estimated by porometry from honey mesquite had similar diurnal patterns except when transpiration rates increased during the afternoon while sap flow declined. This is due to the hydraulic capacitance of plants, which can be involved in transpiration of plants with large stems.

Nicolas *et al*. (2008) monitored sap flow over 2-year old lemon trees grown under shadenet. The study found that the rate of sap flow was reduced under the shadenet compared to the open treatment. They concluded that the reduced sap flow rate and maintenance of photosynthesis under shadenet is key in reducing plant water stress and increasing water use efficiency. Also, enlarging the wetted soil volume up to 75% increases the root growth rate and improves tree water status and transpiration response to high evaporative demands (Cantuarias, 1995).

Heath *et al*. (2005) found that the conductance of avocado leaves continue during the night. Thus, stoma do not completely close and the rate of sap flow is low. Under such conditions, the tree would be expected to have a lower water potential in the morning and any water deficit problems would begin earlier in the day which closes the stomata and reduces assimilation. Thus sap flow is dependent on the number of leaves carrying out transpiration.

Also, different branches have a different number of leaves which gives rise to different flows. Under closed stomata, particularly at night, water status of the entire plant reaches equilibrium which results in zero flow. Fassio *et al*. (2009) found that ‘Hass’ on Duke 7 rootstock had a 29% greater sap flow rate than ‘Toro Canyon’ rootstock trees. The authors concluded that water consumption of ‘Hass’ on different rootstocks is associated with differences in efficiency of the roots to absorb water across conductive tissues linked to differences in the area of the xylem vessels in the root.

Transpiration rate is greater during avocado flowering and this may impose alternate bearing in fruit (Scholefield *et al.*, 1985). Banke and Lovatt (1992) found that avocado flowers resemble the foliage leaves in a protective cuticle and stomata but transpire more than the foliage leaves. The low transpiration rates in leaves is associated with stomatal closure during the day thus allowing the sap to flow to the flowers and fruits for growth and development.

2.4 Conclusion

The common goal among producers is producing food of excellent quality following good agricultural practices. The South African avocado is ranked among the best in the world due to producing fruit of excellent quality and year-on-year supply to local and export markets. The success of the industry is attained through innovative research, co-ordinated by SAAGA (South African Avocado Growers Association).

SAAGA's research focus over the past 35 years was on phytothtotora root rot, rootstock development, postharvest innovation, 'Hass' small fruit problem, etc. Now, with climate change impacts, it is imperative for the avocado industry to address the phenomenon. Thus research focus also has to be on production and pre-harvest. For the avocado industry this means addressing issues of sunburn, wind damage and small fruit size as a result of soil water stress.

'Hass' is the standard cultivar for choice and excellent for local and export markets. Again, fruit quality problems associated with 'Hass' are severe. However, the search for improved "Hass-like" cultivars is motivated by fruit quality defects observed in current cultivars for export markets. There is limited research conducted on 'Carmen®-Hass' thus the literature cited was based on 'Hass'.

Literature cited on crops other than avocados has shown that shadenet does improve agricultural production by manipulating microclimate conditions and this lack of knowledge is the motivating factor for the research proposed in Chapter 1. This implies that the industry will be able to overcome its challenges through the use of shadenets. However, no research has been conducted on the use of shadenet on avocado production. This implies that changes in orchard management will have to be employed. Thus this can be translated into a learning curve for adapting to climate change and global warming.

CHAPTER 3: MATERIAL AND METHODS

3.1 Site and plant material

The experiment was conducted in a commercial avocado orchard in Mooketsi, South Africa (23^{o} 40’ 53” S and 30^{o} 1’49’’ E). The study was conducted during the 2013/14 and 2014/15 production seasons. A 1-ha shadenet structure was constructed at Goedgelegen Estate, Mooketsi, Limpopo province in 2013. The area has a mean annual rainfall of 550 mm, zero frost days, annual mean maximum and minimum air temperature of 25 and 16 ^{o}C, respectively (Holland, 2001). A 20% shadenet (Figure 3.1) was selected for the study (Alnet Pty Ltd). ‘Carmen®-Hass’ trees were grafted on Dusa™ rootstock and planted in 2007.

Table 3.1 Summary of trial design

Location	**Cultivar**	**Area (ha)**	**Plant spacing (m^{-2})**	**Shadenet**	**Height (m)**
Goedgelegen Farm Estate[1]	‘Carmen®-Hass’	1	3 m x 3 m 6 m x 3 m	20% white	6,5

[1] Mooketsi, Limpopo province, South Africa. 701 m altitude, latitude of 23^{o} 40’ 53” S and longitude of 30^{o} 1’49’’ E

Figure 3.1 White shadenet structure over roof top with 40% green on the sides constructed at Mooketsi Valley

3.2 Microclimate

3.2.1 Automated weather station (AWS)

A summary of the AWS and sap flow measurements under the shadenet and open treatment is presented in Table 3.2. To investigate the microclimate of the area, two weather stations and stand-alone air temperature/relative humidity data loggers (Hobo units) were installed both under the shadenet and in the open treatment (Figures 3.1). Figure 3.2 illustrates the AWS components which are also listed in Table 3.2. The weather stations were only installed at the center of the 6 m x 3 m blocks and met the minimum recommendations used by Savage (2012) for AWS system measurements and placement away from obstacles. Two additional air temperature/relative humidity sensors were installed both under the shadenet and in the open treatment at the near and far end of the 6 m x 3 m blocks to investigate any heterogeneity in air temperature and relative humidity.

Table 3.2 Automated weather station and sap flow measurements under the shadenet and open treatment and relevant base-station system details

Station details	Shadenet and open treatment details
Sensor	Hobo[1] units (models H8 Temp or RH/Temp) in seven-plate Gill-radiation shields at 2 m height, solar irradiance (CM3[2]), wind speed[3] (model 03101), leaf wetness sensors[4], IRT[5] (Infrared thermometry) and TDP[6] sap flow meter
Logging equipment	21X and CR10X dataloggers[7]
Power details	Connected to 14 A h (sap flow) and 18 A h (AWS) 12-V batteries
Software	Base station software was PC200[7] for data downloads

[1] Onset Computer Corporation, Bourne, MA, USA

[2] Kipp & Zonen BV, Delft, Netherlands

[3] RM Young Company, Traverse City, MI, USA

[4] Model LWS, Decagon Devices Inc., Pullman, Washington State, USA

[5] Apogee IRT model IRR-P (Half angle of 45˚): Apogee Instruments Inc., Logan, Utah, USA

[6] Dynamax TDP sap flow meter (30 mm needles), Dynamax Inc., Houston, Texas, USA

[7] Campbell Scientific, Inc., Logan, Utah, USA

Figure 3.2 Leaf wetness sensor (left) and CM3 pyranometer (right) above tree canopy

The data loggers were programmed to log every 10 seconds and record data hourly whilst the Hobo units were programmed to log hourly. Solar irradiance was measured above tree canopy and the pyranometers were placed at 4 m. Thermoelectric sensors (pyranometers) with a waveband of 250-2800 nm were used in the study.

The leaf wetness sensors were positioned at 45^{o} to the horizontal at 500 mm above the ground and 3 m away from the nearest tree. Best position for leaf wetness sensors is at the top of the canopy. But the sensors are prone to infrared and ultraviolet radiation, therefore inside the canopy leaf wetness duration is overestimated (Rowlandson, 2011). A UV tech (McNett; Bellingham; USA) spray was applied every 6 weeks to shield leaf wetness sensors against an ultraviolet and infrared radiation (Savage, 2012). As stated by the manufacturers, Decagon Devices, calibrations is not required. The manufacturer (Decagon Devices) recommends that leaf wetness sensor (LWS) voltage of less than 274 mV corresponds to a dry leaf and that equal or greater than 284 mV corresponds to a wet leaf. The IRTs were positioned at 45^{o} to the horizontal and facing south at a height of 3 m and the target area was 9 m^{2}. IRT's were faced south because they need to be in the opposite direction relative to the sun. Based on orchard positioning the sun rises from south of east and sets north of west. Data from the AWS were used to compute short-grass reference evapotranspiration for both treatments.

3.3 Soil-plant water relations

3.3.1 Soil matric potential

A soil water study was conducted with tensiometers. Two tensiometers were installed on each block both under the shadenet and open treatment. They were placed within the root zone at 300 and 600 mm soil depth within the rows (Figure 3.3). Tensiometers were serviced *in situ* prior to installation and placed adjacent to each other. According to Hanks and Ashcroft (1980), tensiometers have a dial, which is calibrated from zero to 100 kPa. Tensiometers measures low soil water tensions or wet ranges directly but may have to be re-saturated due to water cavitation which occurs as a results of soil drying to matric potentials less than -85 kPa or air flowing inside the porous cup (Vaz *et al.*, 2013).

Tensiometers measure the tension with which water is held in the soil and the soil water tension was determined by soil matric water potential (Ψ_m). The Ψ_m was expressed as the sum of the vacuum gauge and the difference in gauge and cup height and depth respectively, i.e. $\Psi_m = \Psi_{gauge} + (Z_{gauge} - Z_{cup})$ (Hanks and Ashcroft, 1980, Or and Wraith, 1999).

Figure 3.3 Tensiometers installed adjacent to each other at 300 and 600 mm soil depths

3.3.2 Sap flow (thermal dissipation method)

Granier (1985, 1987) developed the thermal dissipation method of determining sap flow in woody trees. This experimental method was designed for trees with diameters greater than 40 mm. Two cylindrical probes about 100 mm apart were inserted radially into the stem. The upper probes contained the sensing thermocouple and a heater. The temperature of the upper probe was referenced to the temperature sensed by the thermocouple in the lower probe (Figure 3.4). Constant power of 2.5 mV was applied to the heater and the temperature difference relates to sap flow (Savage *et al*., 2000).

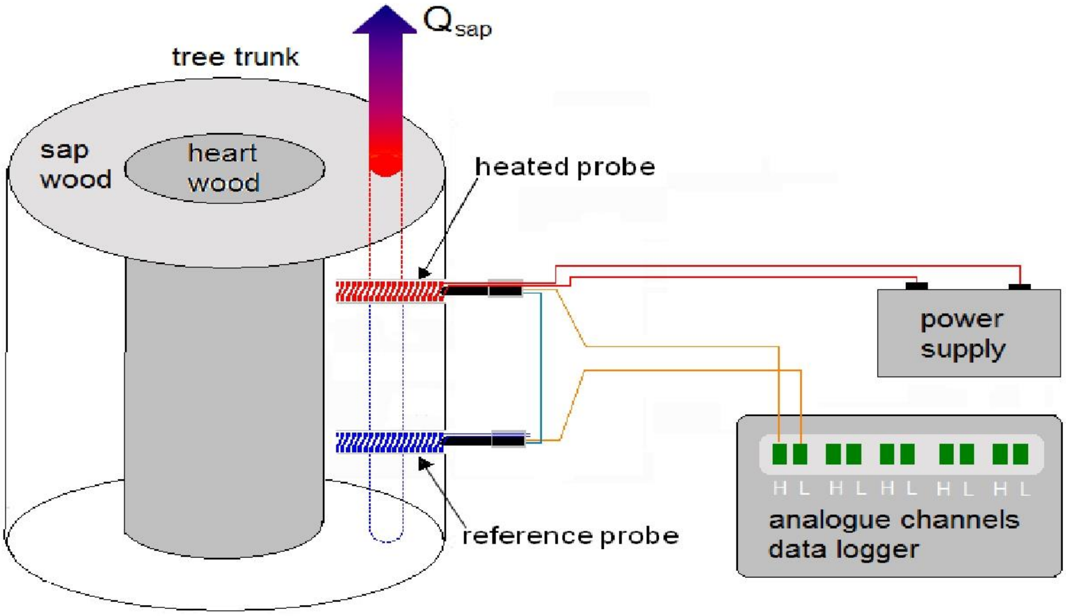

Figure 3.4 Scheme for TDP installation (Meinzer *et al*., 2005)

According to Savage *et al*. (2000), the temperature difference is measured under flow (ΔT) and no sap flow conditions (ΔT_o) and related to sap flow u_v in m^3 m^{-2} s^{-1}, where m^3 s^{-1} measures the sap flow and m^{-2} measures the reciprocal cross-sectional area of the sap wood. The mass flow is then calculated using; $F_w = \rho_s u_v A_{sw}$ where ρ_s is the sap density, u_v is the sap flow velocity and A_{sw} is the area of the sap wood.

3.4 Tree phenology

3.4.1 Leaf area

Fifty trees were sampled for leaf area both under the shadenet and open treatment. Leaf sampling was conducted on the 3 m x 3 m and 6 m x 3 m plant spacing block. Leaves were sampled around the tree(s) and selected trees were from every third row per block. Since 'Carmen®-Hass' produces new leaves every season, sampled leaves were identified as winter, spring, summer and autumn. The leaves were sampled and analysed according to seasonality. The leaves were analysed on a weekly basis using an imaging software (Java®, California) (Figure 3.5).

Figure 3.5 ImageJ software used to scan leaves for leaf area measurements

The leaves were calibrated in order to obtain the precise photosynthesising area of the leaf, i.e. the area measured using the ImageJ and the gradient and the intercept of the slope were used to calculate the actual area of the leaf. Leaves were sampled from mid-height around the tree.

3.4.2 Flowering, pollination and bee activity

The same number of trees monitored for leaf area were examined for flower intensity on a scale of 0 to 100. Flower and shoot rating were monitored on a scale of 1 to 5, where 1 implies no flower or shoot bud and 5 implies a fully developed flower or shoot (Alcaraz *et al.*, 2013, Salazar-Garcia *et al.*, 2013) (Figure 3.6).

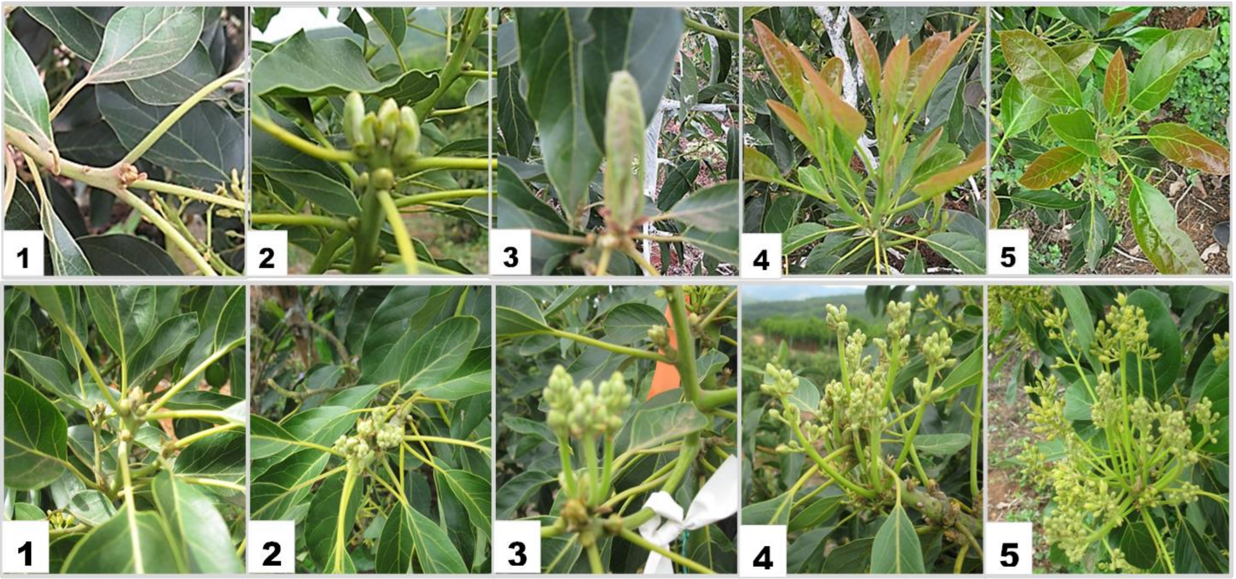

Figure 3.6 Shoot (above) and flower intensity (below) rating scales adapted from Salazar-Garcia *et al*. (2013)

The pollination study was conducted during the normal floral development season between July 2014 and August 2015. Five representative trees from each block were evaluated for pollination and bee activity. A single tree was selected every fifth row closest to the bee hives. On each tree, three inflorescences were tagged and five flowers per inflorescence were marked (Figure 3.7 and 3.8). The different stages of flower development from female and male opening to pollination were monitored.

The inflorescences were monitored every 2 hours from 8 am to 4 pm local time as suggested by Ish-Am (2008) and Alcaraz and Hormaza (2009a). A hand-held tally counter (KW-triO®, Pao Shen Enterprises Co., Ltd; Taiwan; China) was used to count the number of bees visiting the avocado tree in an area of 10 m^2. The count was done on the eastern and western sides of the tree. Both the pollination and the bee activity studies were evaluated on a weekly basis until the end of the flowering period. Five flowers were monitored per inflorescence and flower open over time was monitored. Also, changes in air temperature and relative humidity during the pollination and bee activity were observed. Flower stages terminology and bee scale used for the study according to Ish-Am (2008) is illustrated in Table 3.3 and 3.4.

Figure 3.7 Inflorescences tagged for pollination

Figure 3.8 Inflorescence with majority of the male flowers dehiscing pollen

Table 3.3 Female and male flower opening stage(s) terminology (Ish-Am, 2008)

Flower stage	Terminology
C1	Closed flower
F1	Female flower opening
F2	Fully opened female flower
F3	Female flower closing
F4	Closed female flower
M1	Opened male flower before releasing pollen
M2	Male flower releasing pollen
M3	Closing male flower
C2	Pollinated flower

Table 3.4 Bee activity scale (Ish-Am, 2008)

Scale	Number of bees per tree	Activity
0	0	No bees
1	1 to 4	Slight
2	5 to 9	Moderate
3	10 to 25	Moderate-
4	26 to 55	sufficient
5	>55	Sufficient
		Very sufficient

3.4.3 Shoot and fruit growth rate

For fruit growth, twenty trees were measured per block. Trees were selected every fifth and third row. Each tree was replicated three times, i.e. measurements were made from east, inside and western side of the tree. Measurements were taken from the mid-point of fruit or point of growth expansion and these points were marked on each fruit. Measurements were conducted on a weekly basis with a digital Digi-Max slide calliper (Sigma–Aldrich Co., Germany). The same number of trees used for fruit growth measurements were selected for shoot growth. For shoot growth, the area where growth begins was marked with a permanent marker and measurements were made from the marked point up to the bud tip (Figure 3.9). Each tree was replicated three times and tagged fruit and shoot were positioned on the east side, inside and western side of the tree canopy.

Figure 3.9 Fruit (left) and shoot (right) tagged and marked for growth maturity

3.5 Yield and postharvest

3.5.1 Fruit water content

Twenty mature fruit samples from each block were analysed for fruit water content. Samples were collected weekly until week(s) closer to harvest. Ten samples were drawn from each fruit around the equator with a cork borer. The fruit flush, i.e. not skin or seed of each sample drawn from the fruits were weighed and dried overnight in a convection oven at 70 °C. After drying samples were weighed to obtain dry weight and moisture content was calculated as:

$$Fruit\ water\ content = \frac{Fresh\ weight - Dry\ weight}{Fresh\ weight}\%$$

3.5.2 Yield and quality assurance

A postharvest trial was conducted at Westfalia Technological Services in Tzaneen, Limpopo province, South Africa. Fruit were analysed for quality assurance. For the 2014 normal and out-of-season fruit, four lug boxes were sampled from all four blocks. For the 2015 normal season, eight lug boxes were sampled, four of the eight boxes were cold stored and the remaining were stored at room temperature. The 2014 season, fruit were not cold stored because there were fewer fruit harvested compared to the 2015 normal season. The lug boxes were sorted for count size, i.e. according to their mass range classes and categorised into class 1, 2 and 3 for local and export market.

Fruit were analysed for sunburn, copper residue, and wind, mechanical and insect damage prior to ripening according to SAAGA and Department of Agriculture, Forestry and fisheries standards (Milne, 1998), once ripe, fruit were analysed for colour, grey pulp, vascular browning, bruising, seed health and seed germination (White *et al.*, 2009).

3.6 Statistical analysis

GenStat 14 (VSN International, London, United Kingdom) was used to analyse the fruit and shoot growth results.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This Chapter contains results and discussion of results as listed in the aims and objectives section (Section 1.4). The microclimate results and findings are discussed in Section 4.2. The discussion in Section 4.2, is on solar irradiance, air and canopy temperature, wind speed and leaf wetness duration under the shadenet compared to the open treatment. The results and findings for soil-plant water relations are discussed in Section 4.3. Section 4.3.1, discusses the result for rainfall, irrigation and avocado leaf litter nutrition whilst section 4.3.2 discusses ET_o (short-grass reference evapotranspiration) and sap flow. Section 4.4, discusses the results and findings on tree phenology. Also, findings and results on the behaviour of the 'Carmen®-Hass' flower opening and/or closing mechanism and mobility of the honeybees under the shadenet compared to the open treatment are discussed in Section 4.4.2. The results for the stages of fruit development and maturity are discussed in Section 4.4.3. The results for the 'Carmen®-Hass' yield and postharvest are discussed in Section 4.5. 'Carmen®-Hass' fruit are picked early in the year compared to the conventional 'Hass' cultivar and are not treated with ethylene inhibiting chemicals e.g., 1-MCP (1-Methylcyclopropene) for prolonged cold storage. Hence, postharvest results and discussions were solely based on the shelf-life, ripening nature and internal and/or external fruit quality measures.

4.2 Microclimate

South Africa is a water-scarce country, with high variability in annual rainfall. The agricultural environment is a complex and dynamic system. Also, the microclimate, the crop, biosphere, and management practices interact to determine yield production (Chirkov, 1979). Thus, water quality and quantity are major limiting factors in agriculture. The potential for shadenetting to modify orchard microclimate to make the environment more conducive to fruit production was investigated.

The South African avocado industry is export-oriented, so there is a commercial need to optimise exportable percentage of avocado fruit. Sun- and wind damage and small fruit size as a result of water stress are the major cull factors for South African avocados. It is hypothesised that shadenetting, with changes in management practices, can counter these limiting factors. Since microclimate is an important determining influence on yield and fruit quality was studied in detail. A summary of the mean microclimate measurements collected in this study are shown in Tables 4.1 and 4.2.

Relative humidity (RH) was marginally greater in summer and less in winter under the shadenet compared to the open treatment. But water vapour pressure deficit (VPD) was marginally greater in winter and summer whilst solar irradiance was less under the shadenet compared to the open treatment (Table 4.1). Also, the maximum air temperature under the shadenet was greater compared to the open treatment except in August and December 2014. However, maximum canopy temperature were reduced under the shadenet compared to the open treatment for the same period. Furthermore, the minimum canopy temperature under the shadenet was generally warmer under the shadenet compared to the open treatment (Table 4.2).

The temperature, VPD and RH are important environmental elements which govern plant growth by influencing stomatal opening and closure and the rate of transpiration within the plant leaves (Pallas, 1961, Sinha, 2004). Based on the results illustrated in Tables 4.1 and 4.2, there were monthly variations in air and canopy temperature, RH and VPD. Also, solar irradiance was reduced under the shadenet compared to the open treatment. The results shown in Tables 4.1 and 4.2 are discussed in detail in Sections 4.2.1, 4.2.2 and 4.3.2.

Table 4.1 Monthly mean microclimate data for winter, spring and summer 2014 growing seasons under shadenet and open treatments

Monthly means	Relative humidity (%)		Water vapour pressure deficit (kPa)		Solar irradiance (MJ m^{-2})	
Treatment	Shadenet	Open	Shadenet	Open	Shadenet	Open
July[1]	57,33	57,70	0,99	0,96	21,64	28,95
August[1]	57,06	54,87	1,02	1,01	28,58	35,80
September	52,06	55,33	1,02	1,00	[2]	[2]
October	58,25	59,03	1,19	1,19	38,15	45,04
November	65,28	64,39	1,60	1,59	24,71	29,86
December	75,06	74,03	1,78	1,75	25,33	30,66

[1] Winter measurements from July-August, spring measurements from September-October and summer measurements from November December.

[2] Instrument failure

Table 4.2 Maximum and minimum air and canopy temperature under shadenet and open treatments for the 2014 season

Monthly means	Max air temperature (°C)		Min air temperature (°C)		Max canopy temperature (°C)		Min canopy temperature (°C)	
Treatment	Shadenet	Open	Shadenet	Open	Shadenet	Open	Shadenet	Open
July	31,71	30,98	4,76	4,63	28,90	29,42	5,06	4,49
August	31,11	31,83	4,01	6,17	34,63	35,81	1,10	0,76
September	37,38	37,34	5,62	5,63	35,24	37,55	6,69	6,41
October	38,44	38,37	9,74	9,90	40,04	40,60	8,67	7,65
November	38,56	38,50	9,88	9,71	38,92	39,42	9,74	9,61
December	38,78	36,91	11,42	11,35	38,48	38,55	10,80	11,84

4.2.1 Effects of solar irradiance on tree canopy

A comparison of solar irradiance under the shadenet and the open treatment during the 2014 and 2015 growing seasons is shown (Figures 4.1, 4.2 and 4.3). Solar irradiance under the shadenet compared to the open treatment was reduced by 18%. On average, the amount of solar irradiance transmitted through the shadenet compared to the open treatment was 80 – 82% (data not shown). The variation in solar irradiance under the shadenet and the open treatment was pronounced at midday. In winter of 2014 and 2015, maximum solar irradiance at midday on the open treatment was 800 W m^{-2}, whilst in spring of 2014 and 2015, it was 1000 W m^{-2} (data for spring 2014 not shown). During overcast weather condition, solar irradiance values were below 200 and 300 W m^{-2} under shadenet and open treatment, respectively (Figure 4.3). Figure 4.3, showed that there was a varying degree in solar irradiance between overcast and clear skies.

During overcast conditions, the sky solar irradiance values were less than 300 and 200 W m^{-2} for the open treatment and under the shadenet. In the summer of 2014 and 2015, solar irradiance values were above 1000 W m^{-2} and 1200 W m^{-2} under the shadenet and for the open treatment, respectively. A similar trend was observed in autumn of 2015 (data not shown), whereas, under overcast solar irradiance, values for summer and autumn were below 600 and 400 W m^{-2}, respectively. Solar irradiance values below 300 and 200 W m^{-2} in both treatments were as a result of rainfall.

The solar irradiance transmitted was more stable under clear sky and variable under overcast sky conditions. The results are similar to Kitta *et al*. (2014), who found that the solar irradiance transmitted is stable for clear skies and reduced by overcast skies. But their pearl, white, and green shadenets had shading factors of 13, 34, and 36%, respectively, in a sweet pepper study, were less and greater than that of the current study. Also, sweet peppers grow to a specific height without interfering with the solarimeters as opposed to tree crops which can shade the instrument. According to Stamps (2009), a greater shading factor results in reduced solar irradiance which maintains a stable transmission coefficient depending on sky conditions. Under the shadenet, solar irradiance measurements obtained above tree canopy are also affected by dust accumulation and aging of the shadenet (Haijun *et al*., 2015).

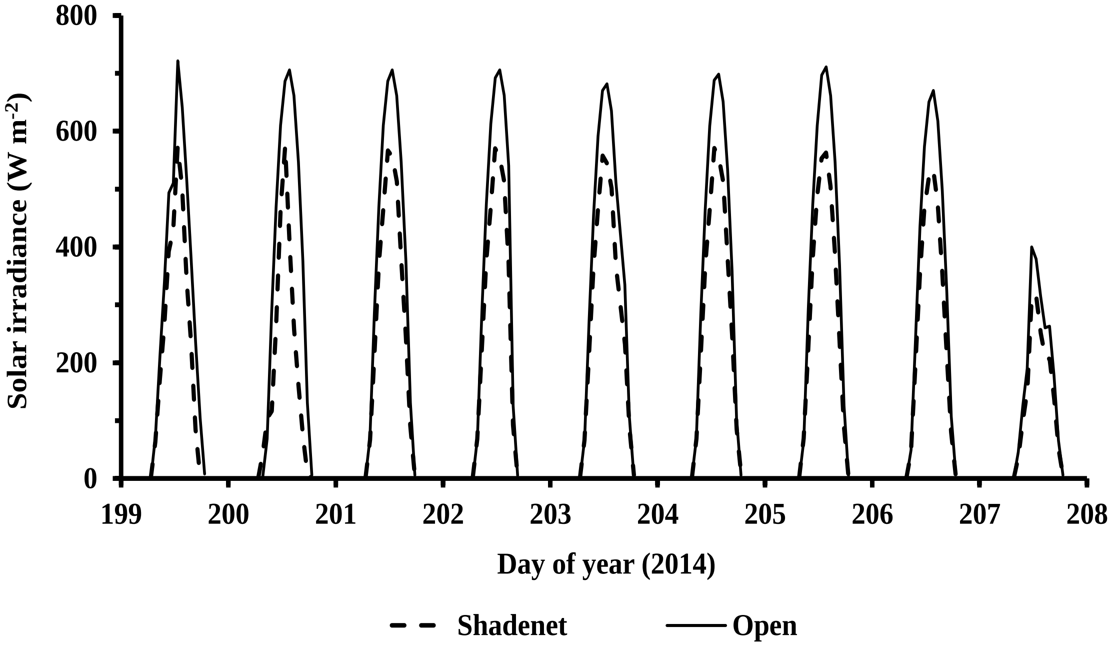

Figure 4.1 Hourly solar irradiance under the shadenet compared to the open treatment for the 2014 winter season

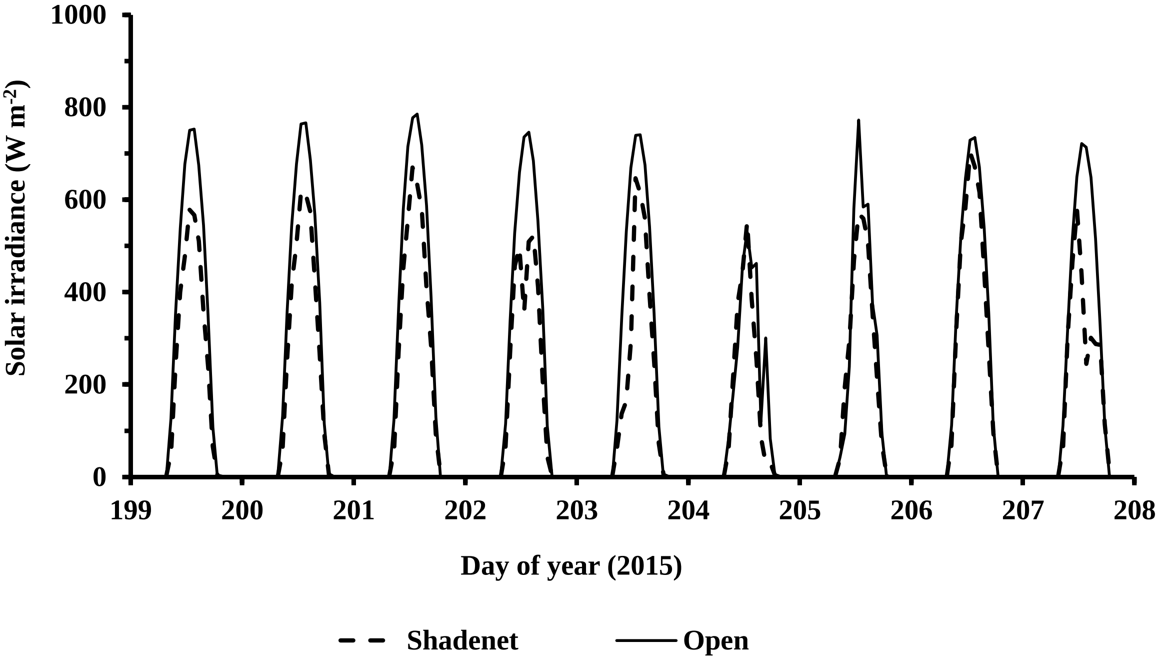

Figure 4.2 Hourly solar irradiance under the shadenet compared to the open treatment for the 2015 winter season

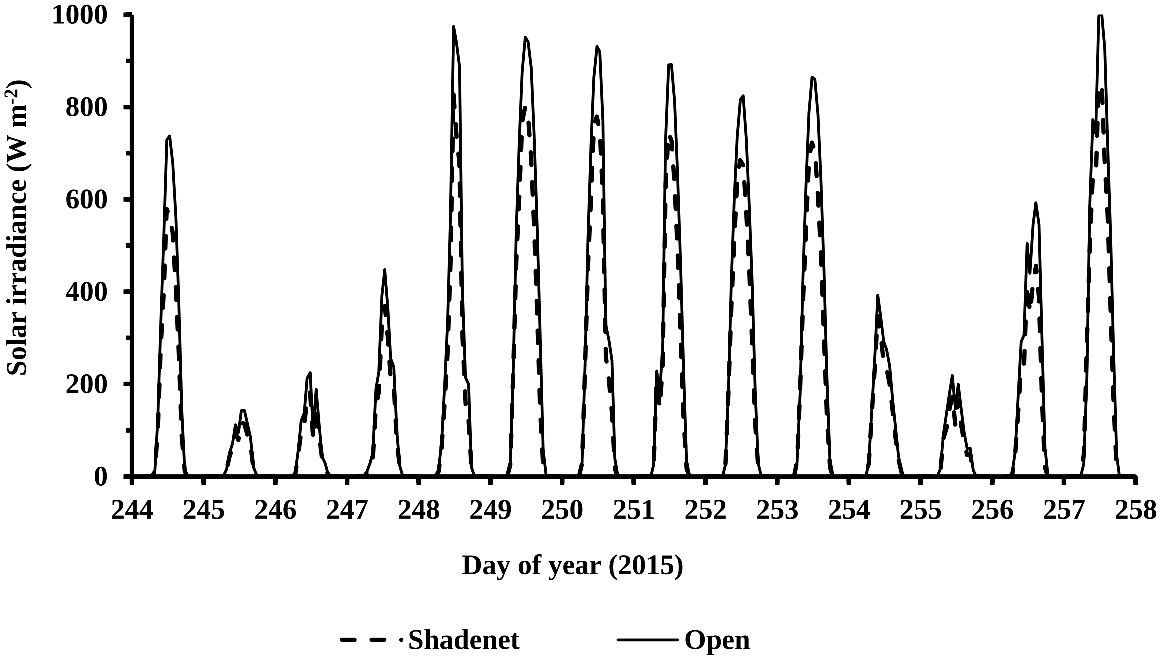

Figure 4.3 Hourly solar irradiance under the shadenet compared to the open treatment for the 2015 spring season

Figure 4.4 The results of sunburn for the open treatment. Different sized fruit are burnt-from golf ball size (left) and mature stage (right)

Solar irradiance entering the shadenet is reduced and in the form of diffuse radiation, resulting in no sunburnt fruit under the shadenet. Similar findings were reported by Smit (2006) and Do-Amarante *et al*. (2011) on apple studies. Sunburn occurs as a result of high air and fruit surface temperatures, and ultraviolet radiation. Only sun-exposed fruit were sunburnt when compared with fruit shaded by the canopy foliage. Sun-exposed fruits, which are a result of determinate inflorescences (Salazar-Garcia *et al*., 1999), become prone to sunburn from fruit set (Figure 4.4). In 2014, 53% sunburnt fruits were found in the open treatment compared to 2% under the shadenet (6 m x 3 m). In the open treatment, the 3 m x 3 m spacing shielded fruits from sunburn, hence only border row tree fruit were sunburned. But in 2015, the number of sunburned fruits in the open treatment increased to 75% compared to 18% under the shadenet in the 6 m x 3 m spacing block (data not shown). Hence sunburn is a result of the excessive solar irradiance received in the open treatment.

Also, solar irradiance is greater in spring, summer and autumn than in winter. Thus, sunburn increases with fruit size development, from early fruit set to a mature stage. This is also the result of poor tree condition and leaf loss caused by wind damage and root rot diseases (Rossouw, 2002). 'Carmen®-Hass' sunburn is severe because the tree bears fruit on the outside of the canopy compared to other black skinned avocado cultivars, e.g., Gem® (Crane *et al*., 2013). Solar irradiance is reduced under the shadenet and there was no sunburn on fruit even on west-facing fruit (Figure 4.5).

Bower *et al*. (1977) found that avocados are able to maintain 15% of their maximal photosynthetic rate at incoming solar irradiance of 1100 W m^{-2}. For an efficient use of solar irradiance by the crop, the greater part of the radiation must be absorbed by the photosynthetic tissues (Whiley, 1994, Schaffer *et al*., 2013a). Based on the current findings, incoming solar irradiances of 1000 W m^{-2} and greater were only recorded for the open treatment. Also, solar irradiance of less than 1000 W m^{-2} received under the shadenet did not limit plant growth or impose ephemeral stress on plants compared to the open treatment as will be discussed in Section 4.3.

Avocados do not require high levels of incoming solar irradiance because they evolved as tropical rainforest sub-storey trees. The tree canopy receives varying amounts of PPFD between shaded and sun-exposed leaves. This creates competition for maximum photosynthesis, but low PPFD compensation point may help maximise photosynthesis of tree canopies (Wolstenholme, 1990). In the case of overcrowded avocado canopies, i.e. when 90% of the orchard floor is shaded, selective pruning techniques help to improve the PPFD penetration and absorption into the orchard floor thus improving maximum photosynthetic rate of shaded leaves.

The current study did not perform any comparison between different colour nets, but it is known that white shadenets have greater solar irradiance transmissivity and reflectivity than black and grey nets (Stamps, 2009). Hence, increased PPFD levels pass through a white shadenet compared to black shadenet. This also depends on the shading factor of shadenet and type of material, i.e. woven versus netted (Middleton and McWaters, 2000).

Figure 4.5 The results of reduced solar irradiance under the shadenet with no sunburn on fruits

4.2.2 Effects of air and canopy temperature and water vapour pressure deficit

Temperature refers to the degree or intensity of heat present in a substance or object, especially as expressed according to a comparative scale. It controls the physical and chemical processes that in turn control biological reactions within plants. Temperature and air temperature in particular plays a role in plant growth and development (Kimball *et al.*, 1997, Mavi and Tupper, 2004, Savage, 2013).

A comparison in air temperature measurements under the shadenet and open treatment is illustrated in Figures 4.6 to 4.9. Air temperature under the shadenet was slightly greater when comared with an open treatment. But in the winter of 2015, air temperature under the shadenet was slightly greater only in the morning and less in the afternoon than in the open treatment whilst in spring 2014 and 2015, air temperature under the shadenet was slightly greater than in an open treatment. The maximum air temperatures occur in spring, summer and autumn (see Table 4.2).

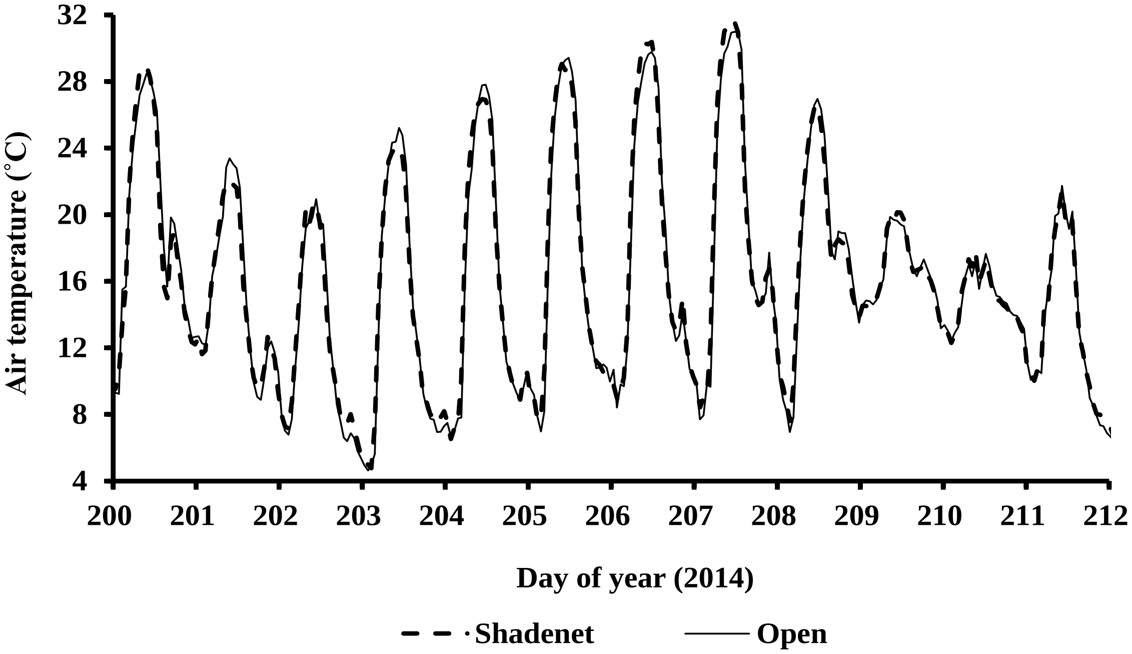

Figure 4.6 The results of reduced solar irradiance under the shadenet with no sunburn on fruits

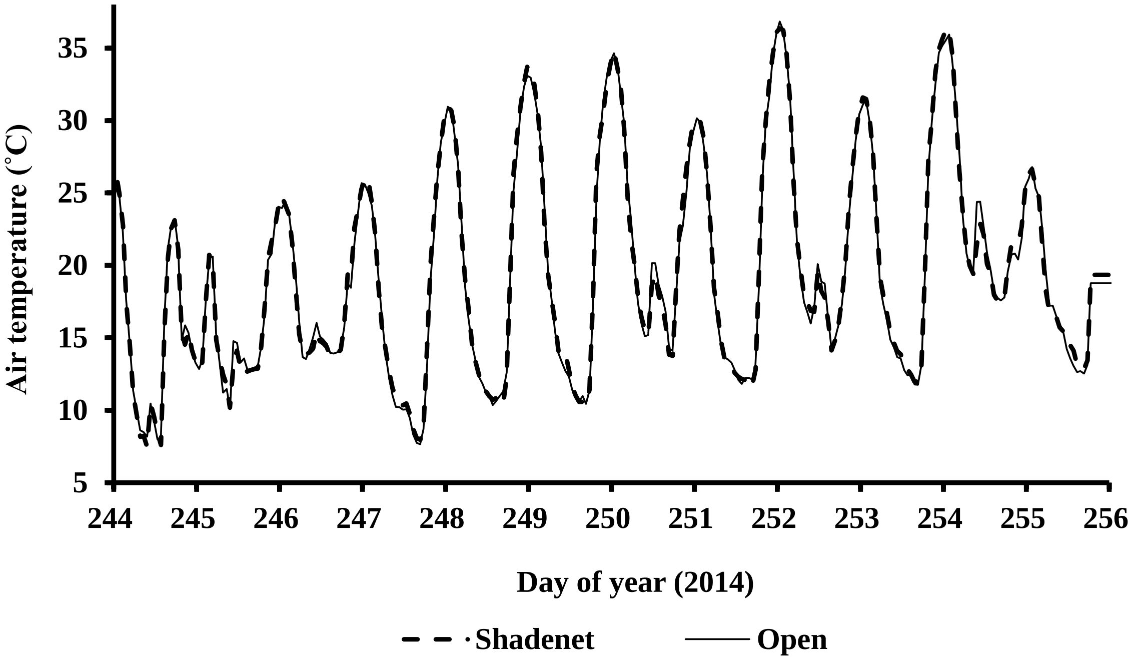

Figure 4.7 Hourly air temperature measured under the shadenet compared to the open treatment for the 2014 spring season

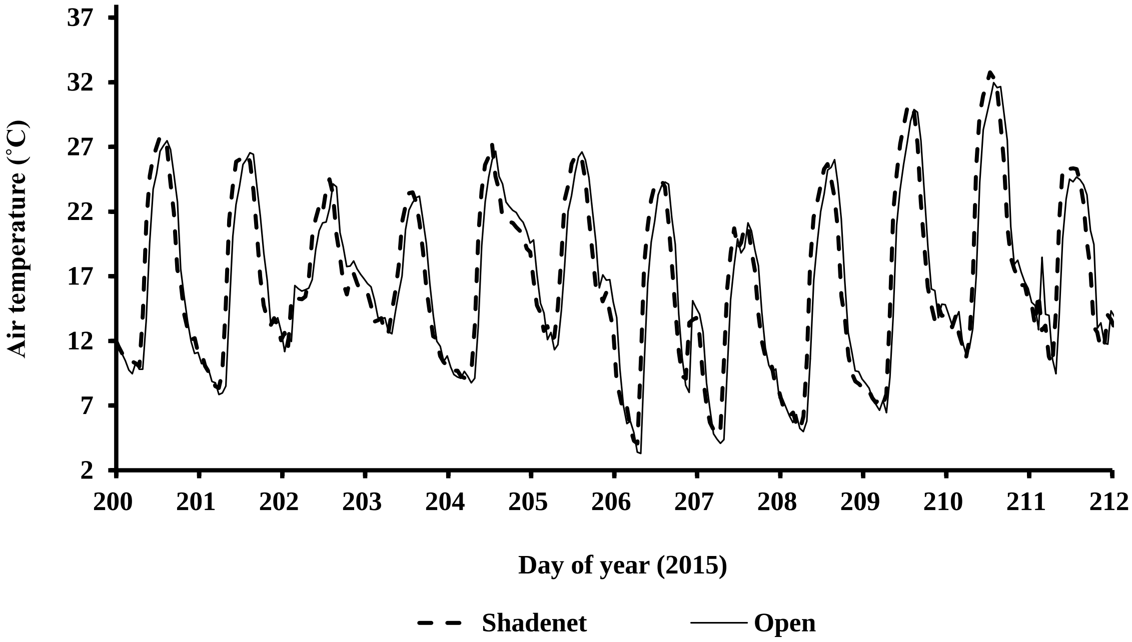

Figure 4.8 Hourly air temperature measured under the shadenet and in the open treatment for the 2015 winter season

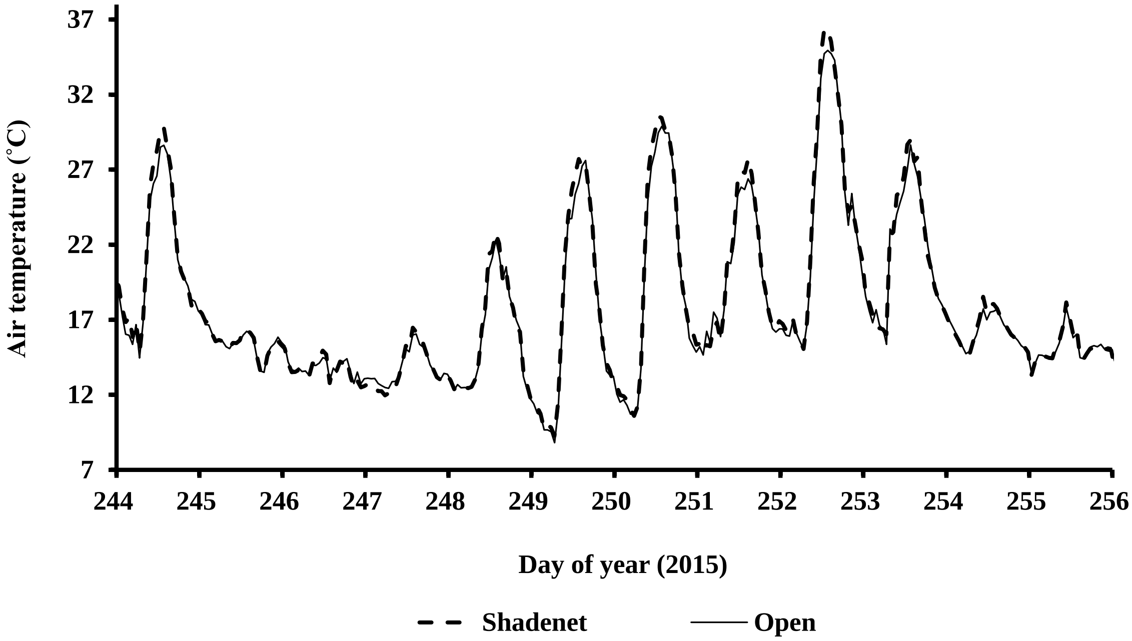

Figure 4.9 Hourly air temperature measured under the shadenet and the open treatment for the 2015 spring season

There were no frost days at Mooketsi Valley but air temperature values less than 5 °C were recorded both under the shadenet and in an open treatment. Moreover, during overcast conditions and rainfall days, air temperature readings are less than 16 °C (Figure 4.9). Air temperature values under the shadenet and in the open treatment were below 35 °C in winter of 2014/15 but slightly greater under the shadenet than in the open treatment.

Air temperature under the shadenet was slightly greater than in the open treatment. Tanny *et al*. (2009) and Siqueira *et al*. (2012) reported similar findings. But Tanny *et al*. (2009) based their apple study on different shading factors ranging from 16 to 60%. The study by Siqueira *et al*. (2012) was more on theoretical measurements of air temperature above and below tree canopy. But variations in air temperature occur above ground, within tree canopies and above tree canopies (Tanny, 2013). For the open treatment, air temperature of the lower air layer is reduced with height but under the shadenet it is increased with the height of the structure (Tanny *et al*., 2008). Also, changes in air temperature occur with change in height above sea level (Smith, 1975).

Wolstenholme (2011a, 2013) observed that the mean annual air temperature is higher at low altitude in warm subtropical areas than at higher altitude in cool subtropical areas. This depends on whether the change is upwind or downwind, but the mean annual air temperature decreases with altitude. In the case of the shadenet, air movement also largely depends on the size of the structure. Wider shadenet structures with considerable height (7 m or more for tree crops) offer better air movement under the shadenet. Shadenets are designed to reduce air pressure reduction which resists air flow under the shadenet. In the case of greenhouses, air flow is achieved by sidewalls and opening of the side or roof top to allow exchange in air flow (Teitel, 2007, Savage, 2014).

Shadenets offer optimum conditions for improved plant growth by reducing excessive solar irradiance (Section 4.3.1). But high air temperatures can only be suitable when there is high solar irradiance available for high CO_2 assimilation. However, air temperatures above 35 °C are undesirable for subtropical avocado cultivars, as occurred for both environments on day of year 252, 2015 (Figure 4.9). High air temperatures lead to fruit drop, particularly in spring and summer (Whiley and Winston, 1987). Optimum air temperature range for maximum net CO_2 assimilation is 20 to 30 °C, which coincides with temperatures for optimal plant growth. Net CO_2 assimilation is reduced at air temperatures above this range and may result in partial stomatal closure (Whiley, 1994).

In the winter of 2014 and 2015 season, the optimum air temperatures were exceeded marginally in both environments on day of year 207 and 210 (July), respectively, (Figure 4.6 and 4.8). But in spring of 2014 and 2015, air temperatures were above 35 °C on day of year 250, 252 and 254 (September, 2014) and day of year 252 (September, 2015). In the winter 2014 and 2015 season, the optimum air temperature were slightly exceeded only on one day (Figure 4.6 and 4.8). But in the spring 2014 and 2015 season, air temperature exceed the optimum air temperature for maximum CO_2 assimilation and plant growth. This implies that subtropical avocado trees at Mooketsi Valley achieve their maximum CO_2 assimilation in winter compared to spring. Hence, tree growth was rapid in winter compared to spring (Section 4.4.1). Also, the maximum air temperatures were recorded around midday when plant stoma were no longer assimilating CO_2.

Whiley (1994) found that air temperatures less than 10 °C during winter reduce the apparent maximum quantum yield of leaves. But the low air temperature greatly disrupted the dichogamy flowering sequence during overcast skies rather than clear skies (Ish-Am, 2008). Hence, the slight increase in air temperature under the shadenet compared to the open treatment was beneficial to the synchronous dichogamy flower opening and bee activity (Section 4.4.2). It is also believed that avocado leaves have the ability to adapt to increasing cold air temperatures and are tolerant to seasonal changes (Mckellar *et al.*, 1992, Schaffer *et al.*, 2013a).

In the winter of 2014 and 2015, air temperatures were less than 10 °C on both treatments more frequently than in spring 2014 and 2015. However, the temperatures were below 10 °C from midnight to sunrise (Figures 4.6 and 4.8). But in spring temperatures were less than 10 °C on day of 244 and 248 (August 2014) and 249 (August, 2015) both under the shadenet and in the open treatment, respectively (Figures 4.7 and 4.9). Air temperatures less than 10 °C did not damage tree foliage because there was no frost damage on the trees.

Canopy temperature relates to the energy transfer between the sun in the form of solar irradiance and transpiration from the tree. Canopy temperature was variable over the growing seasons. In winter 2014, canopy temperature under the shadenet was slightly less in the morning but greater in the afternoon than in the open treatment. Canopy temperature under the shadenet was greater than in the open treatment from day of year 212 (July, 2014) but less under the shadenet than in the open treatment from day of year 206 to 211 (July, 2014) (Figure 4.10).

In winter of 2015 season, canopy temperature under the shadenet was slightly greater than for the open treatment, particularly in the morning but lower in the afternoon. In spring 2014, canopy temperature under the shadenet was 2 °C greater than for the open treatment at midday. However, in the spring of 2015, it was 1 °C less under the shadenet than in the open treatment at midday. A similar trend was observed in summer and autumn (data not shown). Average canopy temperatures range between 10 and 35 °C for summer, autumn and spring but was between 5 and 30 °C in winter for both treatments. During overcast and rainfall conditions, canopy temperatures were similar to those of air temperature in the spring 2015 (Figures 4.11, 4.12 and 4.13).

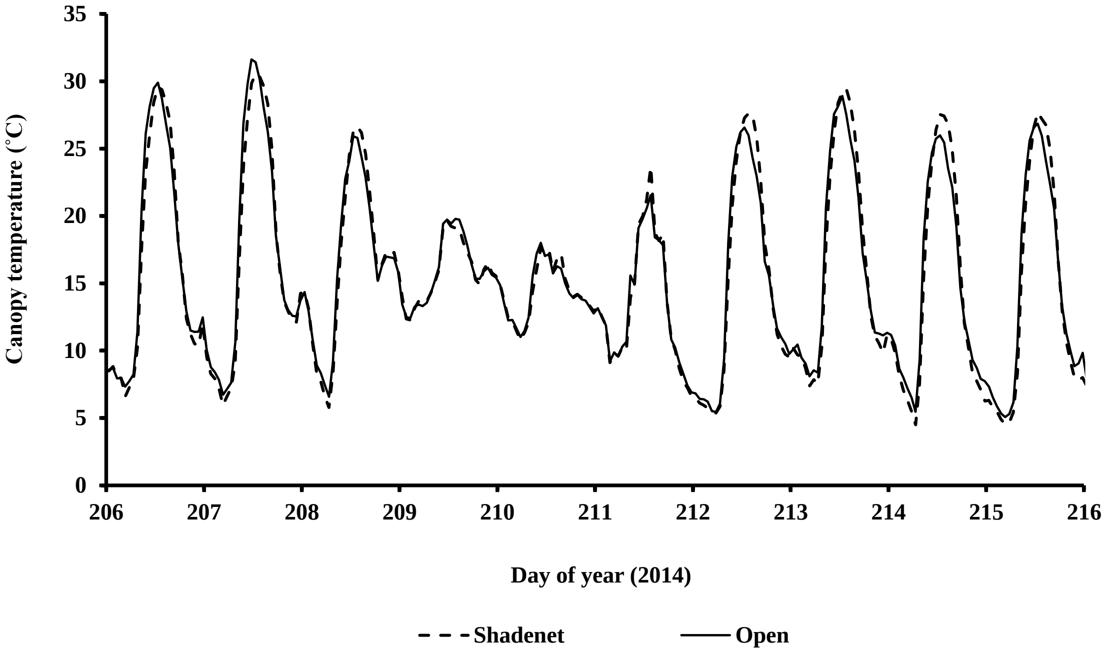

Figure 4.10 Hourly canopy temperature measured under the shadenet compared to the open treatment for the 2014 winter season

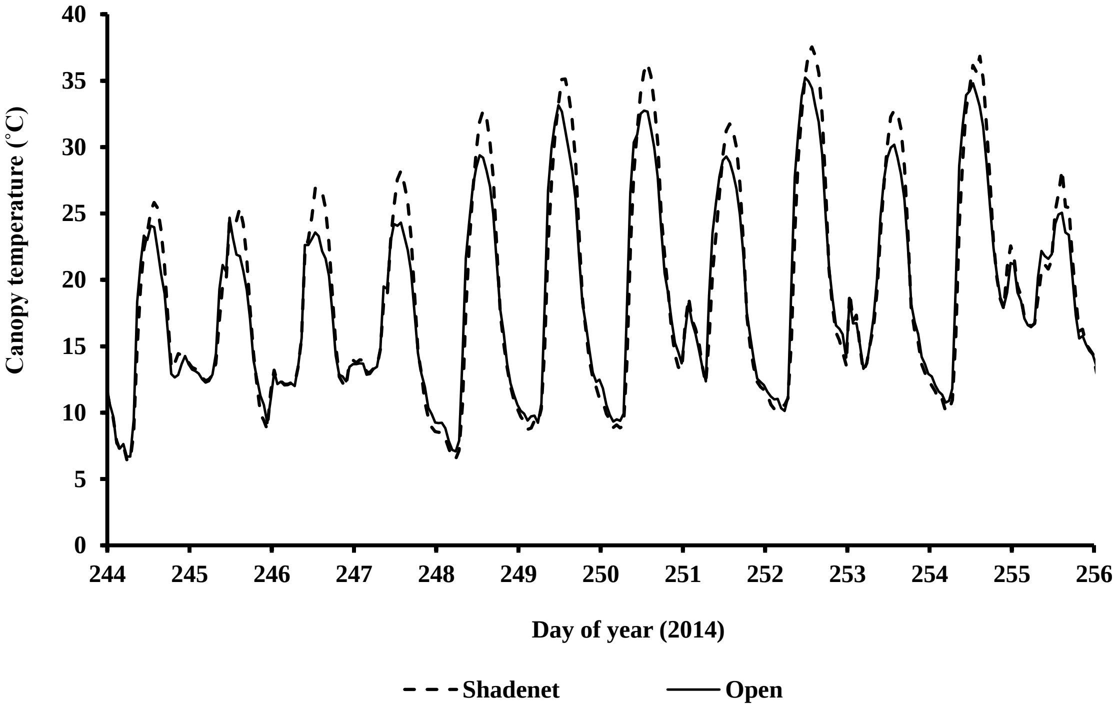

Figure 4.11 Canopy temperature measured under the shadenet compared to the open treatment for the 2014 spring season

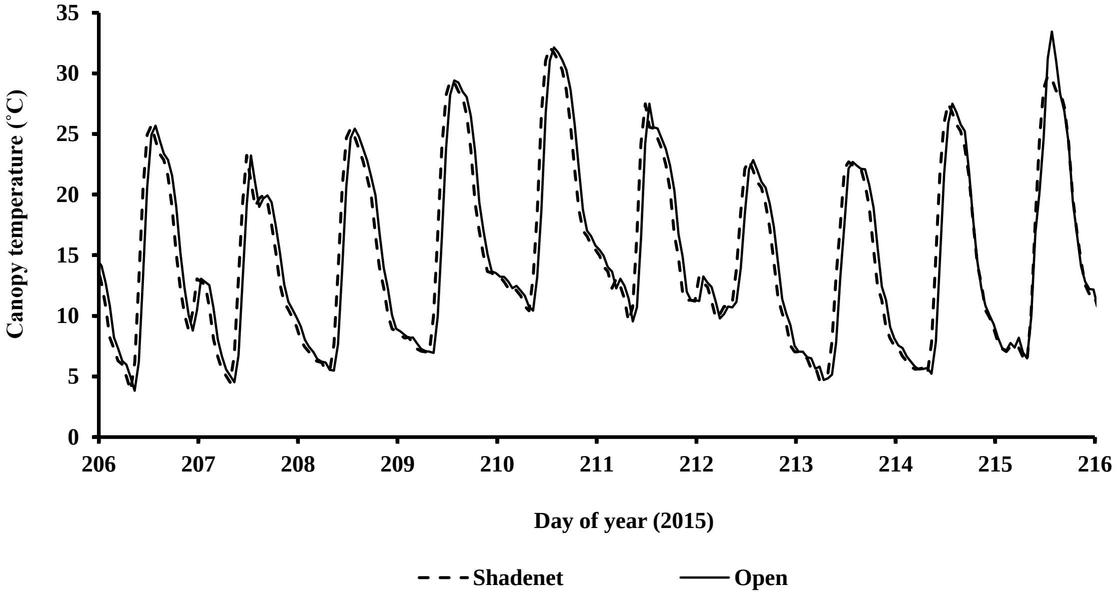

Figure 4.12 Hourly canopy temperature measured under the shadenet compared to the open treatment for the 2015 winter season

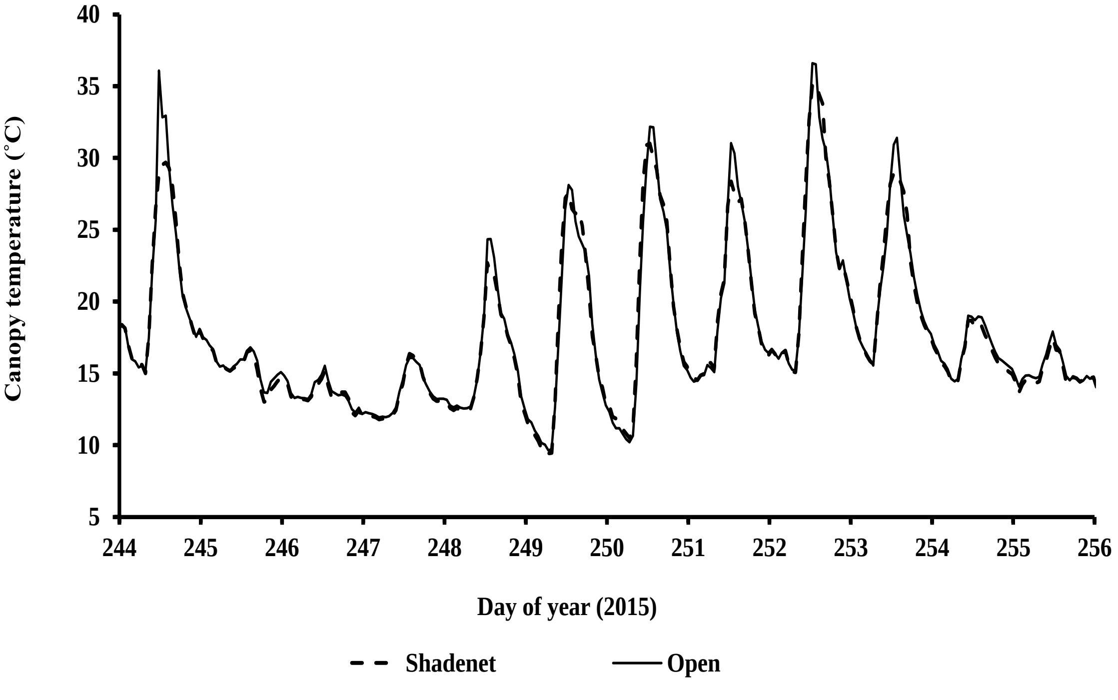

Figure 4.13 Canopy temperature measured under the shadenet compared to the open treatment for the 2015 spring season

Canopy temperature results for the current study contradict those of Smit (2006). Smit (2006) used 30% black shadenet which significantly reduces PPFD when compared with 20% white shadenet and has a greater reflectivity than a black shadenet. The study found that for the summer and spring season under the shadenet, leaf surface temperatures were 4 to 6 °C cooler than in the open-field. In the current study, under the shadenet, canopy temperatures were slightly greater in the morning until midday and slightly less in the afternoon compared to the open treatment (Figures 4.12 and 4.13). But incoming solar irradiance was decreased as it was intercepted through tree canopies. Such ultimately reduces the canopy temperature during daytime under the shadenet compared to the open treatment. However, during night conditions, leaves intercept infrared radiation from the soil which promotes heating.

The tree(s) used for canopy temperature measurements had a shallow canopy cover, i.e. it had gaps. Canopy temperature measurements depend much on tree canopy density. Furthermore, the morphological composition of the leaf exposed to direct sunlight is not only dependent on the solar irradiance received but also on morphological and physiological conditions of the tree (Primault, 1979).

Avocado leaves have a heat acclimation mechanism to prevent photo-oxidative damage to photosystem II (PS II) when there is an increase in air temperature. PS II is more sensitive to heat damage than PS I (Schaffer and Whiley, 2003). Thus when there is an increase in air temperature, concomitantly, there is a shift in solar irradiance energy absorbed from PS II to PS I. Avocado cultivars are acclimatised to different air temperature regimes for growth and development (Lahav and Trochoulias, 1982, Havaux and Lannoye, 1987, Havaux *et al.*, 1987).

Water vapour pressure changes under the shadenet compared to the open treatment and result in diurnal changes in air temperature and relative humidity. The VPD under the shadenet was slightly greater than in the open treatment, occurring with changes in air temperature under the shadenet. The VPD values under the shadenet and in the open treatment were less than 2 kPa, particularly for summer, autumn, and winter of 2014 and 2015 except for the spring of 2015 (only data for spring 2014 and 2015 is shown in Figures 4.14 and 4.15). In the open treatment, increased air movement compared to under the shadenet often offsets an increased VPD. Air under the shadenet was slightly dryer than in the open treatment. Thus, the shadenet restricted air movement resulting in negligible airflow to reduce the greater water vapour pressure compared to the open treatment.

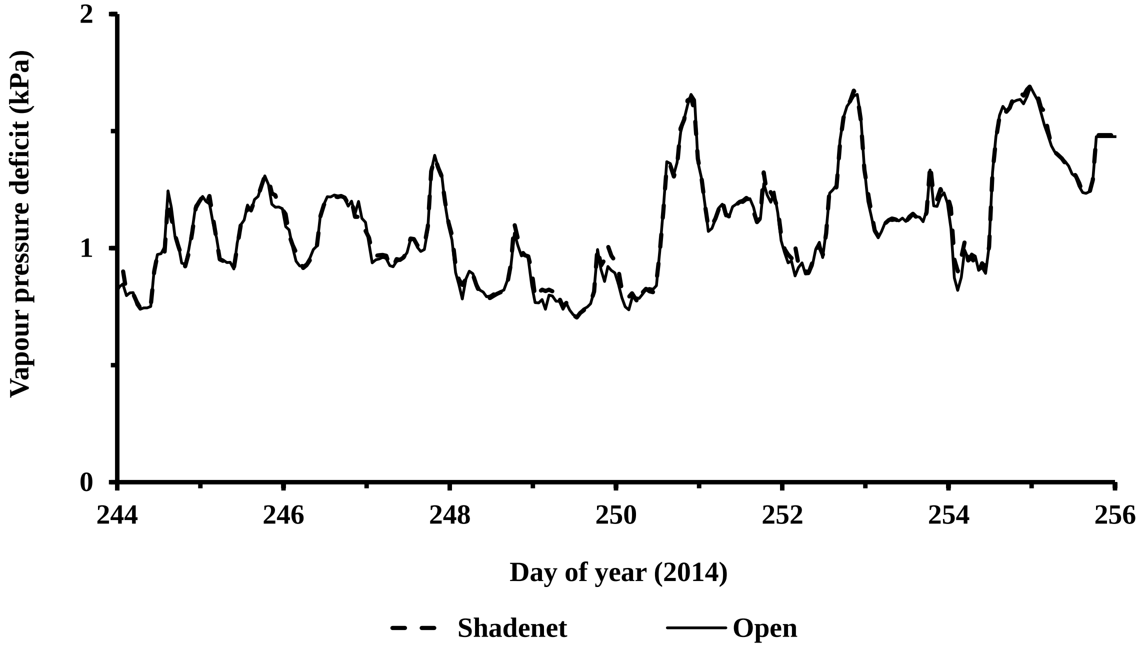

Figure 4.14 Water vapour pressure deficit under the shadenet compared to the open treatment computed from air temperature and relative humidity data for spring 2014

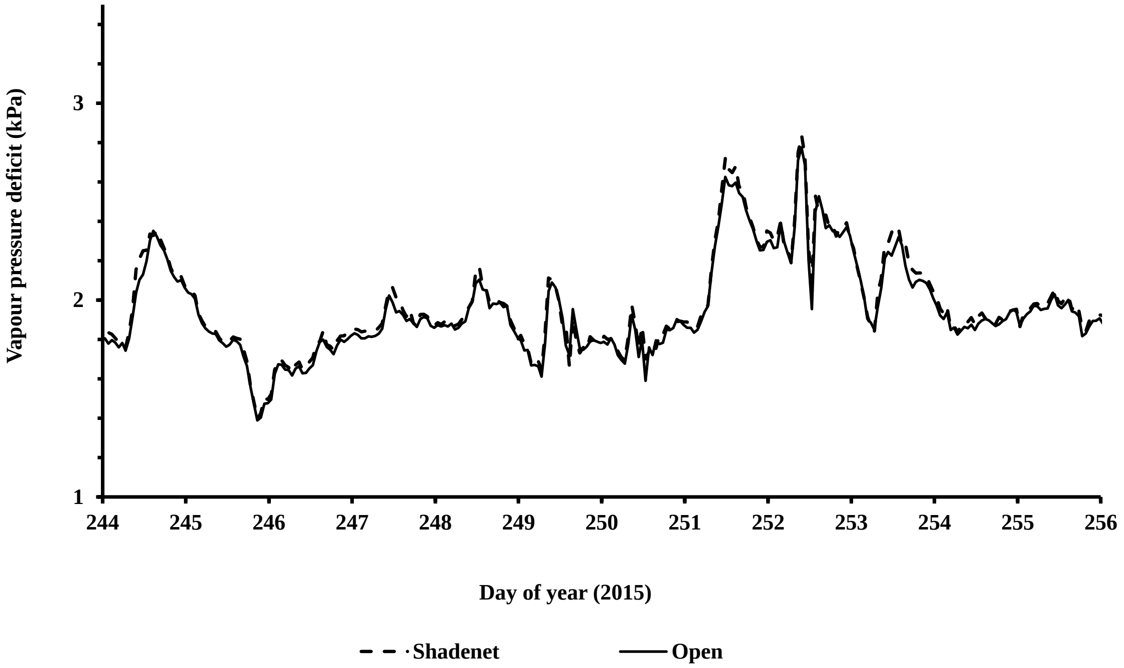

Figure 4.15 Water vapour pressure deficit under the shadenet compared to the open treatment computed from air temperature and relative humidity data for spring 2015

Whiley and Schaffer (1994) found that fruit growth is related to the tree canopy water status and environmental conditions at different stages of fruit growth. Also, the reproductive organs of avocado trees have greater water loss rates than the vegetative component. The leaf area of summer flush is reduced compared to that of winter flush. Thus, more water was partitioned to the maturing fruit in summer than to the tree foliage.

Tanny *et al*. (2008) found that the VPD was reduced within the foliage layer in an insect-proof shadenet used for pepper and decreased towards the shadenet roof. In the current study, VPD was based on air temperature and relative humidity measurements at 2 m height. Peppers also have a different phenological morphology to avocado trees. Siqueira *et al*. (2012) reported similar results to the current study, i.e. 35% increase in VPD under the shadenet (at 5-m height) compared to the open treatment in a banana orchard.

However, VPD under the shadenet is dependent on the height of the shadenet structure and it varies near plants and away from plants (Tanny *et al.*, 2008). In the current study, the VPD results are based on air temperature and relative humidity measurements taken next to the plants both under the shadenet and in the open orchard treatment. Hence, there was less variability in the VPD data compared to those of Tanny *et al*. (2008). Also, VPD varies depending on the microclimate, type of plant species and/or cultivar (Ferreyra *et al*., 2007; Siqueira *et al*., 2012).

VPD differences under the shadenet and in an open treatment were negligible but the VPD inside a tree canopy tends to reach equilibrium point with VPD of the surrounding air (Figures 4.14 and 4.15). Thus, a gradient is maintained irrespective of environmental conditions because the tree itself releases considerable amounts of water vapour pressure through transpiration (Pallardy and Kozlowski, 1979). Hence, VPD inside a tree canopy is less than outside the tree canopy. This occurs as a result of an exchange of water vapour and air between the tree and the surrounding air (Chirkov, 1979).

4.2.3 Effects of wind run and leaf wetness

Shadenet structures are designed to prevent excessive wind damage to trees and decrease the internal mean wind speed (Teitel, 2007; Tanny, 2013). Excessive wind affects plant transpiration because the thickness of the boundary layer is determined primarily by wind speed (Schaffer *et al.*, 2013a). The results of wind run on tree phenology are presented in Figures 4.16 and 4.17. Thus, Figures 4.16 and 4.17 show the wind run for the spring of 2015 and the cumulative wind run from March to October 2015, respectively.

There was little difference in wind run under the shadenet and the open treatment in early autumn whilst in winter, wind run under the shadenet was very low (data not shown). Majority of the winds recorded in autumn and winter were light wind and the shadenet protected the trees against the wind. But in spring, wind was high in such that it was even recorded under the shadenet but did not damage leaves nor fruit. In an open treatment, leaf damage was due to high wind speed when compared with shadenet treatment (Figures 4.16 to 4.18). Thus there was low wind speed under the shadenet compared to the open treatment.

However, wind speed in an open treatment was 65% greater than under the shadenet in winter and spring. The results in the current study are similar to those of Haijun *et al*. (2015) who measured wind speed in a banana orchard. Moller and Assouline (2007) found wind speed under the shadenet to greater than in an open treatment above tree canopy. Under the shadenet, wind run was reduced by 65% compared to the open treatment. Siqueira *et al*. (2012) found that high wind speed occurs with an increase in shadenet height. According to Tiaz and Zeiger (2010), high wind speed result in thickness of the boundary layer being reduced, and therefore, reducing the photosynthesising leaf area. Based on Figure 4.18 under the shadenet, the leaf area was greater compared to the open treatment due to low wind speed under the shadenet.

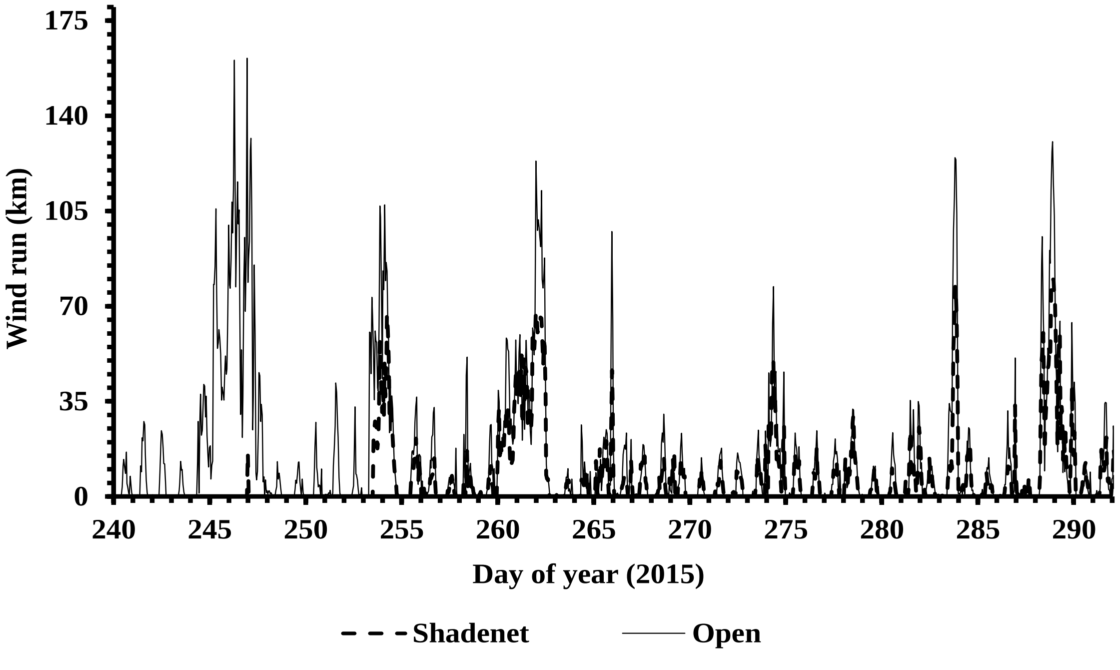

Figure 4.16 Wind run under the shadenet compared to the open treatment for the 2015 spring season

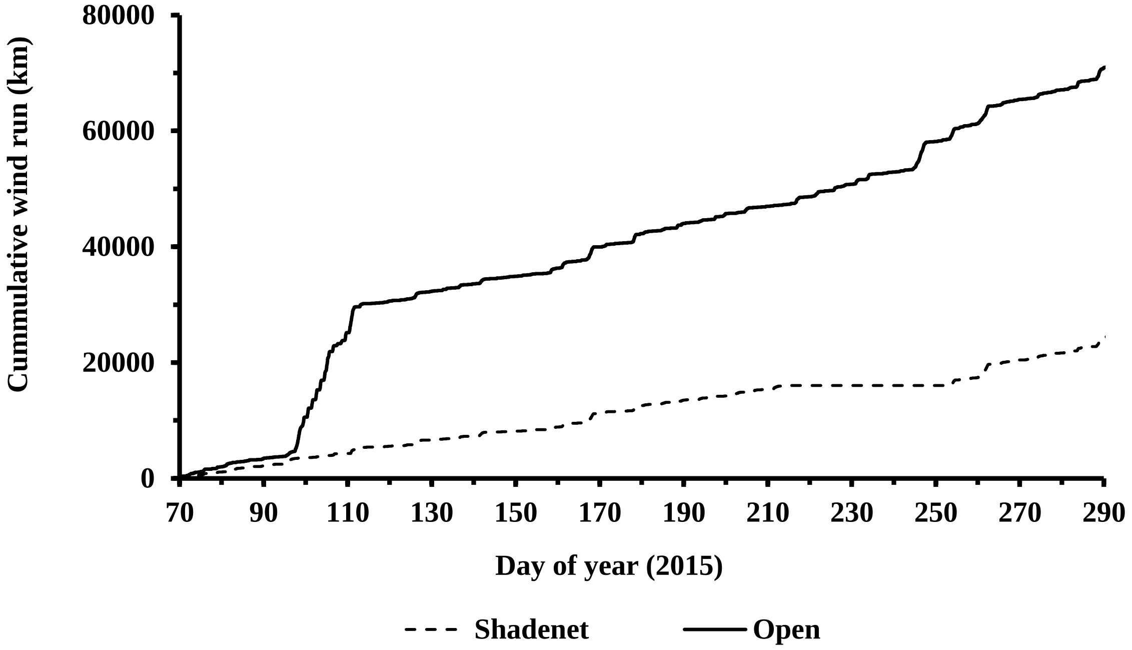

Figure 4.17 Cumulative wind run under the shadenet compared to the open treatment from March to October 2015

Wind speed recorded in the open treatment was detrimental to leaf size and actual growth but it did not affect tree structure. Damage was observed on buds and branch development which could also be related to excessive wind speed or water stress (Heath *et al*., 2005). According to the 'Carmen®-Hass' phenological chart, flower drop occurs prior to periods when excessive winds were experienced whilst fruit drops occur in summer after the windy period (spring). There was no fruit or leaf damage observed under the shadenet compared to the open treatment. But bee activity was harshly disrupted under excessive winds in the open treatment compared to under the shadenet (Section 4.4.2). Under shadenet, wind speed was not eliminated totally because the shadenet entrance was facing the windward side.

According to Chirkov (1979), the orchard operates as a whole in the case of wind, in the sense that prevailing wind is slowed down by the successive action of each tree. Wind direction at Mooketsi is perpendicular to the orchard design such that border rows are mostly affected by excessive wind speed and critically damaged when compared with in-row trees. Also tree spacing had a significant effect in reducing wind speed within the inter-tree rows. If the wind blows perpendicularly to the alignment of the trees in the orchard, it will be intercepted by the first and eventually reduced by the second row (Marshall and Woodward, 1985).

The weather station was positioned in the middle rows of the orchards where the trees experienced less wind damage compared to trees on the first three rows facing wind direction. Thus, wind was mostly blocked both by the trees and the shadenet and slowed in the third row. According to Chirkov (1979), if the prevailing wind blows in the same direction as the rows in the orchards neither its force nor its direction will be affected by the rows to any considerable extent while inside the tree canopy it will be (Haijun *et al*., 2015).

Studies investigating the microclimate under shadenet have always focused on solar irradiance, air temperature and humidity on a large scale but not on leaf wetness and LWD. Leaf wetness estimates provide early predictions of diseases; and thereafter, the required management (Savage, 2012). Figures 4.19 and 4.20 show cumulative leaf wetness duration monitored in 2014 and 2015. In 2014 season, leaf wetness was minimal under the shadenet compared to the open treatment (Figure 4.19). But we found that in summer and autumn 2015, the occurrence of leaf wetness was greater under the shadenet than in the open treatment. Overall, leaf wetness was extended by 12% under the shadenet compared to the open treatment.

Figure 4.18 The result of gentle wind speed on leaves (left) and fruit (right) on the open treatment. The circled area (left) accounts for the reduced area of the leaf

Rainfall and dew are the main environmental phenomena responsible for leaf wetness. Under rainy conditions, leaves intercept part of the precipitation, causing free water on the leaves. The LWD results shown in Figures 4.19 and 4.20 are also the consequence of rainfall on the tree canopy. Jacobs *et al*.

(2006) found that rainfall increases LWD and dominates dewfall. However, the drying process following rainfall is usually faster than that of dew. This is because most of the rain occurs during the day followed by a gradual increase in air temperature and wind speed and offset the precipitation on the canopy (Jacobs and Nieveen, 1995).

Leaf wetness estimates are solely based on the presence of dewfall and rainfall. However, other microclimate effects such as low VPD, high air temperature, incoming solar irradiance and wind speed also affect LWD. Leaf wetness is also dependent on sensor placement within the crop canopy (Rowlandson, 2011). Sensors were placed between tree rows and below the canopy height; and therefore, the obtained estimates and the duration of wetness were accurate.

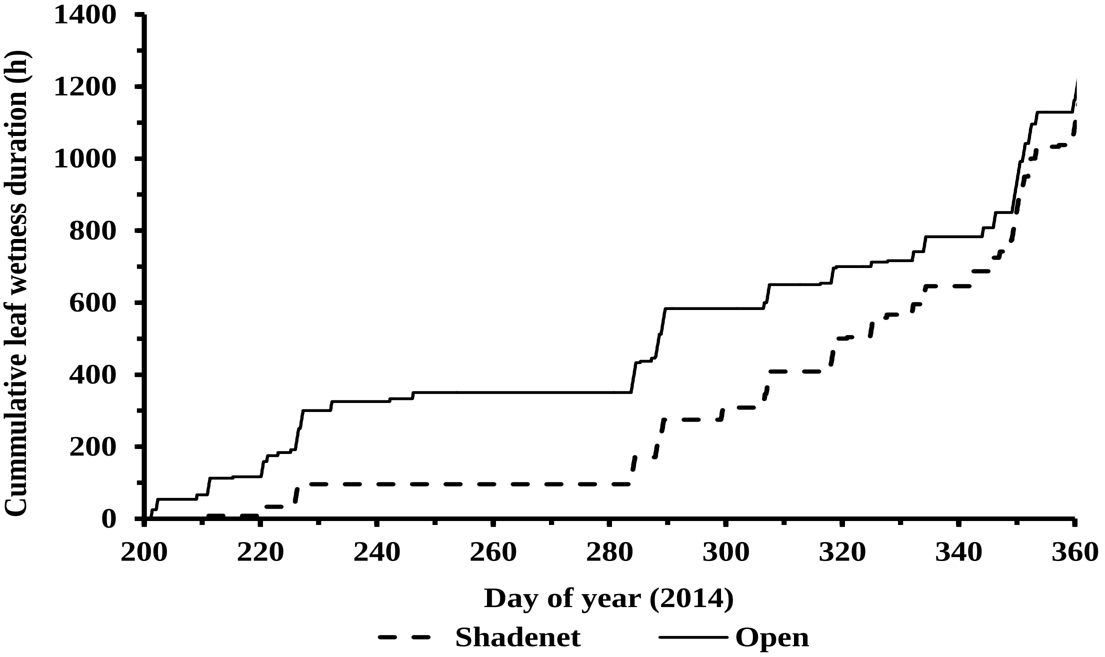

Figure 4.19 Cumulative leaf wetness duration under the shadenet compared to the open treatment for 2014 season

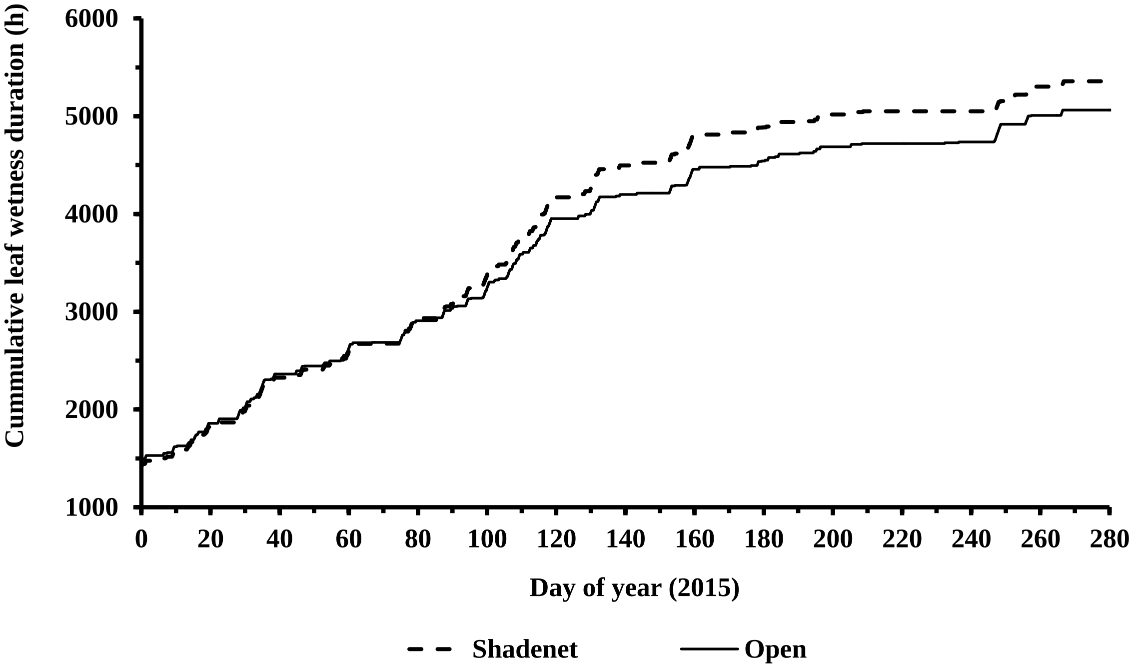

Figure 4.20 Cumulative leaf wetness duration under the shadenet compared to the open treatment for the 2015 season

Dew deposition occurs at night when the canopy temperature is below the dew point of the air. The LWD measurements under the shadenet were a result of the reduced VPD and wind speed during the day time. During overcast conditions, the occurrence of dew is less likely because infrared radiation emitted by clouds may keep the canopy temperature elevated above the dew point temperature (Wittich, 1995). The greatest dew interception occurs at the top of the canopy layer.

Thus, leaf wetness usually starts in the upper layers of the canopy. Also drying starts in the upper canopy layer due to direct solar irradiance after sunrise. The extended LWD is expected to occur in the lower canopy layers and leaf wetness ends when the condensate has evaporated in the morning (Jacobs *et al.*, 2005). According to Giesler *et al.* (1996), leaf wetness in controlled environments is produced quickly and readily visible to the unaided eye. Under field conditions, it develops slowly as a thin microscopic film that is. An increased leaf wetness is offset by an increase in canopy temperature and solar irradiance at sunrise. Under the shadenet, both canopy temperature and solar irradiance are less compared to the open treatment, which offsets increased LWD. Also, the absence of wind speed under the shadenet prevents the evaporation process on the canopy surface. Thus, dew condensates to the lower layers of the canopy. The distribution of dew within a canopy is not homogeneous and changes with time, depending on the weather, leaf distribution and architecture of the plant canopy.

Figure 4.21 Leaf roller (*Archips occidentalis*) as a consequence of increased LWD under the shadenet compared to the open treatment

The increased leaf wetness under the shadenet creates a favourable environment for insect pests. During the first year of the study, the citrus leaf roller (*Archips occidentalis*) was spotted under the shadenet as a result of increased leaf wetness and reduced VPD. The pest damage was greater in the 3 m x 3 m spacing block than the 6 m x 3 m block. This resulted in a decline in fruit quality and yield as the pest were feeding on the fruit (Figure 4.21). But Giesler *et al*. (1996) found that canopy density has no significant effect on leaf wetness; and hence were of the view that disease may occur regardless of the canopy structure. No thorough investigation was conducted on diseases but the common avocado diseases which occur as a consequence of leaf wetness or dewfall include Cercospora spot (*Pseudocercospora purpurea*) and Anthracnose (*Colletotrichum gloeosporioides*).

4.3 Soil-plant water relations

4.3.1 Rainfall, irrigation and nutrition

Fruit production is a high risk and high input cost production system in which water management, is a critical component, particularly irrigation. Thus, many studies focus on the importance of improving water use, yield and/or productivity (Measham *et al*., 2014).

Mooketsi valley has a dry and warm environment with an average annual rainfall of 500-550 mm. The annual rainfall for the valley is very low and restricts land usage and avocado production to the minimum, hence reducing quality and quantity of avocados due to water shortages. Wolstenholme (2011b and 2013) states that the South African subtropical avocado requires an average rainfall between 650 and 1500 mm. Based on rainfall data from 2008 to 2015, the experimental site only received the minimum required annual rainfall between 2011 to 2013, whilst in 2010, 2014 and 2015 annual rainfall was 400 mm, resulting in short- and medium-term drought spells for the valley (Figure 4.22).

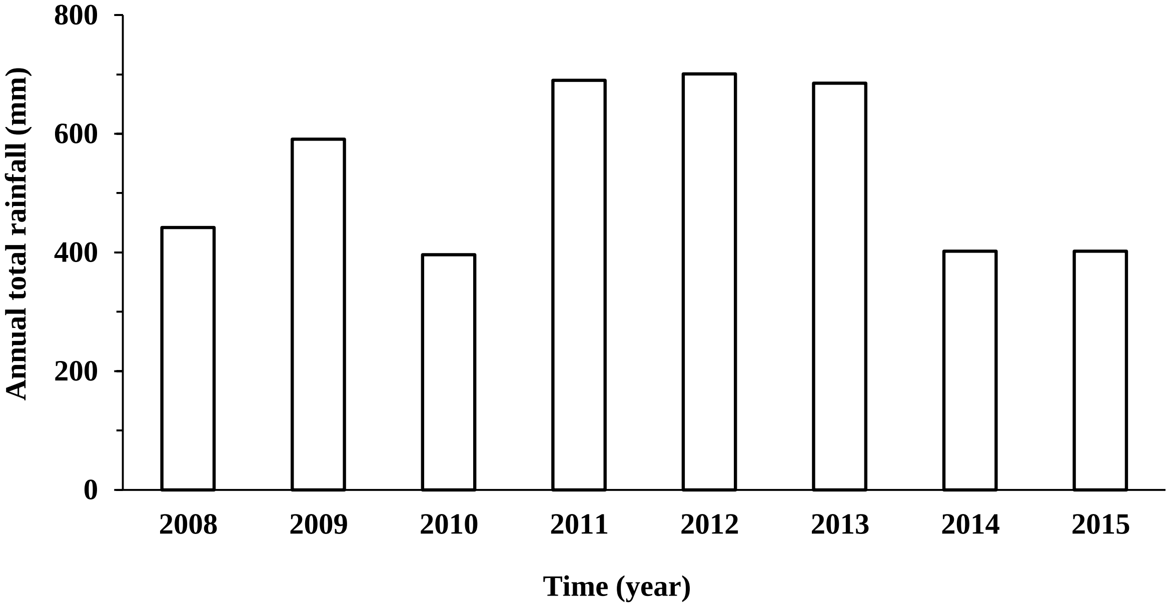

Figure 4.22 Annual total rainfall for the experimental site (Shadenet and open treatment) from 2008-2015

During drought spells in summer, particularly in Mooketsi valley, the rainfall deficit is approximately 1000 mm (De Villiers and Joubert, 2011). Hence, irrigation during water stress conditions helps to ameliorate soil and tree water stress. For the dry and warm environment like Mooketsi valley, water has to be applied based on the phenological cycle of the tree crop. For instance, it is prudent to irrigate with more water during weeks into flowering, early fruit development stages or prior to fruit drop and summer vegetative flush. For 'Carmen®-Hass' these three stages coincide and applying timely irrigation helps to reduce fruit drop, sunburn, and tree water stress (Bower *et al.*, 1977, Bruwer, 2006, De Villiers and Joubert, 2011).

Despite the current drought, there were some significant rainfall events in December 2014 and April 2015. There was no difference in rainfall under the shadenet compared to the open treatment (Figure 4.23). A 20% white shadenet has a greater hole size than a higher density shadenet structure (30-60%)

(Stamps, 2009). A 20% white shadenet is very efficient in protecting against hail damage, but there were no hailstorm events during the experiments. Trees were irrigated frequently in the open treatment compared to under the shadenet. In 2014, there was a slight difference in irrigation under the shadenet compared to the open treatment. But during the 2015, there was 29% reduction in irrigation under the shadenet compared to the open treatment (data not shown). The difference was observed despite the application of compost and eucalyptus wood-chip mulch of 60 and 100 L tree^{-1}, respectively. Mulch application reduced soil water stress particularly under the shadenet compared to the open treatment (Blakey *et al.*, 2015).

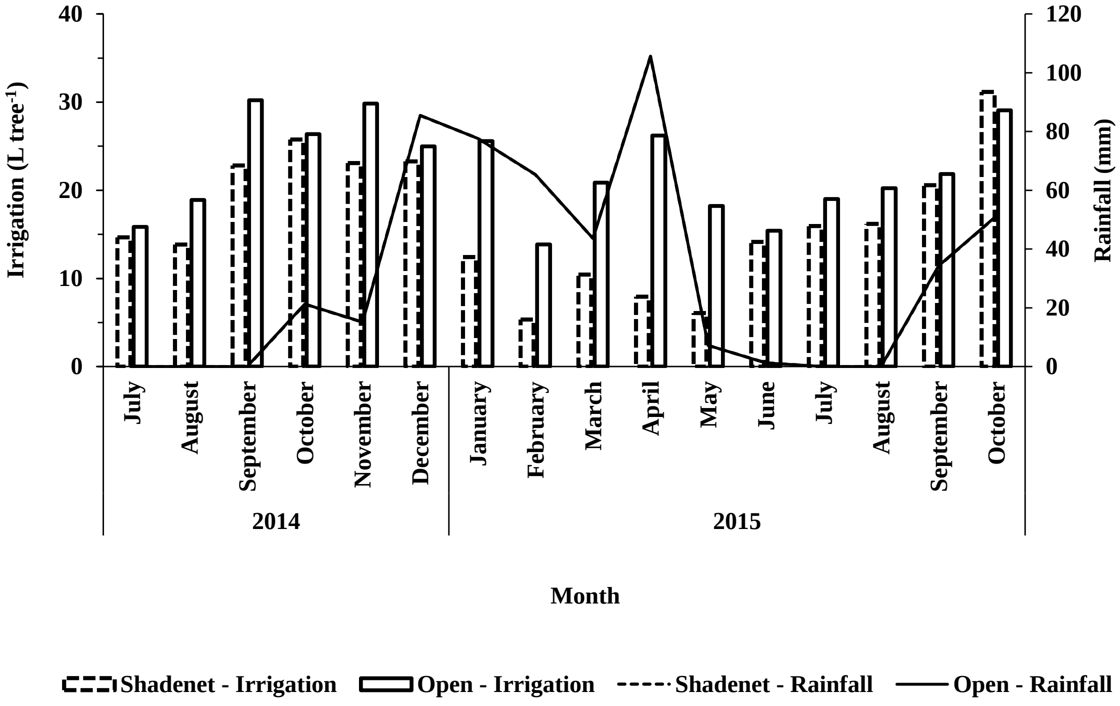

Figure 4.23 Rainfall and irrigation under the shadenet and open treatment for the 2014 and 2015 seasons

In the open treatment, trees were subjected to day time water stress. Thus, a high water holding capacity was required to efficiently reduce soil water stress. In the open treatment, water stress was a result of different irrigation systems to those used under the shadenet. Under the shadenet, micro-spray irrigation was used whilst in the open treatment drip irrigation was used. The drip irrigation was only changed prior to the construction of the shadenet. 'Carmen®-Hass' trees have majority of their roots in the top soil, hence drip irrigation was not suitable for this cultivar.

Also, avocado trees absorb both water and nutrients using the feeder roots mostly located in the top soil. Thus, drip irrigation in the open treatment reduced the wetting surface compared to micro-spray irrigation under the shadenet (Roets *et al.*, 2013). Hence, the feeder roots were not supplied with water and nutrient which could alter the phenological cycle of the trees. Also, changing drip irrigation to micro-spray still did not significantly change in terms of water uptake in the open treatment compared to under the shadenet during the course of the study. Trees in the open treatment required more water than trees under shadenet in order to overcome previous and current water demands for improved tree growth and development (data not shown). However, compost mulch application helped to increase activity of feeder roots on the top soil layer (Wolstenholme *et al.*, 1997, 1998). This significantly improved the soil water holding capacity both under the shadenet and the open treatment.

Also, irrigation under the shadenet was reduced compared to in the open treatment as a result of both the reduced microclimate (solar irradiance and wind speed) under the shadenet and mulch application. The findings of the current study contradicts those of Lahav *et al*. (2013), who found that mulch absorbs most of the irrigation water with little flowing to the soil. But in the current study, the 160 L tree^{-1} mulch (compost and wood-chip) application did not absorb most of the water both under the shadenet and in the open treatment with water availability to the open treatment trees limited compared to the shadenet treatment. Irrigation reduction under the shadenet was significantly influenced by the reduction in environmental stress factors, i.e. solar irradiance, wind speed and/or air temperature, as discussed in Section 4.2 (Wolstenholme, 2011b). Overall, there was a 29% reduction in irrigation under the shadenet compared to the open treatment (data not shown).

According to Bower (1978) and Schaffer *et al.* (2013a), soil water stress, which was imposed in the open treatment, inhibits physiological processes and productivity of the avocado trees. This was supported by measurements of stomatal conductance, stem water and CO_2 assimilation, which were not measured in the current study. Based on the phenological measurements, soil water stress did inhibit physiological processes as will be discussed in Section 4.4. Also, the irrigation frequency under the shadenet was 3 to 4 days compared to 1 to 2 days in the open treatment (data not shown). Even with higher irrigation frequency for the open treatment, tree growth and fruit size in the open treatment were limited compared to under the shadenet (Sections 4.4.1 and 4.4.3). According to Lahav *et al*. (2013) during hot days, the irrigation should be applied several times per day.

In the open treatment, 80 L of water were applied for each irrigation event compared to 54 L under the shadenet, particularly during hot weather. Avocado trees have anatomical features which enable them to tolerate a warm and dry environment, provided there is sufficient soil water to meet growth demands (Whiley and Schaffer, 1994). Because of the 18% reduction in solar irradiance and application of compost mulch under the shadenet, these demands were met with no inhibition in tree growth as a result of water stress under the shadenet compared to the open treatment.

For the shadenet treatment, compost and wood-chip mulch played a major role in preventing soil water stress. The increase in diffuse solar irradiance and photosynthesis for the shaded leaves help to stabilise the boundary layer under the shadenet compared to the open treatment. The reduced environmental factors (solar irradiance, wind speed) under the shadenet and mulch application significantly contributed to the overall effect of improving water usage and greatly demonstrated optimum usage of soil water under these conditions (Siqueira *et al*., 2012; Tanny, 2013). But Siqueira *et al*. (2012) and Tanny (2013) studies were based on different colour shadenets and shading factors compared to the current study.

Mulching is a very important component of the avocado nutrient pool, including soil minerals, soil organic matter (cation exchange capacity) and the avocado leaves (Allwood and Wolstenholme, 1995). Benefits of these components come from irrigation water but run-off and deep drainage may result in nutrient removal from the tree root zone (Lovatt and Salazar-Garcia, 1994, Lovatt, 1996). The nutrients within an avocado tree are inter-connected and are readily available (Lovatt and Salazar-Garcia, 1994). According to Cameron *et al*. (1952), avocado nutrients are recycled through leave fall and decomposition, which are re-absorbed into the vegetative and reproductive parts of the tree. However, avocado trees also lose nutrients through senescence, flowering and during fruit harvest (Lovatt, 1996).

Roots absorb water and nutrients and contribute carbon-based components to root zone (Witney *et al*., 1990a). The anatomy and structure of roots influence their capacity to absorb water and nutrients and transfer them to the upper parts of the tree (Witney *et al*., 1990b, a). Avocado trees have less available nutrients in the root zone particularly, N (Nitrogen). However, nutrients are abundant in leaves, branches, and fruit (Lahav *et al*., 2013). Leaf litter samples were analysed for percentage N, P (Phosphorus), K (Potassium), Ca (Calcium), etc. (Table 4.3).

Table 4.3 'Carmen®-Hass' leaf litter results under shadenet compared to the open for the 2014 season

Avocado leaf nutrients	Shadenet	Open
Nitrogen (%)	2,51	2,43
Phosphorus (%)	0,16	0,16
Potassium (%)	0,77	0,86
Calcium (%)	2,00	1,79
Magnesium (%)	0,73	0,71
Zinc (mg kg^{-1})	23,00	24,00
Copper (mg kg^{-1})	20,50	11,00
Manganese (mg kg^{-1})	219,50	147,50
Iron (mg kg^{-1})	198,00	168,50
Boron (mg kg^{-1})	25,75	22,45

In an avocado, N, P, K and Ca are macronutrient elements, but micronutrients such as B (Boron), Cu (Copper), Zn (Zinc) and Fe (Iron) are important elements in an avocado tree. N and Ca concentrations were slightly greater under the shadenet compared to the open treatment and K concentration was slightly greater in the open compared to the shadenet treatment (Table 4.3). There was no difference in the concentrations of P and Mg under the shadenet and the open treatment. In avocado leaves, the available P and Mg concentrations have no known effect on tree growth, yield and fruit size (Lynch *et al.*, 1954, Koen and du Plessis, 1991, Kremer-Köhne *et al.*, 1993). The concentrations of Cu, Mn, Fe and B were significantly greater under the shadenet compared to the open treatment (Table 4.3).

The leaf litter analysis shows that micronutrients (Cu, B, Fe and Zn) were higher under the shadenet compared to the open treatment (Table 4.3). However, macronutrients were slightly greater under the shadenet compared to the open treatment. Nitrogen was applied by broadcasting around the tree and based on the phenological cycle of the cultivar. Leaf N level was above 2% both under the shadenet and open treatments (Table 4.3). According to Embleton *et al.* (1966), levels of leaf N above 2% is recommended for high yields and fruit size.

Thus, N levels application in the soil and leaves respectively are correlated with yield and at times, they are not. This is because N is easily leached below the tree root zone (Kiggundu *et al.*, 2012). For superior yields and fruit size, it is the timing of N and not quantity applied that is more important. This was well illustrated both on ‘Hass’ and ‘Fuerte’ (Koen and du Plessis, 1991, Loupassaki, 1998, Lovatt, 2001). Percentage leaf K in the open and under the shadenet treatment was below 1%. The higher K levels was stored in the fruit instead of the leaves and tree branches or roots and is easily lost during fruit harvest (Embleton and Jones, 1966).

Embleton and Jones (1964) and Koen and du Plessis (1991) found that increasing the leaf K levels had no effect on yield, but an interaction of K with P and N has been demonstrated to increase yield (Lahav and Zamet, 1975). This depends on the correct application. N, P, and K levels only required in small quantities and used to increase yield and/or fruit size but it is important in maintaining normal tree growth (Lahav *et al*., 2013).

Leaf Ca level was slightly greater under the shadenet than in the open treatment (Table 4.3). Ca is mostly applied as gypsum to increase avocado yield by increasing soil permeability, drainage and aeration (Witney *et al.*, 1990a). This displaces K and Mg in the soil. The higher levels of Ca concentration was found in fruit instead of leaves. This helps to maintain fruit postharvest quality (Du Plessis and Koen, 1987, Witney *et al.*, 1990b). Ca uptake from the soil to the fruit was influenced by irrigation. Bower (1978) found that Ca uptake was influenced by irrigation when the soil matric water potential was -35 kPa.

Despite irrigation reduction under the shadenet, fruit growth was rapid in the first seven weeks and declined afterwards (Section 4.4.3). The work by Witney *et al*. (1990b, a) was primarily based on fruit Ca levels rather than in leaves. Since the Ca levels under the shadenet and in the open treatment were slightly different, fruit growth was influenced by the plant density, phenological and shadenetting factors (Table 4.3).

Leaf Mn levels were greater under the shadenet than in the open treatment based on tree measurements (Table 4.3). The Mn levels did not have any detrimental effects on the trees (Lahav *et al.*, 1993, Lahav, 1999). B and Fe levels were greater under the shadenet than in the open treatment (Table 4.3). Also the difference did not have any negative impact on growth and reproduction. Zn was greater in the open treatment than under the shadenet treatment (Table 4.3).

The level of leaf Cu was significantly greater under the shadenet than in the open treatment (Table 4.3). Cu was applied as foliar spray for fungicide diseases. Thus the high levels of leaf Cu for the shadenet treatment could be a result of a higher application rate than in the open treatment. This is because under the shadenet, pests and disease incidence was greater than in the open treatment. Under the shadenet, wind was significantly reduced and leaf wetness duration was extended when compared with the open treatment. This created a favourable environmental condition for pests and diseases.

4.3.2 Short-grass reference evapotranspiration (ET_o) and sap flow

The demand and rate at which water was lost in soil and tree was dependent on the microclimate, tree size and age. The process whereby water was lost from the soil and tree is called evapotranspiration, i.e. evaporation from the soil and transpiration from the tree. ET_o contributes to the rate of soil and tree water loss to the atmosphere (Chartzoulakis *et al.*, 2002). Hence it is important to quantify the amount of water in the soil used within the tree and released by the tree.

Evapotranspiration is mostly quantified with a Class A pan evaporation and a crop factor. For the current study, evapotranspiration was estimated using a spreadsheet version (Savage, 2016) of the Penman-Monteith equation and hence ET_o (Penman, 1948, Monteith, 1965, 1973). The evaporation Class A pan takes into account irrigation frequency and/or distribution since micro-sprinkler and drip irrigation have an uneven distribution of water on the soil surface (Faber *et al.*, 1994, Lahav *et al.*, 2013). The Penman-Monteith equation and hence ET_o requires knowledge of solar irradiance, wind speed, air temperature and relative humidity. The Penman-Monteith equation requires field locations which are uniform and also crop factor to be applied to the equation. In the case of an avocado tree, the crop factor varies from one location to the other (Rowell, 1979, Du Plessis, 1991, Lahav *et al.*, 2013). According to Allen *et al*. (1998), the crop factor for a mature avocado grown without vegetation cover is 0.73.

Daily ET_o computed for autumn, winter and spring 2015 is shown in Figures 4.24 and 4.25. ET_o was greater in the open treatment compared to under the shadenet (Figure 4.25). Also, ET_o for spring was greater than the ET_o in winter for both treatments (Figure 4.24). This trend was also observed for summer 2014 and 2015 (2014 data not shown). In winter, daily ET_o was on average 3.2 mm day^{-1} under the shadenet and 4.5 mm day^{-1} in the open treatment for spring 2015. In winter, there was a reduction in the atmospheric demand compared to spring, i.e. atmospheric water loss was reduced. Water loss rate was lower under the shadenet compared to the open treatment. But the difference in water loss under the shadenet and in the open treatment was 1 mm day^{-1} whilst in spring it was 2.3 mm day^{-1}.

From mid- to late spring, daily ET_o was greater outside than under the shadenet. Trees also bear a small percentage of out-of-season (OOS) flower in mid-September. In 2015, the percentage number of OOS flower and fruit set from the winter flower was greater under the shadenet than in the open treatment (data not shown). Thus, less water was released into the atmosphere under the shadenet compared to the open treatment. In Figure 4.24, daily ET_o is below 1 mm day^{-1} from day of year 235 to 245 under the shadenet compared to the open treatment. Solar irradiance was reduced by 18% under the shadenet compared to in the open treatment.

Figure 4.25 shows the difference in soil-plant water loss over time under the shadenet and open treatment. The figure (4.25) can be used to estimate whether the trees in both treatment were over- or under-irrigated. Hence, using the information from figure 4.25, the avocado crop factor (0.73) and the irrigation schedules (30 and 50 kPa), the regulated deficit irrigation (RDI) i.e. the amount of water required to replace soil water stress, can be estimated for both treatments. In figure 4.26, both treatments were under-irrigated at 30 and 50 kPa irrigation schedules. However, at 30 kPa irrigation schedule, trees under the shadenet were less under-irrigated than the actual irrigation required compared to the 50 kPa irrigation schedule. In the open treatment, trees required greater amount of water when the irrigation schedule was set at 50 kPa than at 30 kPa. Hence, trees in the open treatment were more under-irrigated compared to trees under the shadenet. Also, the difference in RDI was greater in spring (day of year 250 to 290) and compared to autumn (day of year 90 to 150). Despite both treatment being under-irrigated, under the shadenet trees did not show signs of water stress compared to in the open treatment (data not shown).

Also, the rate of tree water flow (sap flow) was reduced by a similar percentage under the shadenet compared to in the open treatment (Figure 4.27). Sap flow was greater in the open treatment when compared with under the shadenet treatment, but there was no difference in sap flow during cloud cover under the shadenet and the open treatment (Figure 4.27, day of year 169, 173 and 182). Sap flow is dependent on the soil matric potential, which influences the rate of stomata opening and transpiration and/or evapotranspiration. Under the shadenet, the soil matric water potential was reduced because of the reduction in solar irradiance and wind speed (Section 4.2). Moller and Assouline (2007) reported similar findings in a pepper study planted under 30%. Their study also found a reduction in evapotranspiration under the shadenet compared to the open treatment. However, in the current study, sap flow (transpiration) and ET_o were greater in the open treatment compared to the shadenet treatment (Figures 4.24 to 4.27).

Transpiration and stomatal closure are linked to a decrease in soil water, but based on the current study, there was no soil water stress under the shadenet. Trees were irrigated based on the soil matric potential of -30 and -50 kPa under the shadenet and the open treatment. Bower (1978) also found that avocado trees are sensitive to soil water stress so under deficit irrigation, stomata can close for part of the day. This results in reduced transpiration, photosynthesis and tree productivity since flowers and fruit are severely affected by water stress when compared with leaves. Blanke and Lovatt (1993) postulated that 'Hass' irrigation needs to be increased during flowering in order to avoid water stress and stomatal closure.

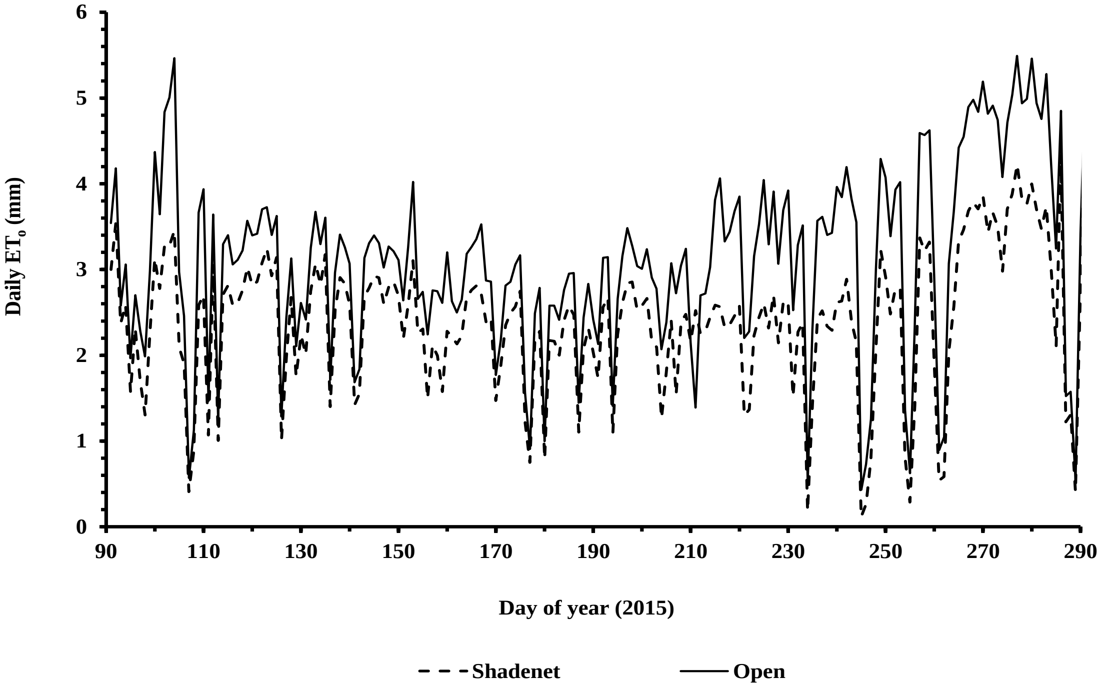

Figure 4.24 Daily reference evapotranspiration (ET_o, mm) computed for winter and spring 2015 under the shadenet and open treatment

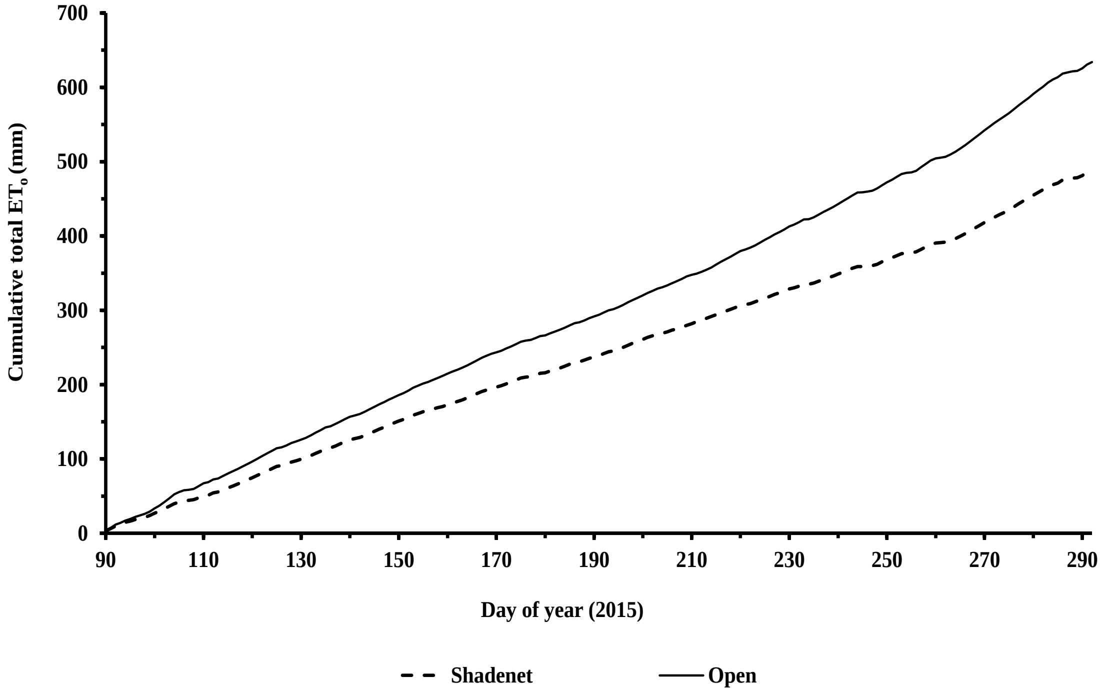

Figure 4.25 Cumulative total ETo (mm) for autumn to spring 2015 under the shadenet compared to the open treatment

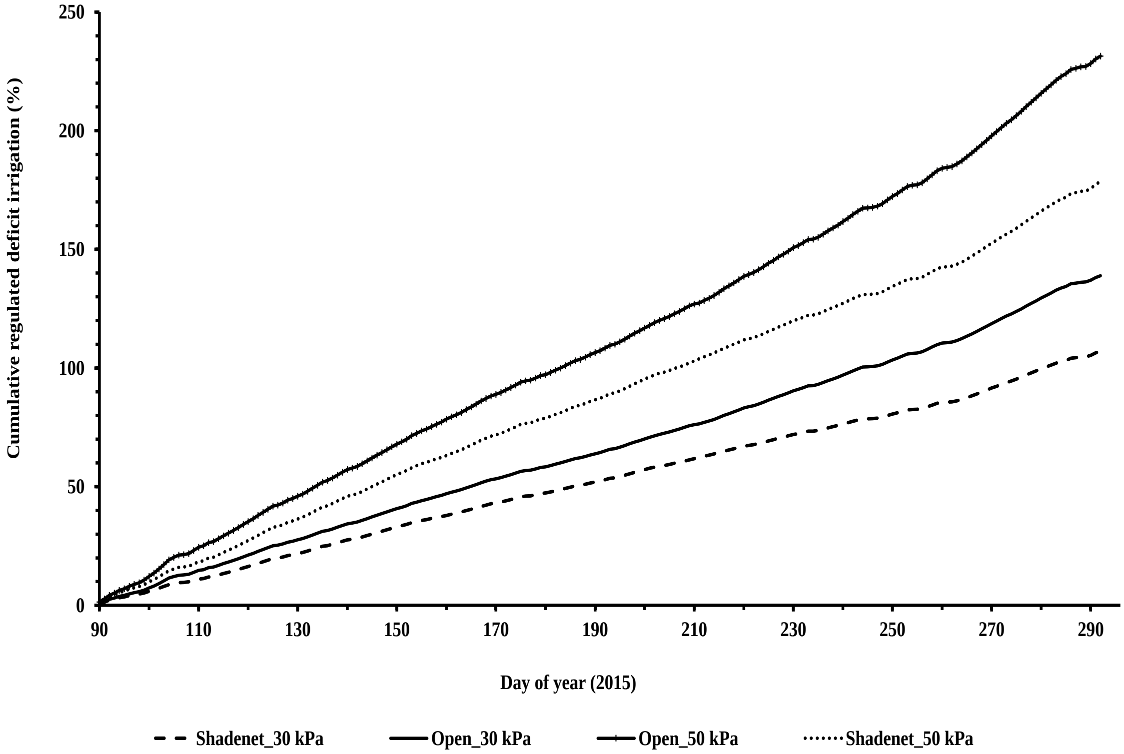

Figure 4.26 Cumulative regulated deficit irrigation requirements at 30 and 50 kPa irrigation schedules under the shadenet and open treatment

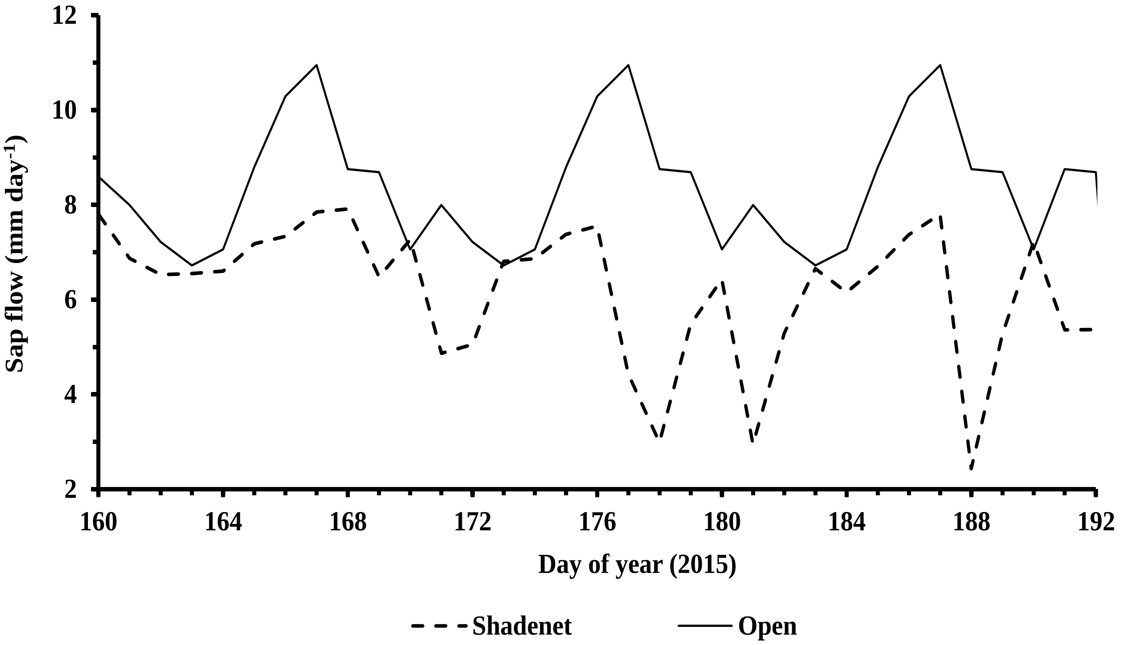

Figure 4.27 ‘Carmen®-Hass’ half-hourly sap flow measurements under the shadenet and open treatment

From figure 4.27, sap flow was estimated by calculating Granier’s parameter K as the difference of dTM and dT over dT. dT is the difference between the heated needles, referenced to the lower non-heated needle (Section 3.3.2, Figure 3.4). This values were recorded between 12 and 10 am each day. The next step was to calculate sap flow velocity in relation to K. This was followed by converting the sap flow velocity to sap flow rate by multiplying by the stem diameter of test trees. The units for sap flow rate were converted from cm^3 s^{-1} to mm day^{-1}. The conversion from cm^3 s^{-1} to mm day^{-1} requires knowledge of the leaf area index of the test tree.

Sap flow was measured during the normal season flowering stage, winter vegetative flush development and OOS fruit development. These stages have high water requirements. ‘Hass’ avocado flowers use 80% of the absorbed soil water and contribute 35% of the total transpiration. The stomatal densities of avocado flower sepals are similar to those found in the leaves, which makes the demand for water to be closely similar to that of leaves (Blanke and Lovatt, 1993). Also, the difference in sap flow under shadenet and in the open treatment could be due to the vigour of the rootstocks and anatomy of the roots (Fassio *et al.*, 2009). According to Bower (1985) avocado flowers transpire more than the leaves and fruit surfaces. Hence, trees which are irrigated more frequently respire more than trees which are not irrigated frequently. In the current study, under the shadenet irrigation frequency was less than in the open treatment. Hence, trees in the open treatment transpired more than under the shadenet (Figures 4.23, 4.24 and 4.27).

Despite both treatments being under-irrigated (Figure 4.26), open treatment trees absorbed and transpired more water than those under the shadenet. The high sap flow rate in both treatment was because tree were measured during the floral development stage (Section 4.2.2). However, flower development commenced a week earlier under the shadenet than in the open treatment. Under the shadenet, trees begun setting fruit prior to open treatment trees. Thus, under the shadenet, absorbed water was used for fruit development and transpired at a later stage, as that was the case in the open treatment.

ET_o and sap flow reduction under the shadenet was due to the reduced solar irradiance and wind speed. In both treatments, air, canopy temperature and relative humidity differences were small and had a significant effect on ET_o and sap flow. A previous study on banana planted under 25% clear shadenet shown a 34 and 10% reduction in ET and sap flow, respectively, (Haijun, *et al.*, 2015). Their study applied a similar crop factor to the one used in the current study for the Penman-Monteith equation. Sap flow, ET_o and solar irradiance all peak at midday, demonstrating that transpiration was strongly affected by solar irradiance.

Mooketsi valley has a dry environment. Hence, the 18% reduction in solar irradiance under the shadenet might have had less effect in reducing transpiration and sap flow when compared to the open treatment. This explains why sap flow and ET_o were greater in the open treatment than under the shadenet treatment. But with high wind speed, water loss due to transpiration can accumulate in the form of water vapour close to the leaf surface.

According to Fassio *et al*. (2009) grafted ‘Hass’ trees absorb and transport more water than non-grafted trees. Hence, the rate of sap flow is greater in grafted trees than in non-grafted trees. In the current study, trees were grafted onto Dusa® (also known as Merensky 2) rootstocks, which are more tolerant to phytophtora root rot than Duke 7 rootstock, used in Fassio *et al* (2009) study. Dusa® rootstock are more vigorous, with a better root system for water absorption than Duke 7 roots (Kremer-Köhne *et al.*, 2011). Also, the functionality of the stomata and movement of water under the shadenet might have functioned at different times due to the reduction of solar irradiance under the shadenet compared to the open treatment. The sap flow was measured above the graft union on the main stem of the trees in question. Also, water movement across the trees, flowers or leaves was not measured. Hence, more research is needed to understand the phenotypic and genotypic difference among different cultivars and rootstocks, under shadenet structure(s).

4.4 Tree phenology

4.4.1 Shoot growth and leaf area (vegetative growth)

Tree phenology refers to the relationship between the microclimate and periodic biological events of a tree species. The most important developmental events for an avocado tree include shoot and root growth flushes, flower initiation and development, fruit-set, fruit drop and maturation and leaf senescence (Wolstenholme and Whiley, 1989).

Avocado trees are evergreen with shoot growth in mature trees synchronised into flushes of varying vigour, duration and extent (Verheij, 1986). Different cultivars flush at different times and extent depending on environmental conditions (Chanderbali *et al.*, 2013). ‘Carmen®-Hass’ flushed once in winter and autumn and three times in spring and summer (data not shown). Based on the ‘Carmen®-Hass’ phenological chart, the winter and summer flushes are less compared to the early and late spring flushes. But ‘Hass’ trees have one winter flush and three summer flushes (Salazar-Garcia *et al.*, 2006). The reduction in these flushes is a result of the floral bud initiation and development that takes place during this period, i.e. the normal and OOS flowering periods. Shoot growth and leaf area of the different seasonal flushes were measured under the shadenet and in the open treatment. Shoot growth was only compared for summer, autumn and winter 2015 (Figure 4.28).

Figure 4.28, shows leaf area for winter, spring and summer 2014 and 2015 season. Fifty leaves samples were selected randomly across the 3 m x 3 m and 6 m x 3 m orchard blocks in both treatments. Leaf samples were selected on the east and west facing side of the trees. Only the fully developed leaves were selected over newly developing leaves. The selection was based on the fact that newly developing leaves are still expanding in size i.e. photosynthesising whilst fully developed leaves do not increase in size. Avocado fully developed leaves are dark green whilst the newly developing are light brown to light green. Also the leaves had to be sampled before senescing and fall to the ground. Based on an anova test ($P < 0.05$), shoot growth was significantly greater under the shadenet compared to in the open treatment (Figure 4.29). There was no significantly difference in shoot growth for summer under the shadenet compared the open treatment. Shoot growth was not significant for autumn and winter under the shadenet, but it was significantly different to open treatment for the same period.

Leaf area was greater under the shadenet compared to in the open treatment (Figure 4.28). In the open treatment, leaf area was reduced during winter and summer 2015 compared to 2014 season (Figure 4.28). In winter 2015 season, the open treatment had the least leaf area (< 80 cm^2) compared to winter 2014. Under the shadenet, leaf area was on average less than 100 cm^2 in spring 2014 compared to 2015. Also, leaf area was greater than 120 cm^2 in summer 2015 compared to the open treatment.

Overall, leaf area was greater under the shadenet in 2015 compared to 2014 (Figure 4.28). Leaf area and shoot growth were greater in winter and summer 2015 under the shadenet compared to in the open treatment (Figures 4.28 and 4.29). Water stress reduces photosynthesis and transpiration of sun-exposed and shaded leaves within the tree canopy (Kriedemann and Smart, 1971, Schultz and Matthews, 1988, Escalona *et al.*, 2003). Hence, leaf area in the open treatment was greatly reduced as a consequence of the day-time water stress (Section 4.3), whilst there was no reduction in leaf growth under the shadenet (Figure 4.28).

However, leaf reduction in the open treatment was also attributed to excessive heating and wind damage (Section 4.2). Flexas *et al*. (1999) postulated that fully expanded sun-exposed leaves show large variations in photosynthesis. Under the shadenet, there was no difference between sun-exposed and shaded leaves (data not shown). But there was a difference between sun-exposed and shaded leaves in the open treatment. Leaf area for shaded leaves was accelerated compared to the sun-exposed leaves in the open treatment (Figure 4.29).

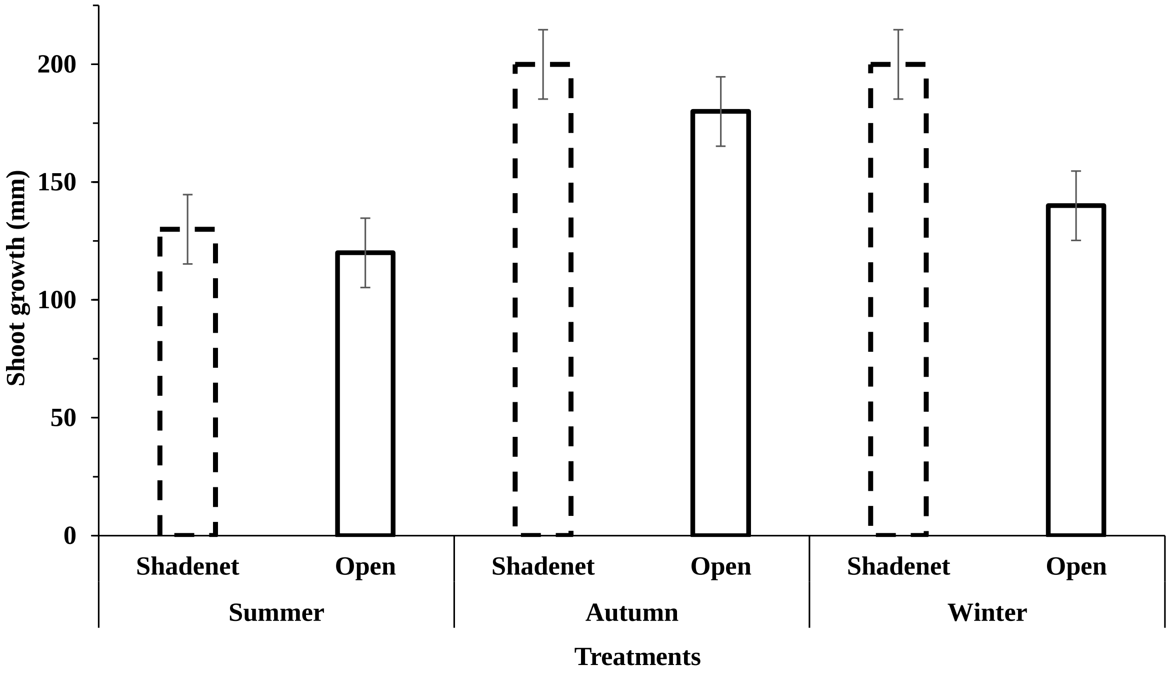

Figure 4.28 Shoot growth for summer, autumn and winter 2015 season under the shadenet and open treatment

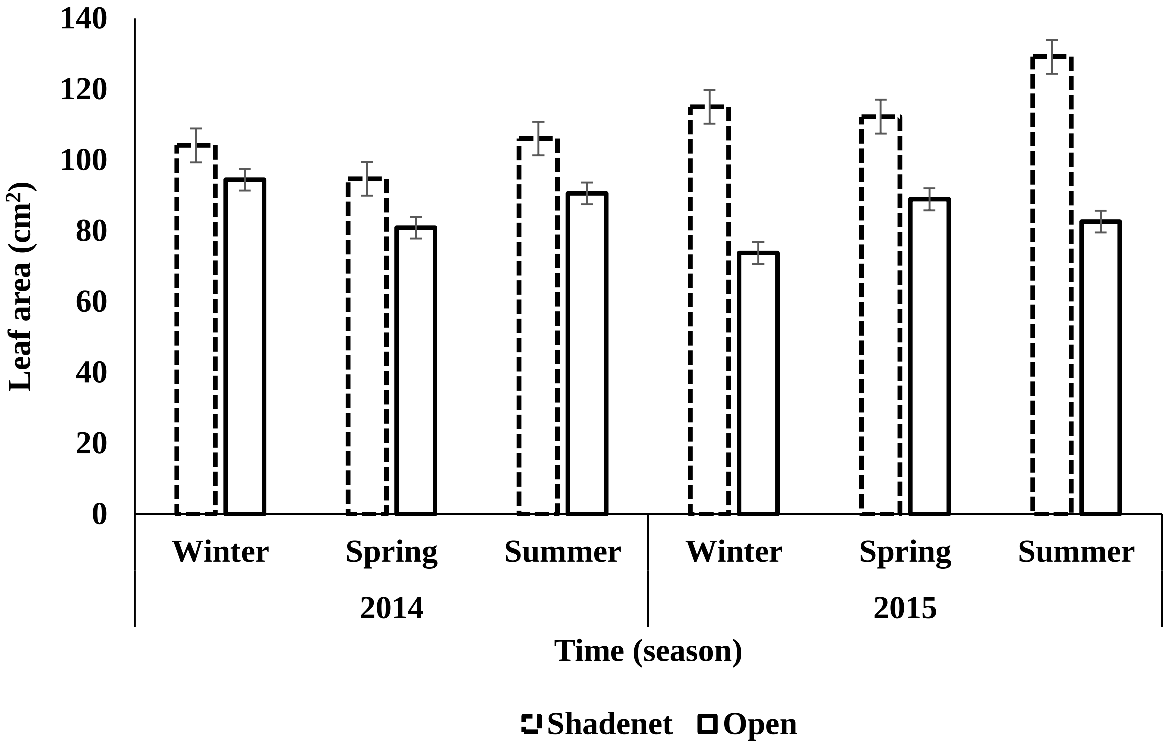

Figure 4.29 Leaf area comparison for winter, spring and summer 2014 and 2015 under the shadenet and open treatment

Variations in photosynthesis within the tree canopy also depends on leaf orientation, pruning, and crop load and leaf age (Havaux *et al.*, 1987, Havaux and Lannoye, 1987, Salazar-Garcia *et al.*, 2006). Water stress with varying amounts of incident PPFD intercepted within the tree canopy led to reduction in photosynthesis (data not shown). Hence, reduction in leaf area as a result of water stress, particularly in the open treatment (Section 4.3.1), starts at the beginning of the growing season when vegetative growth is maximal (Winkel and Rambal, 1993).

CO_2 and PPFD are the fundamental raw materials for leaf growth. According to Chaves (1991) leaves can photosynthesise, but the type and distribution of growth depends on how the photosynthates are distributed within the tree. However, a reduction in leaf area as shown in the open treatment (Figure 4.29), reduces the photosynthetic area of the leaf (Lovatt, 2010). Also, the circle of feedback control is instituted as the tree strives to restore the root: shoot equilibrium (Chaves, 1991, Heath *et al.*, 2005). Heath *et al*. (2005) postulated that leaves of an older flush become inefficient as a new flush develops and do not provide important resources during development of the new flush. In the current study, when leaves reached maximum leaf expansion, growth was partitioned to the newly developing leaves (data not shown).

Thus each new developing flush creates its own carbohydrate assimilates for growth and development (Wolstenholme and Whiley, 1989, 1990). The differences in shoot growth and leaf area were independent of the carbohydrate assimilates produced from the previous flush, whilst CO_2 and canopy temperature dictate the maximum assimilation rate and respiration depending on leaf age. Hence, the difference in shoot growth and leaf area under the shadenet and in the open treatment was a result of shadenet having greater carbohydrate assimilates distribution than in the open treatment (Figures 4.28 and 4.29).

Shoot growth and leaf area were promoted as a result of the altered microclimate, improved soil water and nutrient availability under the shadenet compared to the open treatment (Section 4.2 and 4.3). According to Scholefiled *et al*. (1985), leaf abscission and senescence reduces growth, CO_2 intake and therefore rate of photosynthesis on older flushes. The greater shoot and leaf area under the shadenet compared to the open treatment is correlated with flowering and fruit set (Figures 4.28 and 4.29) for the 2015 season. The greater shoot growth and leaf area for winter 2015, under the shadenet compared to the open treatment were a result of an indeterminate shoot (Figures 4.28 and 4.29). Indeterminate shoot is a cluster of flower and leaf buds that develop simultaneously. The leaves formed protect flowers and fruit against sunburn (Salazar-Garcia *et al*., 2013).

Smit (2006) found that during development of a new flush in a tree with a reduced crop load, greater amounts of photosynthates are partitioned into the vegetative sinks. This was observed in 2014 under the shadenet, 3 m x 3 m planting densities plot (data not shown). Trees were pruned more frequently under the shadenet than outside to prevent trees growing into the shadenet and improve PPFD interception for the following flower. Reserve carbohydrates account for one of two quarters of the building materials for new growth until floral buds begin to show colour. Floral and fruit development are strong sinks for carbohydrates and reduced vegetative growth (Crane *et al*., 2013). In 2014, floral and fruit development were greater in the open treatment compared to the shadent (data not shown). In 2015, increased vegetative growth under the shadenet was due to reduced crop load during 2014 season (Figures 4.28 and 4.29).

According to Wolstenholme and Whiley (1990), excessive shoot and leaf growth are wasteful of scarce energy resources, protein, minerals and water at the expense of fruit growth. Also, assimilates differ with individual tree components depending on their metabolic rate and size. Whiley (1990) found that when shoots reach maximum CO_2 assimilation fruit loss was stabilised. Determinate shoots are more productive than indeterminate shoots whilst the autumn shoots only produce a single terminal indeterminate floral shoot (Köhne, 1986, Köhne and Kremer-Köhne, 1987). But winter shoot growth is key to a good return bloom. Thus the more winter vegetative shoot and leaf growth, the greater the bloom and yield (Lovatt, 2010). Based on the current findings, shoot and leaf area were improved under the shadenet compared to the open treatment (Figures 4.28 and 4.29). Hence a 20% white shadenet is ideal for improving avocado vegetative growth. However, vegetation growth may differ with different cultivars and shadenets (Tanny, 2013).

4.4.2 Flowering, bee activity and pollination

Mature avocado trees produce up to a million flowers but not more than 200 flowers per tree set fruit that will hold and develop to maturity and harvest (Bender, undated). Avocado flowers are governed by the protogymous diurnally synchronous dichogamous mechanism (Stout, 1923). This mechanism enables avocado flowers to function as female and male flowers at different times of the day within the same flower. According to Robbertse (2011), the mechanism functions optimally when weather conditions are ideal (10 - 20 °C) and (25 - 30 °C) night and day, respectively, as was generally the case in the present study (Figures 4.6 and 4.8).

Figure 4.30, illustrates the percentage of trees under the shadenet and open treatment at full flower intensity during the 2015 winter season. Flower intensity was greater under the shadenet compared to the open treatment (Figure 4.30). Also, the rate of flower development under the shadenet was greater than in the open treatment (data not shown). Shadenet trees reached anthesis a few weeks earlier than open treatment trees. Flowering in a cool environment is mostly stimulated by low air temperatures and short day lengths. But it is induced by photoperiod more than low air temperatures in warmer environments (Davenport, 1986, Salazar-Garcia *et al.*, 2013). Nevin and Lovatt (1989) and Salazar-Garcia, *et al*. (1999) found that ‘Hass’ avocados grown in controlled environments require not more than four weeks of low air temperature stress to induce flowering. But their studies were solely based on cool avocado producing regions.

Flower initiation commences shortly after the autumn rainfall. Hence, soil water stress also inhibits ‘Hass’ avocado flowering, depending on the microclimate to which the trees are subjected (Bernier *et al.*, 1981). Prior to flower initiation and development, air temperature under the shadenet was less than in the open treatment (Figures 4.6 and 4.8). Despite lack of the much needed autumn rainfall to induce flowering (Figures 4.22 and 4.23), there was no day-time soil water stress under the shadenet compared to in the open treatment. Hence, reduced air temperature (Figures 4.6 to 4.9) and adequate soil water under the shadenet led to flower initiation and development earlier than in the open treatment. The majority of the floral shoots under the shadenet (Figure 4.30), also produced indeterminate inflorescences compared to the open treatment (Salazar-Garcia and Lovatt, 1998).

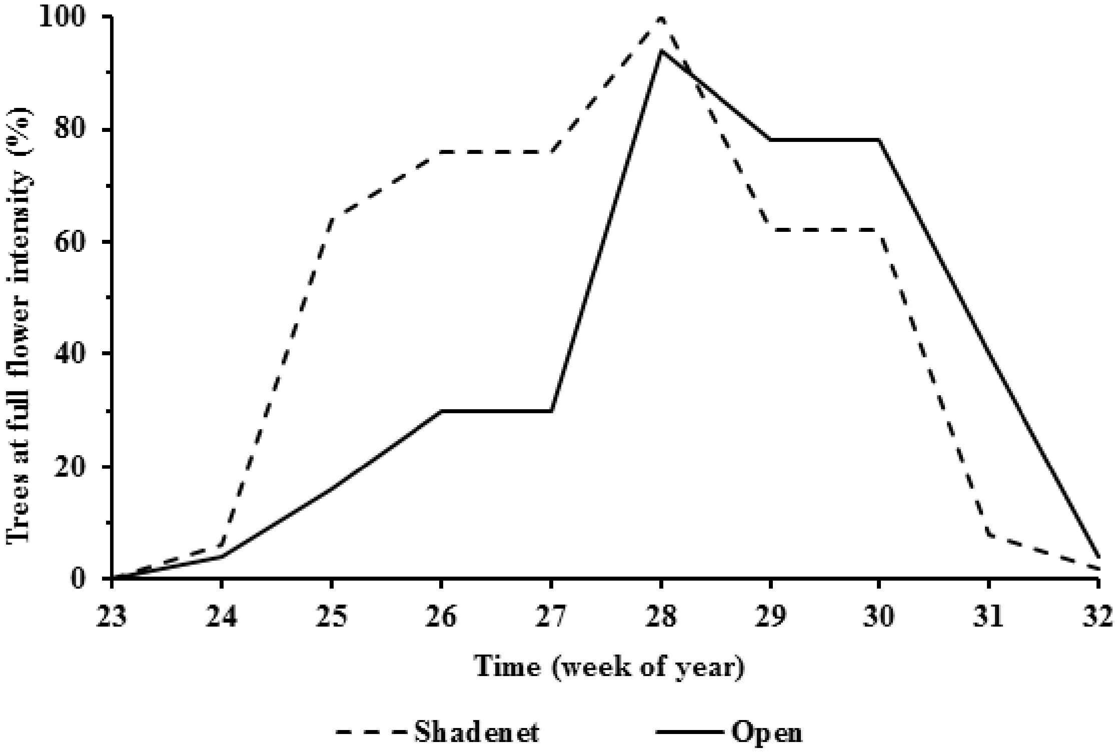

Figure 4.30 Percentage of trees at full flower intensity under the shadenet compared to the open treatment during the 2015 winter season

Flowering length both under the shadenet and in the open treatment were extended during the early stages of flower development. Pollination was also rapid once flowers reached anthesis both under the shadenet and in the open treatment (data not shown). In the current study, pollination was monitored by tracking the female and male flower opening stages (Protogymous diurnally synchronous dichogamous) and the bee activity. Figures 4.30 and 4.31 show events in female and male flower changes over time both under the shadenet and open treatment.

Ish-Am (2008) and Alcaraz and Hormaza (2009) reported similar findings on ‘Hass’ avocado flower opening. However, the ratio of male to female flowers opening was relatively similar from day 8 to 17 (July, 2015) under the shadenet compared to the open treatment. The stable warm day and night air temperature under the shadenet resulted in a 2-hour overlap between the male and female flowers. Air temperature for the open treatment was not conducive for the female flowers’ stigmas to be receptive, largely resulting in a greater ratio of male flowers opening to female flowers (Figures 4.31 and 4.32). Also female flowers opened twice due to greater low relative humidity in the open treatment compared to under the shadenet (Davenport *et al.*, 1994).

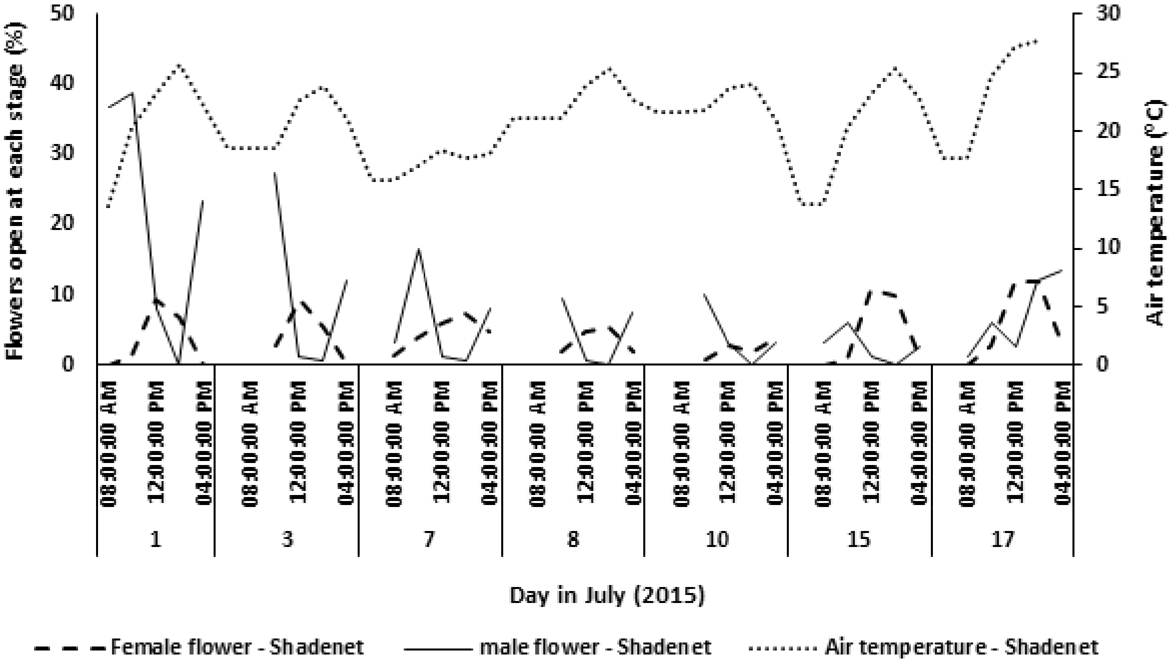

Figure 4.31 Flower opening at different stages under the shadenet over time and the variation in air temperature

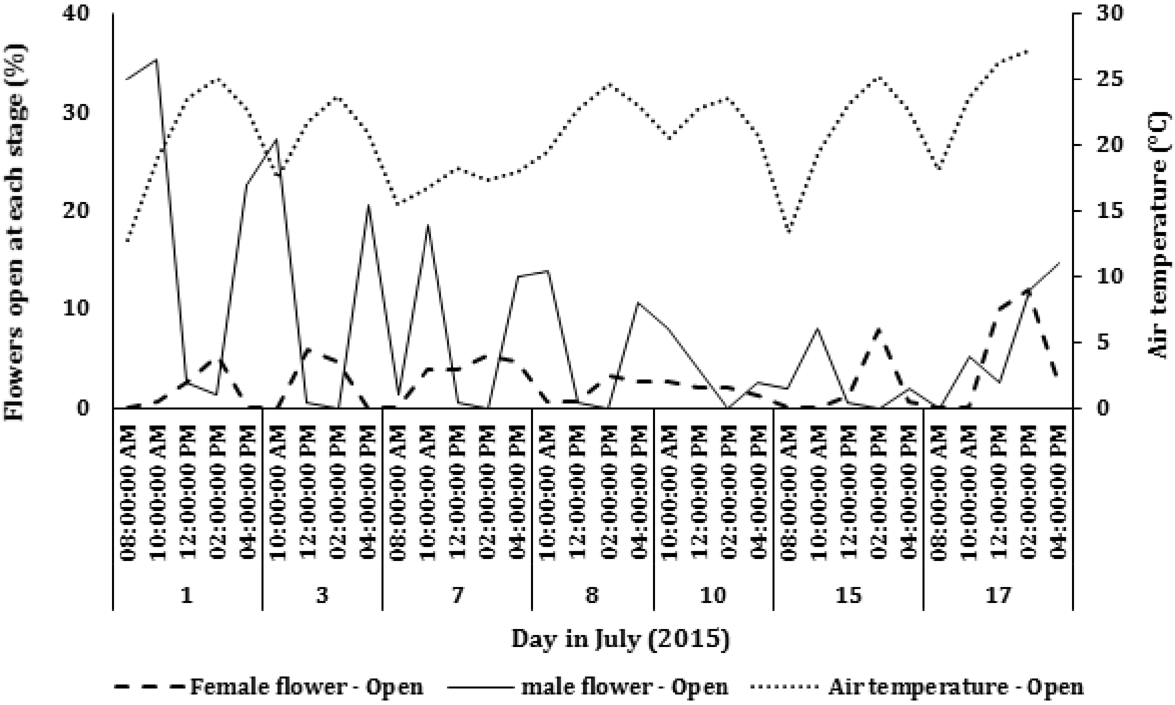

Figure 4.32 Flower opening for the open treatment and the variation in air temperature during anthesis

Flower opening under the shadenet was significantly influenced by the stable air temperature and reduced wind speed, whilst cloud cover greatly disrupts the overlap (Figures 4.8 and 4.31). In Figures 4.31 and 4.32, there was a 2-hour overlap between the female and male flowers resulting in a close pollination and limiting self-pollination (Robbertse *et al.*, 1997). Figures 4.31 and 4.32 show that the female flower phase is sensitive to lower air temperature than the male phase. During a cold morning, for example on day 3, 8 and 15 of July 2015 both under the shadenet and open treatment (Figures 4.31 and 4.32), flowers were late to open in the female phase until air temperatures were well above 20 °C (Ish-Am and Eisikowitch, 1992).

Pollen grains and pollen tube growth are also sensitive to air temperature where pollen tube growth is terminated when air temperatures are above 30 °C (Figure 4.8). Davenport *et al*. (1994) demonstrated that a pollen tube could reach the egg apparatus within 48 hours of pollination by pollinators. However, their study did not provide the required stimulus required for the survival of the pollen tube growth. Sedgley (1976) showed that hand-pollinated pollen tubes could reach the ovary within 24 hours.

Hand pollination was also carried out following the low flower set and lack of bees activity under shadenet during the 2014 season. Successfully hand pollinated flowers under the shadenet were 4% greater than in the open treatment (2%) (data not shown). Hand pollination was greater on indeterminate compared to determinate inflorescence both under the shadenet and in the open treatment. However, hand pollinated flowers that later set fruit were only counted prior to first fruit drop and could not be counted at a later stage of development due to destructive machinery operations within the orchard blocks. This resulted in a greater number of potential hand pollinated fruit being damaged, and therefore dropped prior to the final count.

Pollinators are more effective at pollinating avocado flowers compared to hand or wind (Salazar-Garcia *et al*., 2013). Honeybees are the most effective avocado flower pollinators but are not attracted to the flowers compared with other fruit crops (Ish-Am and Eisikowitch, 1993, Robbertse *et al.*, 1997, Alcaraz and Hormaza, 2009b). However, the flower nectar contains high potassium and phosphorus levels, which makes it unattractive to bees (Afik *et al.*, 2006b). Bee activity under the shadenet was greater compared to in the open treatment (Figure 4.33).

Bee activity was as high as 5 to 8 bees per tree under the shadenet compared to a maximum of three bees per tree for the open treatment (Figure 4.33). This greatly limited pollination in the open treatment compared to under the shadenet. Under the shadenet, 11 beehives were closely distributed along the orchard. Bee activity was less for trees furthest from the hives and higher for trees closest to the hives (data not shown). The furthest trees were 60 m away from the beehives. However, bee activity under the shadenet did not correspond to findings by Robbertse (1997) and Johannsmeier and Morudu (1999) who found that bees move freely when orchard trees are young. But these findings, were based on an open environmental condition instead of a shadenet environment. Thus in the present study, bees preferred to pollinate flowers which were closer to the beehives and failed to pollinate flowers furthest from the beehives (data not shown).

For the Mooketsi Valley, Robbertse (1997) recommended five bees per tree but under the shadenet this number may not be sufficient for improved yield or pollination and may largely depend on tree size and flower intensity. The major challenge of bees under shadenet was bee disorientation particularly following strong winds and cold weather conditions.

Ying *et al*. (2009) demonstrated that avocado trees grown under bee exclusion nets had significant yields similar to those pollinated by bees and concluded that wind pollination is more effective. But Ish-Am and Lahav (2011) found that bee visitations to flowers correlated to pollination and wind pollination were insignificant in an exclusion net. Both studies did not mention the magnitude of wind speed required for pollination. Also, avocado flower nectarines and small stigmatic surfaces are inconsistent with the typical morphology of wind pollinated flowers (Vithanage, 1990).

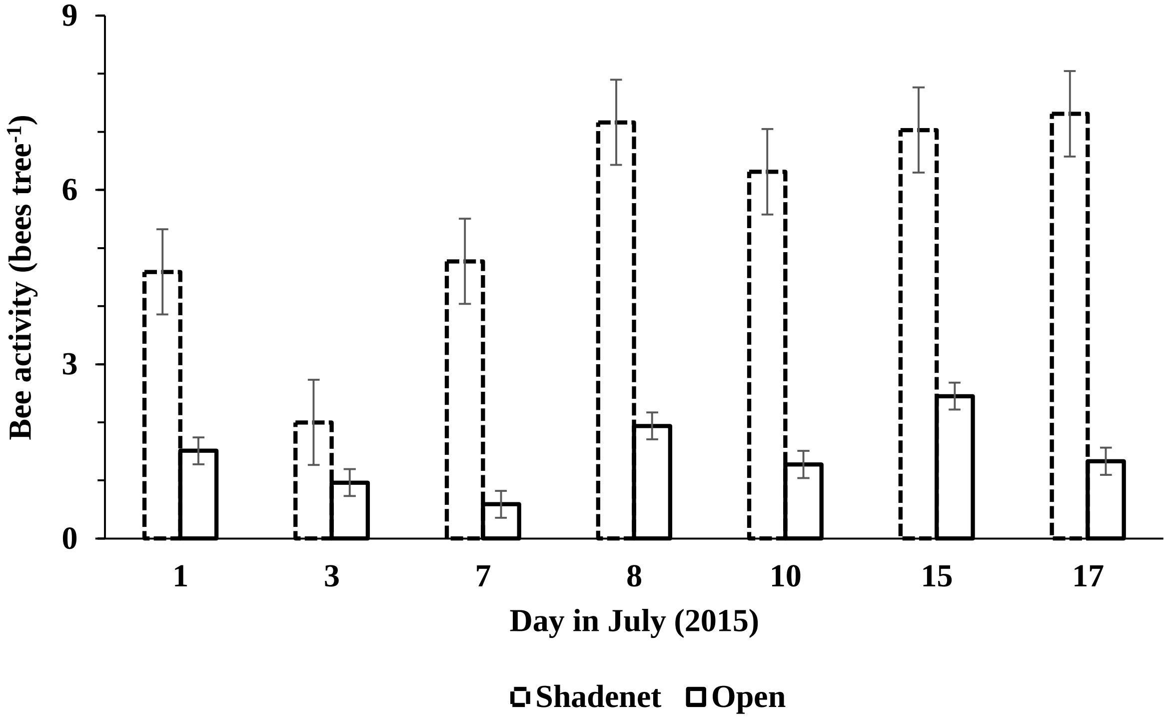

Figure 4.33 Bee activity per tree during anthesis in July 2015 under the shadenet and open treatment

Both the bee activity and the pollination rate were greater under the shadenet compared to the open treatment (Figure 4.33), which showed the positive effect of microclimate improvement on the pollination. In avocado production, bee activity is a major concern, as pollination can be considered a limiting factor for the production. The number of bees per tree needs to be greater than what was observed during the flowering season. Eleven bee hives per hectare will be necessary to have enough pollinator activity in order to achieve a greater production, instead of three bee hive per hactare present at this stage in commercial orchards. However, farm management practices still need to be optimised for improved avocado production under shadenets.

4.4.3 Fruit development and maturity

In avocado production, effective pollination is followed by fertilisation for a good fruit set. Fruit drop occurs due to the stigma not being pollinated, pollen tube growth does not occur and the ovule does not develop into the seed. But favourable weather conditions and healthy trees are required to prevent fruit drop (Rossouw and Robbertse, 2001). In 2015, fruit set was greatly improved under the shadenet compared to the open treatment, particularly for the indeterminate inflorescences.

However, Köhne (1986) found that the indeterminate inflorescence is correlated with poor fruit set, and concluded that excessive growth results in high fruitlets abortion rate. According to Wolstenholme and Whiley (1990), it is not the excessive growth per se but the amount of incident PPFD which influences a relatively high flower bud initiation and development and fruit set within the tree canopy. Also, fruit set and vegetative growth compete for nutrients and hormones (Wolstenholme, 1990).

Thus, fruit set and development in the avocado is dependent on pollination and fertilisation. But avocado fruit may still develop after fertilisation without seed and are referred to as cukes. Cukes arise due to embryo and endosperm abortion and are common on ‘Fuerte’ and girdled ‘Hass’ tree branches (Garner, 2004). Cukes were not found on the ‘Carmen®-Hass’ trees both under the shadenet and in an open treatment. Fruit growth under the shadenet was significantly different from the open treatment using the anova test ($P < 0.05$). Hence, fruit development was greater under the shadenet compared to in the open treatment (Figure 4.34).

However, there was no significant difference in fruit development within the canopy, i.e. east vs middle vs west (data not shown). ‘Carmen®-Hass’ minimum fruit maturity is set at 77% fruit water content. Normal season fruits under the shadenet reached the minimum maturity 2 weeks earlier than the open treatment fruits during 2014 and 2015 seasons (Figures 4.35 and 4.36). Out-of-season fruits were hung until early summer and fruit water content measurements were not conducted. In figure 4.34, avocado seasonal fruit growth follows a single sigmoid curve as confirmed by Salazar-Garcia *et al*. (2013).

However, when observed carefully there are daily fluctuations in growth during the day and enlargement at night (Robertson, 1971). According to Bower and Cutting (1988), fruit size variation resulted primarily from differences in the rate of cell division during the first several weeks of fruit development. From figure 4.34, fruit growth was rapid within the first five weeks of measurements, and thereafter uniform. Thus, fruit growth was rapid because of the continuous high rates of cell division and expansion.

In figures 4.35 and 4.36, the fruit water content measured are illustrated for 2014 and 2015 season. The normal season refers to fruit that were harvested in autumn (March and April). 'Carmen-Hass' bears fruits twice in a year and the second crop which and harvested later in the year is referred to as the out-of-season crop. The normal season crop begins in winter (mid- June to early July) to flower whilst the out of season crop starts flowering in summer (December/January). Out-of-season fruit are picked in late spring to early summer (October and November) (Van Rooyen, 2011).

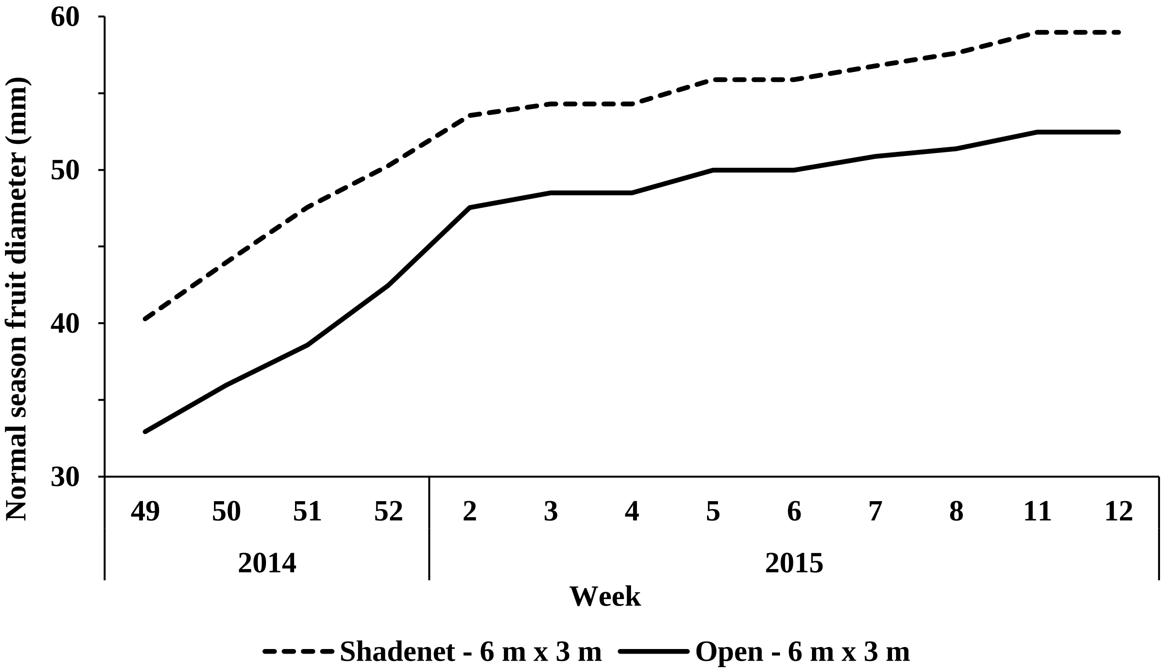

Figure 4.34 Sigmoid fruit growth curve measured on the 6 m x 3 m planting densities under the shadenet and open treatment

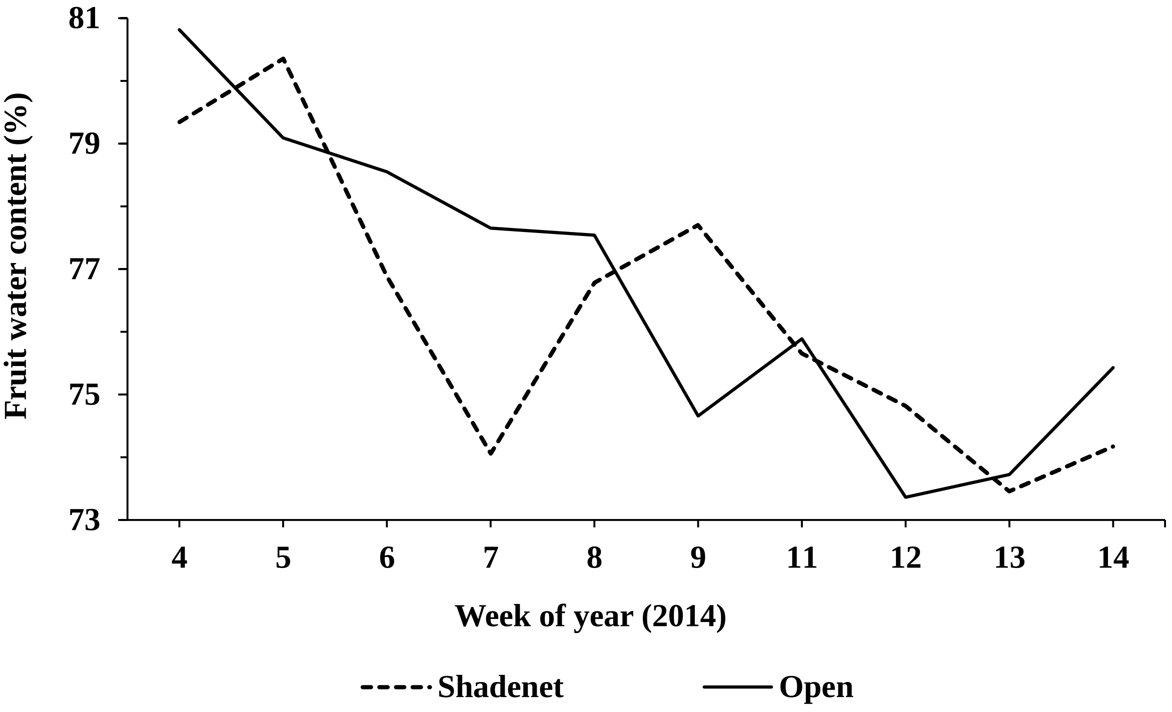

Figure 4.35 Normal season fruit water content averaged weekly under the shadenet and open treatment

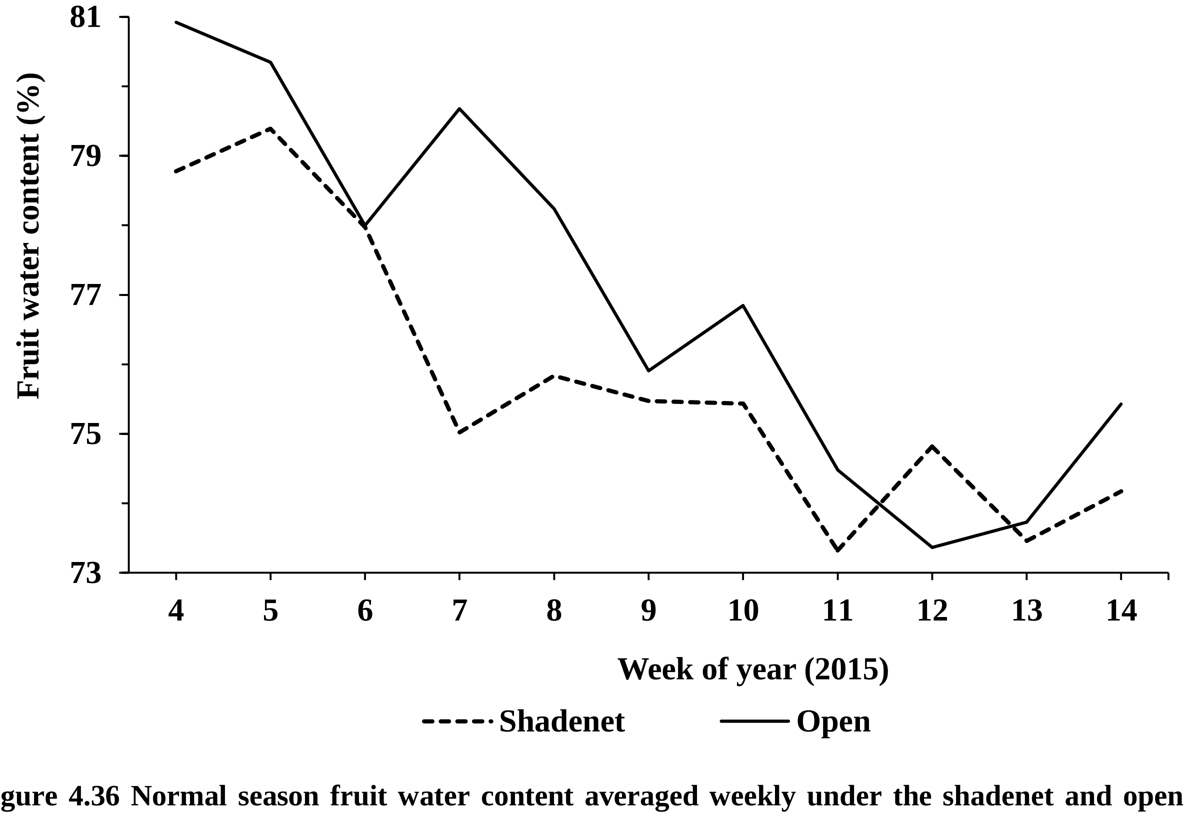

Figure 4.36 Normal season fruit water content averaged weekly under the shadenet and open treatment for the 2015 season

In figure 4.34, avocado fruit growth was attributed to seed growth (Mougheith *et al.*, 1978). But the role of the seed in fruit growth varies with fruit species and cultivars (Smit, 2006). Fruit growth is largely dependent on their seeds for growth and development. Auxin increases the sink strength of avocado fruit and regulates endosperm development (Bower and Cutting, 1988). Cell enlargement stops when avocado fruit reaches 50% of its fruit size whilst cell division accounts for the continued growth.

According to Van Den Dool and Wolstenholme (1983), mesocarp cell division in the mesocarp is not restricted but continues during fruit development (Figure 4.34). Eaks (1990) found that the seed is surrounded by an activity of dividing mesocarp that accumulates carbohydrates, proteins and fatty acids. But during growth, the mesocarp water content decreases as oil content increases (data not shown). Hence, avocado fruits have a greater protein and carbon seven (C_7) sugars (Cowan, 2004, Bertling *et al.*, 2007)

Fruits of the same cultivar vary in size due to cell number, cultural practices, yield, water relations and climatic condition (McOnie and Wolstenholme, 1982). But within the same tree, there was insignificant fruit size variation under the shadenet when compared with the open treatment (data not shown). Thus, shadenet improved fruit size particularly in 2015 compared the 2014 season (Figure 4.34). Soule and Harding (1955) reported that differences between large and small fruits become less pronounced at harvest (Figure 4.35 and 4.36). Therefore, we do not know what was contrary, since we do not know their fruit water content.

In figure 4.34, the improved fruit size under the shadenet was attributed to the improved soil water and nutrient uptake, whilst for the open treatment, fruit size and growth were retained as a result of the day-time soil water stress (Table 4.33, Figures 4.22 and 4.34). Despite fruit size increasing shortly after fruit set, soil water stress also results in fruit shrinkage as air temperature increases (data not shown). Air temperature was slightly greater in the open treatment compared to under the shadenet during fruit growth and development (Figures 4.6 to 4.9). Thus fruit shrinkage during soil water stress and warm air temperature accelerates the rate of transpiration resulting in the withdrawal of water from the fruit and adjacent leaves (Bower and Cutting, 1988).

The findings of the current study found that a vast number of fruits were small in the open treatment due to water stress (Figure 4.34 and Section 4.4.1). Kaiser (1993) also linked small fruit size to limited assimilate movement with inactive phloem cells and accumulation of phenolics. The results shown in Figure 4.22, 4.34 and Section 4.4.1, confirm that the small fruit size is highly linked to abiotic stress within the orchard (Cowan, 1997, Cowan *et al.*, 1997).

Köhne and Schutte (1991) reported that ‘Hass’ small fruit problem can be improved through the application of cytokinin. But it was later discovered that cytokinin had no effect on fruit size and reduced yield (Köhne *et al.*, 1993). Cowan *et al*. (1998) and Cripps *et al*. (1999) postulated that 'Hass' small fruit size problem was a result of an imbalance between cytokinin and abscisic acid (ABA). But an increased ratio of cytokinin, ABA and 3-indoleacetic acid (IAA) results in normal fruit growth. Figures 4.35 and 4.36, prove that avocado fruit growth is dependent on a fundamental seed coat until maturity (Blakey and Wolstenholme, 2014).

But variation in fruit maturity within the same orchard and/or tree exists (Kotze and Kuschke, 1978). Fruit maturity is greatly influenced by the microclimate conditions during fruit set. Thus cold air temperature delays fruit maturity (Burelli, 1982) and lower air temperature causes variation in fruit water content (Kruger and Claassens, 1996). Despite the seasonal variations in air temperature under the shadenet, fruit matured earlier and fruit size was increased when compared with an open treatment fruits (Figures 4.35 and 4.36).

Kotze and Kuschke (1978) found that fruit from shaded sides of a 'Hass' tree canopy had lower fruit oil content. Kruger and Claassens (1996) concluded that fruit water content was less variable than fruit oil content. Also, fruit water content does not increase following rainfall and irrigation, but irrigation increases oil content and fruit size and does not delay fruit picking (Nzanza and Pieterse, 2012). Under the shadenet, fruit can be picked earlier than fruit in the open treatment. But this did not happen, fruit were picked simultaneously with the open treatment fruit.

4.5 Yield and postharvest

4.5.1 Yield, fruit size distribution and packout

Like 'Fuerte', 'Carmen®-Hass' is an early season fruit (Illsley-Granich, 2011; Van Rooyen, 2011). The 2014 seasonal yields under the shadenet were low compared to in the open treatment (Figure 4.37 and 4.38). However, fruit size distribution (FSD) and packout were greater under the shadenet compared to in the open treatment (Figures 4.37 and 4.38). The improved packout under the shadenet compared to the open treatment was due to the reduced sunburn, wind damage and improved soil water availability.

The infestation of the leaf roller pest during the 2014/15 season under shadenet (3 m x 3 m) block damaged a greater number of fruit and reduced the highly anticipated yield and packout (Section 4.2.3). Tree spacing was too dense to permit air flow and insect pest control. 'Carmen®-Hass' bears a greater amount of small fruit (Figure 4.37). The size of small fruit was greater in the open treatment compared to under the shadenet. Moreover, small fruits were greater for the OOS compared to the normal season fruit (Figure 4.38). However an improved FSD under the shadenet was attributed to the improved soil water availability. In Figure 4.38, the numbering system used in the legend refers to the count fruit sizes used to pack fruit. Hence, count 14 and 16 are large sized fruit, count 18 and 20 are medium size and > 20 is small fruits. Preferably count 18 and 20 are exported compared to count 14 and 16 sized fruit.

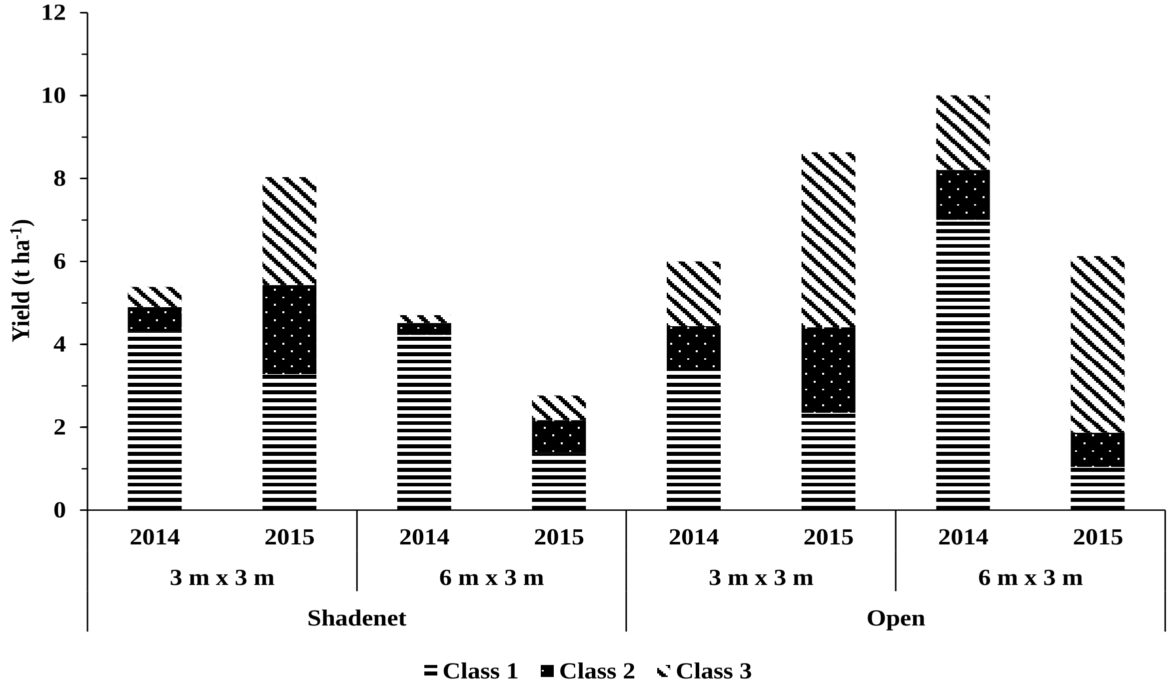

Figure 4.37 'Carmen®-Hass' normal season yield and packout for 2014 and 2015 normal season (March) from Mooketsi Valley. Class 1 is export grade, Class 2 is local market grade, and Class 3 is factory grade

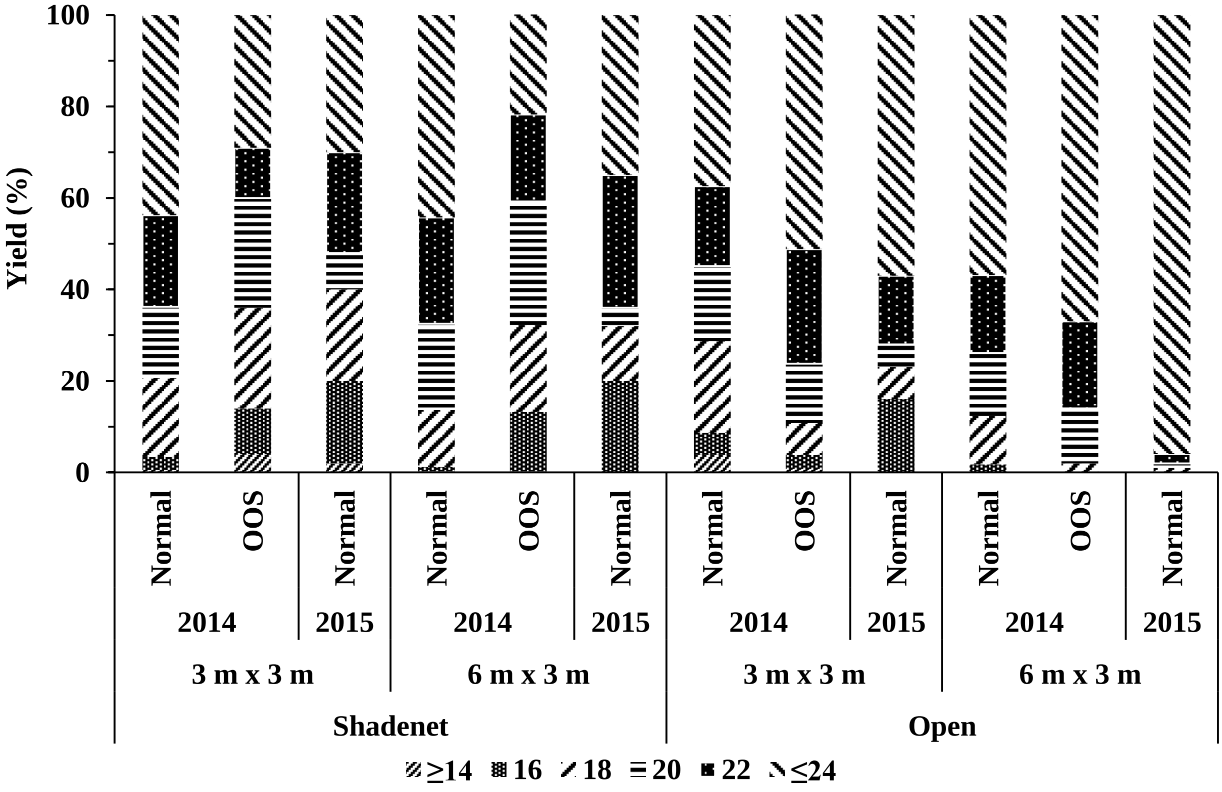

Figure 4.38 'Carmen®-Hass' Percentage yield for 2014 and 2015 normal season (March/April) and 2014 out-of-season (OOS – October/November) for Mooketsi

In 2014, yield was greater in the open treatment (6 m x 3 m) than under the shadenet (6 m x 3 m) (Figures 4.37 and 4.38). The 6 m x 3 m block was irrigated with microsprinklers while the other three blocks were under drip irrigation, although irrigation was changed to micro-sprinkler (27 L h^{-1}) in June 2013. The reduced yield in the OOS crop is because bees were intentionally not introduced into the orchard block(Figures 4.37 and 4.38). This was done to determine whether fruit set from the OOS flower could be largely eliminated by not introducing bees.

It is apparent that fruit set was greatly reduced when bees were not introduced, providing an option to set a single crop for 'Carmen®-Hass' if the grower so desires. Like 'Hass', 'Carmen®-Hass' fruit is generally medium to small. Under the shadenet, fruit were generally larger than those grown in the open treatment (Figures 4.37 and 4.38), but it is acknowledged that FSD was greatly affected by yield. Also FSD and yield will only be possible once a mechanism to enhance a greater bee activity and pollination under shadenet in order to obtain much higher yields is tailored (Blakey *et al.*, 2015).

4.5.2 Ripening and quality assurance

According to Bower and Cutting (1988), avocado fruit tissue is in a juvenile physiological phase during development. This is because of the high rate of cell division contributing young cells to the tissues. Thus, when physiological maturity of individual cells is attained, there is a decrease in respiration and the fruit begins a ripening process after harvest. The transition in colour change arises due to chlorophyll loss and an increase in anthocyanin concentration (Cox *et al.*, 2004, Ashton *et al.*, 2006).

'Carmen®-Hass' changes from green to dark purple when ripe and low storage temperatures often delay fruit colouration (Hofman *et al.*, 2013). The 2014 normal and out-of-season fruit under shadenet had the least sun and wind damage compared to in the open treatment fruit (Figures 4.38 and 4.39). But during the 2015 season, the normal season packout was reduced due to insect damage. Grey pulp and chilling injury incidents were not found in either treatment during the 2014/15 seasons.

When fruit were stored at 5.5 ˚C during the 2015 season, they still exacerbated the least chilling injury compared to the open treatment fruit (data not shown). Chilling injury results primarily from low storage temperature exposure of fruit. In addition, the severity of chilling injury is dependent on cultivar, maturity and duration of the exposure (Hofman *et al.*, 2013). The significance of the cold storage was that fruit ripened late (30-40 days from harvest) compared to when they were stored at room temperature, during the 2014 OOS (Figure 4.40).

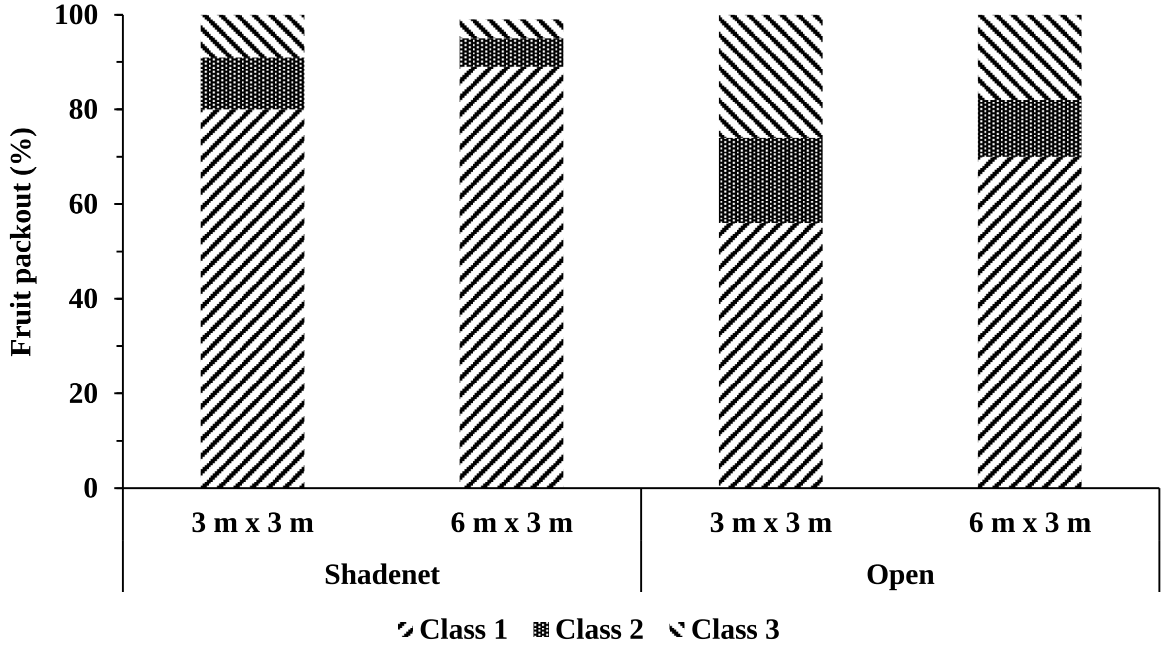

Figure 4.39 Normal season ‘Carmen®-Hass’ packout percentage for the 2014 season

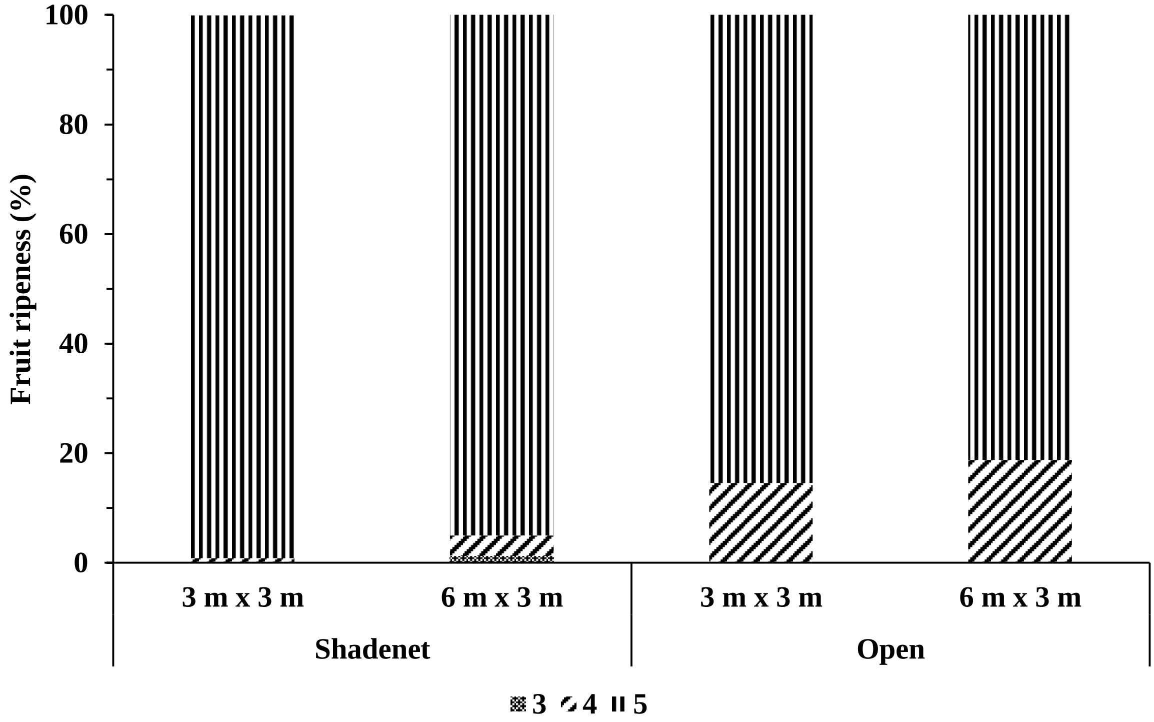

Figure 4.40 Normal season fruit ripeness under the shadenet compared to the open treatment for the 2014 season: 3 - green fruit colour, 4 - dark green, 5 - purple colour and 6 - black

Some fruit were slightly bruised during picking and handling processes but had no detrimental effects on quality of the ripe fruits. ‘Carmen®-Hass’ vary in skin colour despite being ripened simultaneously (Figures 4.41 and 4.42). According to Cox *et al*. (2004), the contributing factors are ripening and storage temperature. Plant growth regulator, PPFD and nitrogen availability influence ripening but Ca and ethylene delay fruit ripening (Crane *et al*., 2013). Hofman *et al*. (2002) found that a high flesh calcium concentration might influence fruit to ripen rapidly and have less disease. This influences greater fruit skin chlorophyll content at harvest and minimises chlorophyll loss during ripening. As discussed in Section 4.3.1, the concentration of Ca was slightly greater under the shadenet compared to the open treatment. Hence, fruit ripening was influenced more by irrigation and plant density than the Ca concentration (Figures 4.23 4.42).

Moreover, open treatment fruit had rapid water loss during the ripening process compared to shadenet fruit. Hence open treatment fruit had a greater incidence of fruit shrivel due to fruit water stress. Also during picking, fruit should be kept under shade to avoid rapid fruit water loss. However, seed health was unchanged both under the shadenet and in the open treatment (data not shown). ‘Carmen®-Hass’ fruit are picked early in the year and do not have grey pulp diseases compared to ‘Pinkerton’. Stem-end rot was treated during picking but its development was greater during the OOS compared to the normal season, particularly under the shadenet compared to in the open (Figure 4.43). The susceptibility of avocado fruit to physiological and pathological vary differs with cultivar, maturity level, stage of ripeness and relative humidity (Bower and Cutting, 1988, Hopkirk *et al*., 1994, Van Rooyen and Bower, 2006).

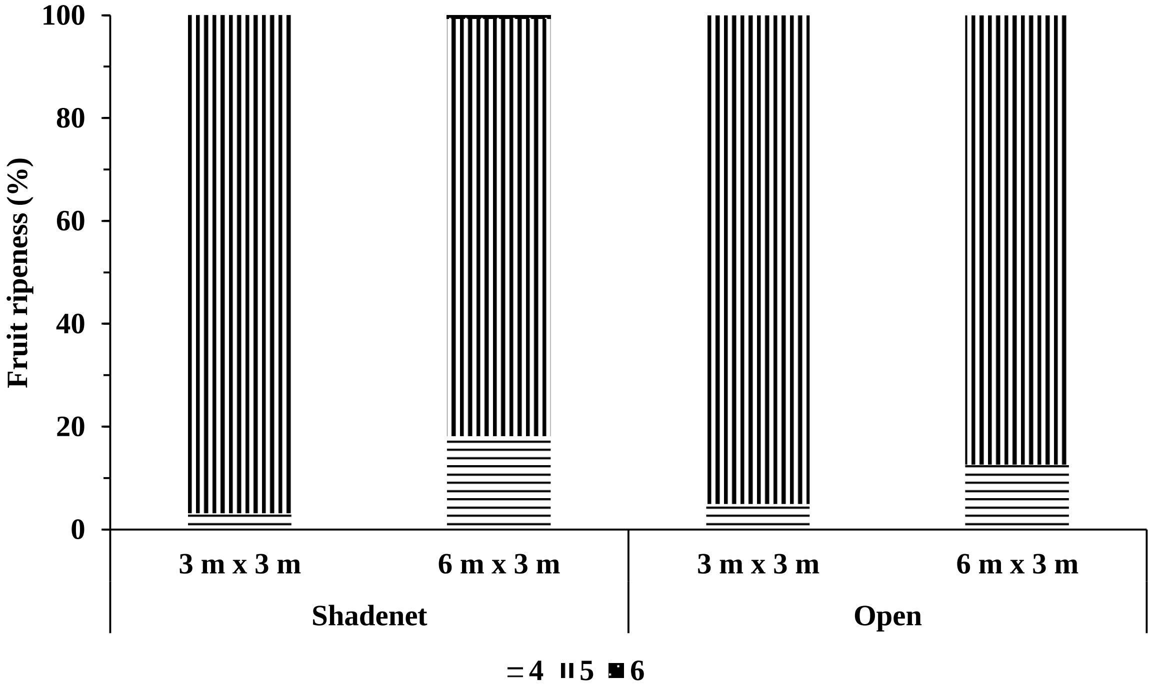

Figure 4.41 Normal season fruit ripeness for the 2015 season

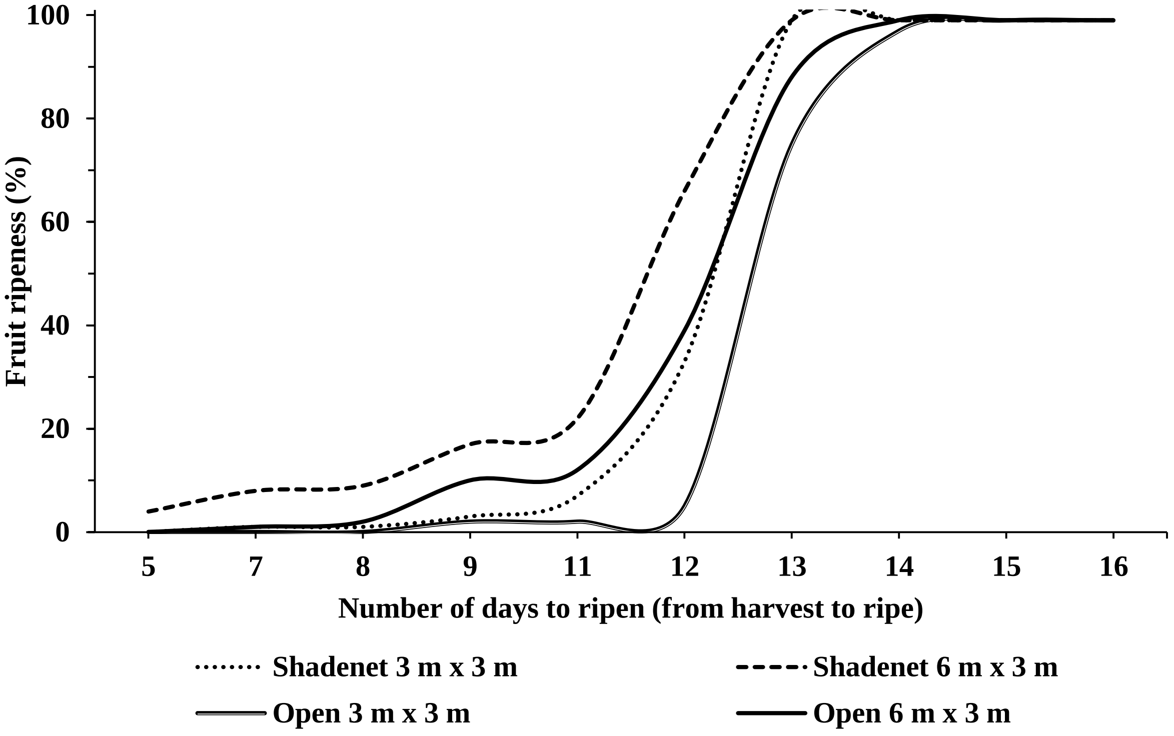

Figure 4.42 Number of days to ripeness from harvest to fully ripe for the 2014 out of season

OOS fruit are picked in November when air temperature is above 30 ˚C for most days. This created a greater incidence of stem-end rot (SER) both under the shadenet and in the open treatment. However, the incidence was more pronounced on the 6 m x 3 m blocks (Figure 4.43). Duvenhage (1993) found that picking wet fruit increased lenticel and vascular browning in 'Hass' fruit. In both treatments, the internal fruit quality of normal and OOS fruits was excellent. However, slight lenticel damage was found in the open treatment fruit compared with shadenet fruit.

Cutting and Wolstenholme (1992) demonstrated that postharvest fruit age and prevailing temperature were identified as the main factors that affect fruit internal and external quality. In both treatments, older and soft fruit developed more physiological and quality disorder during storage and transport quicker. Thus, it is important so as to maintain fruit in an adequate storage conditions to reduce avoidable quality disorder.

Preharvest factors have a significant effect on postharvest fruit quality. Excessive vegetative vigour increases the risk of poor internal fruit quality due to increased nitrogen and reduced calcium concentration in the fruit pulp (Blakey and Wolstenholme, 2013). Fruit water potential is affected by long-term soil water potential. Low water potential can have a negative effect on fruit quality by reducing the accumulation of calcium in the fruit. Calcium is required for cell wall and membrane stability among other physiological roles. But fruit diseases and disorders increase with fruit maturity (Cutting and Wolstenholme, 1992, Kruger *et al.*, 2004, Van Rooyen and Bower, 2006).

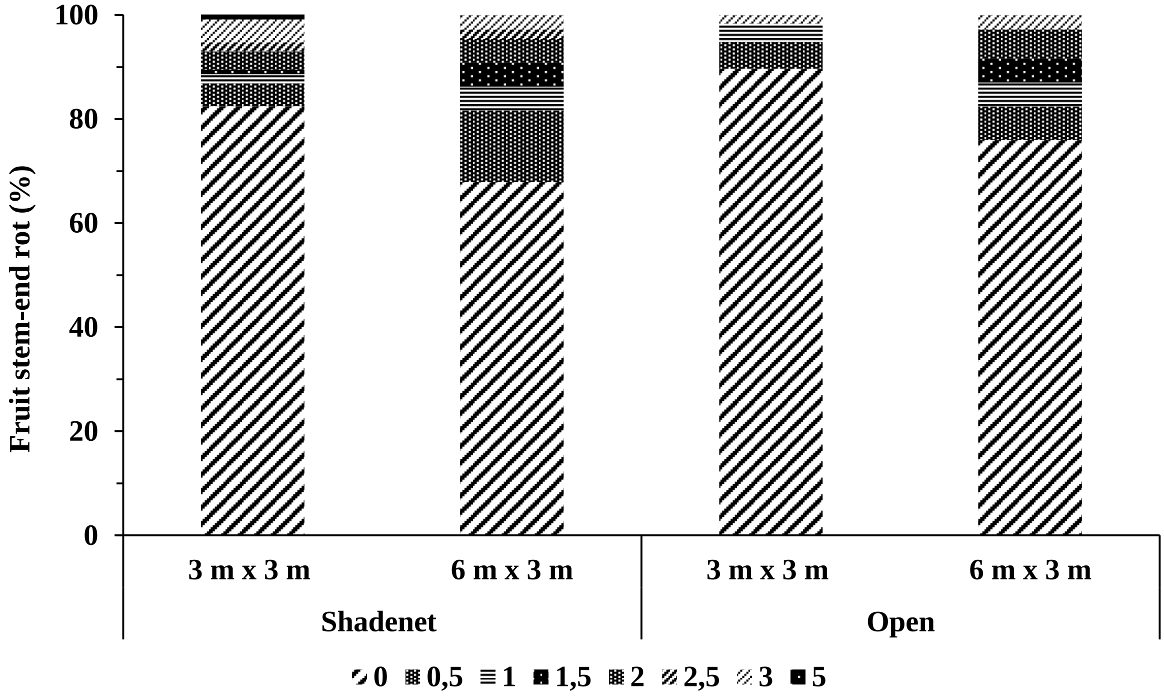

Figure 4.43 Fruit stem-end rot for the out-of-season quality assurance evaluation. 0 – no SER; 0,5 to 1,5 – slight SER; 2 – SER; 3 to 5 – severe SER

Tree yield has an effect on fruit quality as high yielding trees ripen faster than those from low yielding trees (Hofman *et al.*, 2002). Avocado has a high respiration rate compared to other fruit crops. Hence pre-cooling fruit shortly after picking reduces incident of softening. But cellulose is the main enzyme involved in the softening process and its activity is low in freshly packed fruit compared to mature fruits.

Increased fruit water loss during storage enhances polyphenol oxidase (PPO) activity, physiological and pathological disorders (Bower and Cutting, 1988). Thus, relative humidity needs to be kept at optimum levels during storage to avoid fruit water stress. 'Hass' fruit can be stored at temperatures as low as 2 °C. Hence, chilling injury increases with storage temperature, fruit age and time, where brown cold damage only develops when fruit are stored at room temperature following cold storage. Irrigation during flowering and fruit set are important in improving fruit quality and size.

4.6 Conclusion

Temperature (air and canopy) and relative humidity were slightly reduced within the shadenet structure. Air flow was restricted to a certain degree, and canopy temperature depended on tree density and the incoming solar irradiance received on the sun-exposed leaves. There was low wind under the shadenet and 80% of the incoming solar irradiance was transmitted, increasing the LWD by 12 h.

Leaf roller pests were observed on fruit as a result of the increased LWD inside. ET_o was reduced by 14, and 29% less water was applied inside the shadenet. The mechanism which drive sap flow are not yet fully understood. More studies are required to understand the phenotypic and genotypic mechanism for avocado sap flow both under the shadenet and in the open environment. Fruit reached maturity two weeks earlier under the shadenet than in the open treatment. The fruit size distribution was greater under the shadenet but yield was affected due to pollination difficulties inside the shadenet. Internal fruit quality disorders were low and fruit was resistant to chilling injuries. Also, fruit shrivelling proved that in the open treatment fruit were water stressed and warrants strong pre-harvest measures to be taken to prevent tree water stress during flowering and fruit set.

The 20% white shadenet resulted in improved fruit quality and size due to reduced wind damage and sunburn. There were difficulties in the 2014 bee activity and pollination but slight improvements were observed in the 2015 season. However, a thorough investigation on bee management under shadenet is required to optimise pollination in order to obtain high yields under the shadenet.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Aims and objectives

The aim of the study was to determine the effects of a 20% white shadenet on 'Carmen®-Hass' microclimate, avocado tree phenology, fruit quality and yield under the subtropical conditions in the Mooketsi valley near Tzaneen in the Limpopo province, South Africa. The objectives of the research were:

1. To determine the effect of a 20% white shadenet on 'Carmen®-Hass' so as reduce abiotic stress and in particular heat, solar irradiance and wind.
2. To investigate and monitor the 'Carmen®-Hass' phenological responses under the shadenet in order to optimise bee activity and pollination.
3. To monitor the bee activity and pollination so as to increase long-term yield and profitability of 'Carmen®-Hass' avocados in the Mooketsi Valley.

5.2 Findings

Air and canopy temperature variations were beneficial during certain phenological events. The greater air temperature under the shadenet compared to in the open treatment improved bee activity and pollination in 2015. A 2-hour flower opening overlap between the female and male flowers was observed between 12 am and 2 pm. However the overlap and bee activity largely depended on air temperature and cloud cover. The 18% reduction in solar irradiance correlates to the 20% shading factor of the shadenet. This proved to have a positive effect on soil water and nutrient availability. Evapotranspiration and sap flow were reduced by 14% as a result of the reduced solar irradiance and wind speed where differences in air temperature were variable under the shadenet and the open treatment and did not have an effect on evapotranspiration.

The response of avocado to solar irradiance under shadenets is not well documented. Yet, most avocado leaves develop in full sun and exist in shade parts of the canopy whilst others will develop in deep shaded parts of the canopy. Thus, avocado is very efficient at utilizing low PPFD levels and has mechanisms that allow them to respond quickly to changing solar irradiance. Wind speed reduces transpiration due to partial closing of the stomata. This is a result of increased VPD at the leaf surface. High wind speed with low air temperature have shown to reduce fruit set, quality and mechanically damage fruit. Establishing shadenets in an avocado orchards helps to reduce wind damage which will act as an artificial windbreak as opposed to using natural windbreaks.

Soil water stress reduces plant biomass, crop yield and plant growth and leaf senescence. This complexity is due to some factors such as plant species and variety, duration and intensity of soil water depletion. Availability of water to agriculture is predicted to decrease in the future making efficient use of the available water very important. However water use depends on cost of production, productivity of crop and the price of the crop product. Even though intensive research in the areas of crop physiology, irrigation engineering, agronomy, and agricultural economics has developed several ways to improve the efficiency of irrigation water, a multidisciplinary approach is often regarded as the best future approach to achieve water-use efficiency.

5.3 Challenges

The challenges that were experienced during the experiment were data logger and sensor failure both under the shadenet and in the open treatment. Mooketsi valley receives little annual rainfall hence water for irrigation was limited and reduced tree flowering in 2015, in the open treatment compared to under the shadenet. Under the shadenet, bee population was less and did not pollinate flowers in 2014. Also the 3 m x 3 m spacing plots both under and in the open treatment required frequent farm maintenance i.e. pruning, spraying, etc. whilst under the shadenet there was an infestation of leaf roller pest in the 3 m x 3 m plots. The use of shadenet to grow avocados is expensive, cost of the current shadenet structure was over R110 000.00 and the financial viability of growing avocados under the shadenet is currently unknown. Thus it may be a challenge for both smallholder and commercial growers in uphill slopes to use shadenets in their avocado farms.

5.4 Future possibilities

Further research will also have to address the financial challenges of growing avocados under the shadenet. It is important to know whether it is financially viable to implement shadenet-grown avocados on a large scale. But this may differ among growers taking into account production regions, i.e. slopes and aspects of farms, cultivars and grower incentives. There is also a vast number of different colours and shading factors which can be tested for different cultivars, but the most important consideration will have to be durability of the shadenet structure.

Further research should focus on optimizing these challenges in order to improve yield under the shadenet. ‘Carmen®-Hass’ has earned its name as a black skinned cultivar with excellent postharvest quality. Like, ‘Hass’ the fruit size problem is not only a result of water stress but it is also gene-related. Hence studies on ‘Carmen-Hass’ gene mapping may be fundamental in understating the small fruit size of the cultivar. Overall, the use of shadenet in avocado production should not only be interpreted as an innovation of the industry, but it greatly suggests key steps in adapting to climate change and global warming. This ensures excellent internal and external fruit quality for local and export markets.

5.5 Final comments and summary conclusions

The mechanism by which flowering, fruit set and maturity were triggered early under the shadenet compared to in the open treatment is attributed to the improved microclimate and the rapid training of trees (pruning). If shadenetting is to be implemented on a large scale, changes in orchard management will be vital. This will mostly relate to pest and bee management. Striking a balance within the management tools is key in improving not only fruit quality and size but yield. Overall, the use of a 20% white shadenet on ‘Carmen®-Hass’ did improve microclimate, water use and fruit size and quality. Thus, this implies that sunburn, wind damage and small fruit size were improved with the use of a shadenet despite reporting variations in air and canopy temperature under the shadenet compared to in the open treatment.

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APPENDICES

The statistical analysis results for shoot growth are illustrated both in Appendix 1 and Figure 4.25. Shoot growth under the shadenet was significantly different to shoot in the open treatment. Thus shoot growth under the shadenet was greater compared to in the open treatment. There was no difference in shoot growth for summer under the shadenet compared the open treatment at 5% least significant difference. Shoot growth was not significant for autumn and winter under the shadenet, but it was significantly different to the open treatment for the same period.

Appendix 1: Shoot growth

```
Analysis of variance

Variate: Shoot_length_cm

Source of variation          d.f.        s.s.        m.s.      v.r.    F pr.

Tree stratum                   19     3960.49      208.45      5.36

Tree.*Units* stratum
Treatment                       1     4785.55     4785.55    123.10    <.001
Residual                      579    22508.26       38.87

Total                         599    31254.30

Tree 1 *units* 7                                     25.             s.e.   6.
Tree 1 *units* 13                                    25.             s.e.   6.
Tree 1 *units* 19                                    26.             s.e.   6.
Tree 1 *units* 25                                    26.             s.e.   6.
Tree 6 *units* 19                                    25.             s.e.   6.
Tree 6 *units* 25                                    25.             s.e.   6.
Tree 7 *units* 1                                     22.             s.e.   6.
Tree 7 *units* 7                                     24.             s.e.   6.
Tree 7 *units* 13                                    25.             s.e.   6.
Tree 7 *units* 19                                    25.             s.e.   6.
Tree 7 *units* 25                                    25.             s.e.   6.


Tables of means

Variate: Shoot_length_cm

Grand mean 17.

   Treatment      Inside    Outside
                     20.        14.


Standard errors of differences of means

Table               Treatment
rep.                      300
d.f.                      579
s.e.d.                    0.5
```

Least significant differences of means (5% level)

Table	Treatment
rep.	300
d.f.	579
l.s.d.	1.0

Stratum standard errors and coefficients of variation

Variate: Shoot_length_cm

Stratum	d.f.	s.e.	cv%
Tree	19	2.6	15.4
Tree.*Units*	579	6.2	36.5

The statistical analysis results for shoot growth are illustrated both in Appendix 2. Data for the fruit growth from the statistical analysis are not shown in the results and discussion Chapter. However, the fruit growth under the shadenet was significantly different to fruit in the open treatment. However there was no difference in fruit development within the canopy, i.e. east vs middle vs west.

Appendix 2: Fruit size analysis

Analysis of variance

```
Variate: Fruit_size_mm

Source of variation          d.f.  (m.v.)        s.s.        m.s.     v.r.   F pr.

Tree stratum                   19             5678.11      298.85     6.38

Tree.*Units* stratum
Treatment                       1            13545.10    13545.10   289.31   <.001
Residual                     1430   (169)    66950.27       46.82

Total                        1450   (169)    84735.35
```

Tables of means

```
Variate: Fruit_size_mm

Grand mean  50.

   Treatment     Inside   Outside
                    53.       47.
        rep.        780       840
```

Standard errors of means

```
Table                   Treatment
rep.                      unequal
d.f.                         1430
e.s.e.                        0.2      min.rep
                              0.2      max.rep
```

Standard errors of differences of means

```
Table                   Treatment
rep.                      unequal
d.f.                         1430
s.e.d.                        0.3

(Not adjusted for missing values)
```

Least significant differences of means (5% level)

```
Table                   Treatment
rep.                      unequal
```

```
d.f.                     1430
l.s.d.                    0.7

(Not adjusted for missing values)
```

Stratum standard errors and coefficients of variation

```
Variate: Fruit_size_mm

Stratum                          d.f.          s.e.        cv%
Tree                               19           1.9        3.9
Tree.*Units*                     1430           6.8       13.7
```