THE EFFECT OF SHADENETTING ON ‘3-29-5’AVOCADO PRODUCTION UNDER SUBTROPICAL CONDITIONS

by

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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 Campus, South Africa. The research was financially supported by the Hans Merensky Foundation and Westfalia fruit.

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

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Date: 29 March 2016

DECLARATION 1: PLAGIARISM

I, Evidence Mazhawu, 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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ABSTRACT

The South African avocado industry is export-oriented. Hence there is a need for the continuous production of high quality fruit that can meet international standards. In avocado production, adverse weather events such as heavy or low rainfall, frost, Berg winds, high wind speed, hail and higher than normal temperatures can result in yield and quality losses. The South African avocado industry is also vulnerable to the effects of adverse weather conditions with a negative effect on avocado trees and fruit yield and quality. However, due to increasing competition from other avocado producing countries, there is a need to increase production of quality fruit and thus increasing exportable fruit. Shadenetting can potentially provide a solution for many fruit production problems such as damage from sunburn, high wind speed, hail storms, intense rain, drought and other problems encountered during the pre-harvest period.

In order to evaluate the role played by shadenetting in avocado production in South Africa, the study took place at Everdon Estate in KwaZulu-Natal under cool subtropical conditions using 30% crystal (clear) shadenetting covering '3-29-5' (marketed as Gem®). This study took place from 2014-2015, thus covering two harvesting seasons. The main objective of using shadenet under these conditions was to be in a position to supply very late season fruit when there is lack of supply, which is likely to increase profits. However, a long season exposes fruit to a long period of risk of abiotic damage. In this case, the study area has a high risk of cold weather, wind and hail incidence, which could reduce avocado fruit yield and quality. Microclimatic measurements were taken under the shadenet and in the open field. These included air temperature, relative humidity, canopy temperature, leaf wetness, rainfall and wind speed. Water use was measured in terms of sap flow using the thermal dissipation (TDP) system.

From the studied orchard, the use of shadenet altered the microclimate of the orchard. Air temperature under the shadenet was between 0.5 and 0.9 ºC higher during the day and lower during the night compared to the open field measurements. Relative humidity pattern differed with season, with differences between the two treatments ranging up to 8%. Solar radiation under shadenet was reduced by 18% compared to the open field whilst wind speed was reduced to negligible values under shadenet. Canopy temperature was also significantly reduced under shadenet. The leaf wetness was reduced. The altered microclimate also influenced the evaporative demand of the atmosphere. The changes in the microclimate due to the use of shadenetting resulted in a 21% reduction in short grass reference evapotranspiration (ET_o). ET_o

was determined by the Penman-Monteith method using meteorological data from the open field and under the shadenet. There was reduced sap flow under shadenet implying reduced water use by trees under shadenet. On the other hand, rain penetration through the shadenet was reduced by 40% compared to the open orchard. The difference in measured rainfall and evaporation between the two environments may therefore necessitate different irrigation schemes.

The influence of shadenetting on vegetative and reproductive growth was determined. Flower opening and closing was similar for both treatments, following the same trend for both shadenet and open field. The flowering intensity was higher for fruit trees grown under shadenetting. Fruit growth rate was greater under shadenet. Changes in the microclimatic conditions under shadenet are likely to have had an effect on fruit size. Fruit size distribution (FSD) from 2015 showed an increased proportion of large fruit compared to FSD for 2014. Shoot length of trees under shadenet was less compared to the open field. There was reduced bee activity under shadenet, but the final yield was not negatively affected. However, the activity in both treatments seemed to be dependent on the microclimate at that given time.

Fruit quality of '3-29-5' was evaluated for trees under shadenet and in the open field. Fruit from both treatments were free from physiological disorders and diseases after direct ripening and storage for two weeks. Mean yield per tree (kg tree^{-1}) decreased for both treatments year-on-year. The average yields for shadenet was 16.50 and 14.73 t ha^{-1} in 2014 and 2015 respectively, while for open field it was 14.73 and 9.18 t ha^{-1}. There was a low incidence of sunburn under both treatments because '3-29-5' bears fruit inside the canopy. A positive effect of shadenetting was the reduction of wind damage and thus an increase in pack out.

Since South Africa is generally a water scarce country with high rainfall variability, the study was able to show the potential of shadenets in areas in which irrigation water is in short supply, and in times of high evaporative demand. Even though protection against hail is a positive factor, the shadenet was never put to test with regards to hail damage.

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“Our deepest fear is not that we are inadequate

Our deepest fear is that we are powerful beyond measure

It is our light, not our darkness that most frightens us. We ask ourselves, Who am I to be brilliant, gorgeous, talented and fabulous? Actually, who are you not to be? You are a child of God. Your playing small does not serve the world. There is nothing enlightened about shrinking so that other people will not feel insecure around you. We are all meant to shine, as children do. We were born to make manifest the Glory of God that is within us. It is not just in some of us; it is in everyone and we let our own light shine we unconsciously give others permission to do the same. As we are liberated from our own fear, our presence automatically liberates others.”

Marriane Williamson

‘I can do all things through Christ who strengthens me’

-Philippians 4:13

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CHAPTER 1: INTRODUCTION

1.1 Background

The South African avocado industry is export-oriented, with approximately 60% of the production being exported mainly to Europe. Hence, there is a need for the continuous production of high quality fruit that can meet international standards. Despite South Africa being one of the leading avocado exporters to Europe, adhering to these standards is still problematic. Nelson (2010) reported the 2009 avocado export season to Europe was affected by a high proportion of fruit of poor quality. Chilling injury, internal greying, lenticel damage and wind damage and scratches negatively impacted on the 2009 export season. Nelson (2012, 2014) further asserts the need to improve the quality of South African avocados. In November 2010, severe hailstorms throughout the main production areas in South Africa greatly reduced the fruit output and quality, lowering export volumes (Donkin, 2012). These hailstorms were also experienced in February 2016. In the face of competition from other avocado producing countries, such as Peru, there is a need to increase production of quality fruit and thus increasing class one fruit.

Many practices to ensure good fruit quality have been introduced over the years, especially for storage in transit. Fruit firmness in transit has been improved with the introduction of controlled atmosphere storage and later on with the introduction of 1-methylcyclopropene (1-MCP) which delays fruit ripening and the development of internal greying (Mare *et al.*, 2002; Kruger and Lemmer, 2011). However, external fruit quality aspects such as sunburn and wind damage must be addressed pre-harvest. The use of “Shadow” a wettable powder for sunburn control increased tonnage of export grade fruit by 2% (Rossouw, 2002). Wind damage has commonly been controlled by the use of windbreaks (Holmes and Farrell, 1993). *Casuarina cunninghamiana* (beefwood) windbreaks are commonly used, resulting in a 26% reduction in fruit scarring by wind; however, the disadvantage in using some trees, such as casuarina resulted in competition between windbreaks and avocado trees for water, nutrients and radiation and hence yields could be decreased.

High fruit quality is as a result of the interaction between pre-harvest and post-harvest factors. The environment in which a tree is grown plays an important role in the successful production of crops. Microclimate encompasses environmental variables such as air temperature, solar radiation, relative humidity and wind speed which have an effect on productivity due to their influence on photosynthesis, respiration, translocation of photoassimilates and evapotranspiration (Jones, 1993, 2013). In avocado production, adverse weather events such as heavy or low rainfall, frost, Berg winds, high winds, hail and higher than normal temperatures can result in yield and quality losses (Arpaia *et al.*, 2004). The South African avocado industry is also vulnerable to the effects of adverse weather with a negative effect on avocado trees and fruit yield and quality.

Traditionally, the use of shadenetting is common for greenhouse crops such as tomatoes, cucumbers and lettuce, proteting crop against environmental stresses, especially solar radiation (Bailey, 1981, cited in Tsokankunku, 2012). In fruit crops, research has been conducted on apple, (Smit, 2007; Shahak *et al.*, 2008; Solomakhin and Blanke, 2007; Bastías *et al.*, 2012), kiwi fruit, peaches (Shahak *et al.*, 2008), pears (Shahak *et al.*, 2008) and citrus (Nicolas *et al.*, 2008). In South Africa, documented information is on apples (Gindaba and Wand, 2005; Smit, 2007). The results, from both theoretical and experimental studies, indicate that the use of shadenet improves water use efficiency (WUE) and has an effect on microclimatic changes, namely relative humidity, air temperature and solar radiation (Shahak *et al.*, 2004). WUE is defined in many ways depending on the ones' scientific interest. WUE can be defined as the quantity of assimilated carbon and crop yield for every unit of transpiration (Sharma *et al*., 2015). Microclimatic changes associated with shadenet result in a number of benefits which include reduced solar radiation, reduced wind damage and hail protection for apple, bell pepper and peach production (Shahak *et al.*, 2004; Iglesias and Alegre, 2006; Stamps, 2009). Provided shadenets have been supplied by a good company, they do withstand tear, hence perfect for hail protection. Shadenetting can potentially provide a solution for many fruit production problems such as damage from sunburn, high wind speed, hail storms, intense rain and other problems encountered during the pre-harvest period.

At the commencement of this research project, there was no published information about the effect of shadenet on avocado productivity. However, SAAGA is very interested in shadenets and commissioned another project on coloured shadenets.

1.2 Motivation of the study

The KwaZulu-Natal midlands has a cool and wet climate. Thus avocado fruit mature later than most areas in Limpopo and fruit can be 'hung late' with a reduced risk of fruit drop. Supplying late season fruits to the South African market is likely to increase profits. However, a long season exposes fruit to a long period of risk of abiotic damage, particularly at Everdon estate in the KwaZulu-Natal Midlands. In this case, the study area was Everdon Estate located in the cool subtropical KwaZulu-Natal midlands where there is a high risk of cold weather, wind and hail incidence, which could reduce avocado fruit yield and quality. Therefore, producing avocados under shadenet in Everdon conditions could improve fruit quality, but without certainty of the effects on yield. 'Gem®' ('3-29-5') can be hung into the summer months, during which there is a greater chance of hail and high winds. However, with the use of shadenet, the risk will be greatly minimised. With shadenetting, there will be an advantage of providing the market with fruit during the period of short supply and high demand.

Another important potential benefit from this research is the improved water use efficiency of the fruit crops under shadenet. This will enable farmers to know the amount of water to be applied, avoiding water wastage and decreasing costs associated with irrigation particularly in times of reduced rainfall. However, possible negative aspects of the use of shadenetting also need to be investigated. These may include reduced bee activity and hence reduced pollination, increased disease incidence and increased risk of frost.

1.3 Hypotheses, aim and objectives

1.3.1 Hypotheses

The main hypothesis of this study was:

The changes in the microclimate associated with the use of shadenetting in the subtropical climate may result in an improved fruit quality of '3-29-5' avocado relative to fruit grown in the open.

In addition to the main hypothesis are the following:

1. microclimate is altered under protected cultivation;
2. there will be an increase in vegetative growth of trees under shadenetting;
3. flowering and bee activity may be negatively impacted through the use of shadenet;
4. water use may be altered under shadenet;
5. shadenetting may reduce wind and sunburn damage and therefore, may positively affect fruit quality characteristics.

1.3.2 Aim

The aim of this research was to quantify the changes in tree growth and yield parameters of '3-29-5' avocado grown under shadenet *versus* in a conventional orchard.

1.3.3 Objectives

The objective of the study were to investigate the microclimatic changes associated with the use of shadenetting and the impact on water use, yield, tree growth, flowering and bee activity of '3-29-5' avocado compared to open field production. The specific objectives were:

1. to evaluate the effects of shadenetting on orchard microclimate;
2. to determine the effects of shadenet on the water use of the avocado trees;
3. to determine the effect of shadenet on avocado yield and fruit quality;
4. to evaluate the effect(s) of shadenet on the phenology
5. to determine the effect of shadenet on bee activity in the orchard.

1.4 Dissertation structure

This dissertation is structured in a 'paper form' in which some of the chapters are viewed as individual papers. It is made up of related chapters reporting on how different aspects of avocado growth and production are affected by the use of shadenetting. A brief literature review is provided for each chapter, while this chapter provides a brief review covering some broader aspects which relate to the subject. Each of the experimental chapters consists of its own introduction, materials and method, results and discussion and conclusion. The dissertation is made up of seven chapters.

The present chapter, Chapter 1, introduces the study, giving brief information on the problems faced by the South African avocado export industry and the possible mitigation measures. It also covers the motivation for the study as well as the aims and objectives of the study. Chapter 2 is the literature review. Chapter 3 is the beginning of the experimental chapters and focuses on the microclimate study. Modification of the microclimate is investigated and discussed as well as a brief explanation on the spatial variation of air temperature and relative humidity within the shadenet structure. Chapter 4 is the investigation into sap flow and water use. Chapter 5 investigates flowering, bee activity, fruit and shoot growth. Chapter 6 is the final experimental chapter addressing the effect on yield, maturity and quality. Chapter 7 is the general discussion and recommendation for future research.

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CHAPTER 2: LITERATURE REVIEW

2.1 Avocado production and microclimatic limits to growth

The subtropical conditions in South Africa avocado production areas are characterised by mild winters and long warm summers (Wolstenholme and Whiley, 1999). Avocado (*Persea Americana* Mill) has three horticultural races are namely, West Indian, Mexican and Guatemalan. Despite being originally from the humid subtropical and tropical regions of North and South America were climate is characterised by wet summers and dry winters, avocados can be grown under varied conditions (Lahav and Whiley, 2002). The 'horticultural races' thrive under different climatic conditions (Wolstenholme and Whiley, 1999). However, the major limiting factor to avocado tree growth and fruit production is its sensitivity to frost with the Mexican race being cold tolerant and West Indian being the least cold tolerant (Bower and Cutting, 1988). In relation to solar radiation, avocados of the Guatemalan and Mexican race are characterised by low sun stress (Wolstenholme and Whiley, 1999).

However, morden cultivars are a mixture of the races, with varying percentage of genome from each race which confer certain attributes to the cultivar. Higher than normal air temperatures as well as low humidity negatively affect flowering and fruit set and hence lower productivity. Bower and Cutting (1988) reported the climatic recommendations for South Africa as being less than 31 °C (absolute maximum) in summer, 4 °C less in winter, and a relative humidity of more than 32 % for the duration of flowering and fruit set.

2.2 Effects of microclimate on avocado growth

Climate is defined by the weather trend over a long period for a large geographic area and is influenced by site elevation, latitude, closeness to water bodies, and topography (Hogan, 2012). Hogan (2012) further defined microclimate as the weather condition of a small area different from that of the surrounding areas. It incorporates solar radiation, relative humidity, air temperature, wind speed and precipitation (Jones, 2013). Previous studies have shown that microclimatic interactions have a major effect on the orchard output in terms of yield and quality of fruit produced (Bastías and Correlli-Grappadelli, 2012; Retamal-Salgado *et al.,* 2015). Solar radiation, relative humidity, air temperature, precipitation and wind speed are discussed.

2.2.1 Solar radiation

Solar radiation levels in South Africa are sufficient to sustain plant growth (De Vieser and Dijkxhoorn, 2012). Fitch and Kemker (2014) defined solar radiation as "radiant energy from the sun" made up of different wavelengths, namely ultra violet (UV), visible and near infrared (IR). Solar irradiance is defined as "amount of radiant flux on an area" and measured in watts per meter squared (W m^{-2}) (Fitch and Kemker, 2014). Plant physiologists are concerned with radiation spectra between 280-800 nm, namely UV-B (280-320 nm), UV-A (300-400 nm), photosynthetically active radiation (PAR, 400-700 nm) and far red (FR, 700-800 nm). PAR is further divided into blue (BL, 400-500 nm), green (G, 500-600 nm) and red (R, 640-700 nm) radiation which have different physiological effects.

Wavelengths between 400 and 700 nm (PAR), are the source of energy for photosynthesis. In some instances, PAR is expressed as photon (quantum) flux which refers to the number of photons found in the 400 – 700 nm range per unit time interval per unit area and is denoted as photosynthetic photon flux density (PPFD in µmol s^{-1} m^{-2}). Radiation distribution within a plant canopy changes with the structure of leaves, fruits and branches. Thus, PAR is divided into direct and diffuse PAR. From studies carried out in green house structures, diffuse radiation has more influence on photosynthesis than direct PAR (Li *et al.,* 2014). Diffuse radiation results from scattering of radiation in many directions at the same time whilst direct radiation reaches the earth in a straight line without scattering. Efficient use of diffuse radiation by plants is derived from more uniform distribution within the canopy since it infiltrates deeper into the canopy. Hence lower leaves are exposed to higher irradiances (Johnson *et al.*, 2010). Increased diffuse radiation is to be expected with the use of shadenetting (Shahak *et al.*, 2008).

Besides photosynthesis, two other photoradiative processes namely, photomorphogenesis and photoperiodism affect plant growth. Weller and Kendrick (2015) defined photomorphogenesis as a series of responses to solar radiation that collectively improves the likelihood of individual plant survival. Plant growth responses are curbed by photomorphogenic responses controlled by phytochromes (Weller and Kendrick, 2015). Photoperiodism is the reaction of plants to duration of daylength (Bjorn, 1994). However, photoperiodism is not important in all flowering plants and fruit trees are generally day neutral.

2.2.1.1 Avocado response to solar irradiance

Schaffer and Whiley (2002) described the avocado tree as "having a natural vegetative bias to greater distribution of photo-assimilates to shoot growth than reproductive organs". This results in more short-lived leaves being produced, at the same time increasing shading within the tree canopy. This reduces the proportion of well-lit terminal shoots which develop flower buds (Schaffer and Whiley, 2003). However, failure to flower can be mainly a result of poor radiation quality. Vegetative growth has been noted to increase linearly with accumulated solar irradiance up to a limit beyond which there are no further increases (De Costa *et al.*, 2007). High solar irradiance results in excessive heat load on leaves and fruit, later on resulting in sunburn (Gindaba and Wand, 2007). In the tropics, the sun is more overhead and thus there is more shade, but in subtropical conditions with lower solar elevations greater incidence of sunburn may be expected. Full exposure of 'Hass' avocado trees to sun resulted in increased dry matter and greater concentrations of potassium, calcium, magnesium and oil in fruits (Woolf *et al.*, 1999).

2.2.1.2 Photosynthetic response curve

Few experiments have been undertaken to create an avocado photosynthetic response curve. This is due to the problems involved in finding a direct relationship between solar radiation interception and yield per tree (Bower, 1978; Schoefield, 1980). The photosynthetic response of plants to irradiance can be depicted in a photosynthesis response curve, which illustrates how different solar irradiances result in different responses as measured by CO_2 consumption. Two main photosynthetic irradiance (PI) stages are important in a photosynthetic response curve, namely the PI saturation point and PI compensation point.

The net photosynthetic response of 'Edranol' to different solar irradiances, where the rate of photosynthesis increased linearly to solar irradiance was illustrated by Bower *et al.* (1977). Only 65-70 % of incoming solar irradiance can be intercepted by full tree canopies in an orchard. In avocados, leaves of container-grown trees have been reported being photosynthetically saturated at levels as low as 20 % incoming solar irradiance on a summer's day in South Africa (Bower, 1978). Plant response during different seasons differs as shown for 'Hass' avocado (Figure 2.1). On a clear summer's day, the measured solar irradiance recorded at midday in KZN is roughly 1100 W m^{-2} and the maximum rate of photosynthesis was reached at 200 W m^{-2}. Rosenberg *et al.* (1983) mentioned that C3 plants can be saturated at irradiance levels as little as a quarter of the full sunlight.

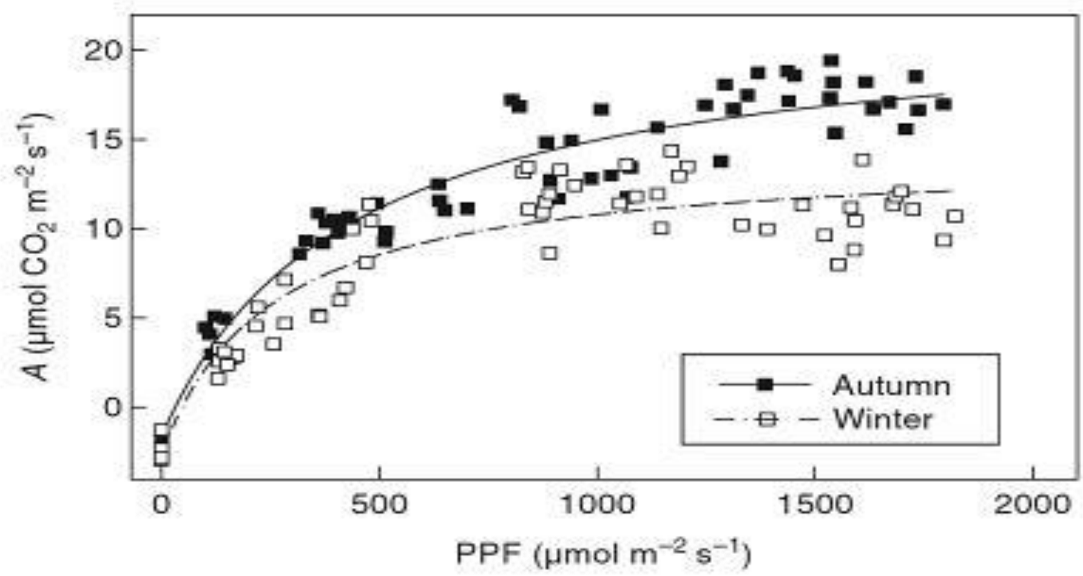

Figure 2.1: Photosynthetic response curve of field grown 'Hass' avocado tree at varying PPFD (taken from Schaffer *et al.*, 2013).

Photosynthetic irradiance compensation point

Schaffer *et al.* (2013) defined PI compensation point (CP) as the "PPFD level at which net photosynthesis is 0". At PAR levels below the CP, the rate of respiration is greater than the rate of photosynthesis and there is net energy consumption. For container-grown 'Fuerte' and 'Hass', the PI compensation point was 63 and 12 µmol s^{-1} m^{-2} respectively (Mickelbart, 2003). In another study in an orchard in Australia, by Whiley (1994), the PI compensation point for container-grown 'Fuerte' avocado trees was deduced to be 30 µmol s^{-1} m^{-2}, whilst for field grown trees it was 10 µmol s^{-1} m^{-2}. The values indicate differences between field-grown and container-grown trees. On the other hand, shade tolerant trees have a low compensation point with photosynthesis sustained at low PPFD levels.

Photosynthetic irradiance saturation point

The PI saturation point is defined as the PI at which further increase in PI would not result in an increase in net CO_2 assimilation; hence, as the PI of avocado is relatively low, PI is not a limiting factor for photosynthesis (Schaffer *et al.,* 2013). Different PI saturation points have been reported for avocado cultivars. PI saturation point for container-grown ‘Fuerte’, ‘Edranol’ and ‘Hass’ were 500 µmol s^{-1} m^{-2} (Schoefield *et al.,* 1980), 660 µmol s^{-1} m^{-2} (Bower, 1978) and 1100 µmol s^{-1} m^{-2} (Whiley, 1994), respectively. Above the PI saturation point, there is a higher production of adenosine tri-phosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) than needed for CO_2 fixation (Foyer *et al.,* 2012). Leaves that are shaded remain below the PI saturation point for most of the day and have a lower photosynthetic potential compared to unshaded leaves (Mohotti and Lawlor, 2002). ‘3-29-5’ is a relatively new cultivar and photosynthetic response curves have not been determined at the time of writing.

2.2.2 Temperature

Temperature is the most important climatic factor determining which species and varieties of plants can be grown economically in a particular area. The ecological races of avocado respond differently to temperature (Whiley and Schaffer, 1994). Internal temperature alters physiological growth of plants as well as the rate of many biochemical reactions (Craita and Gerats, 2013). Photosynthesis is affected by temperature. Avocado, being a C3 plant, is affected by higher than normal temperatures, which lower net photosynthesis and radiation use efficiency due to an increase in the ratio of photorespiration to photosynthesis. The ideal temperature range for photosynthesis in ‘Edranol’ is 19 ºC to 24 ºC (Bower *et al.,* 1977). Net photosynthesis declined by 20 % within 5 ºC of this temperature range. Maximum net photosynthesis of container-grown ‘Fuerte’ trees was found to occur between 28 and 31 ºC (Scholefield *et al.,* 1980).

High temperatures that are associated with water loss can result in a disproportional supply of some nutrients within fruit, potentially causing physiological disorders. Fruit growth rate, fruit development and fruit quality are affected by temperature (Woolf and Ferguson, 2000; Sheard *et al.,* 2006). The variance between day and night temperatures is able to disturb normal plant growth. Previous studies have shown the importance of day and night temperatures on root growth of avocado seedlings. The optimal temperature range at a depth of 300 mm was reported by Lahav and Trochoulias (1982) to be between 21.5 and 25.2 ºC and 14.0 and 18 ºC for day and night temperatures, respectively. Lahav and Trochoulias (1982) also reported that higher temperatures were likely to reduce leaf area, resulting in intensified competition between vegetative growth and fruit. Elevated temperatures were found to promote shoot growth thus affecting root:shoot ratio (Lahav and Trochoulias, 1982). At the above given range, grafted ‘Fuerte’ and ‘Hass’ performed well producing large and thick leaves, even though they are adapted to extreme temperatures (Lahav and Trochoulias, 1982). ‘Fuerte’ survives cold temperature, but with very low productivity. Fruit quality is affected by high ambient temperatures during growth and development. Fruit temperature is an important aspect in fruit growth and excessive temperature can result in sunburn and also increases neckiness of fruit (Woolf and Ferguson, 2000).

Low temperatures affect avocados in two ways, namely: frost and chilling. As a subtropical crop, avocados are sensitive to frost. Defoliated branches and brown leaves usually are signs of frost damage, whilst severe frost can cause the death of the whole plant (Witney and Arpaia, 1991). Chilling is common in temperate regions and refers to any temperature between 0 and 12 ºC which can affect plant productivity. Even though subtropical crops are sensitive to temperature, flowering is also affected by water stress (Sheard *et al.*, 2006). Salazar-Garcia *et al.* (1998) concluded that flowering in avocados is associated with temperatures less than or equal to 15 °C. Low temperatures are associated with a prolonged bloom whilst it is the reverse at high temperatures.

Flowering in avocado is dependant on whether the variety in question is Type A or B (Arpaia *et al.*, 2001). On the first day, flower type A open as a female in the morning and closes in the afternoon, and open as a male in the afternoon the following day. ‘3-29-5’has flower type A. Daily cycle of flower opening and viability of pollen is dependent on temperature (Hatfield and Prueger, 2015). Flowering is affected by night air temperatures of more than 12 ºC, and hence reduce fertilization by decreasing the number of flowers in the female stage. Pollinator activity is also hindered by low temperatures. However, self-pollination is promoted under these circumstances as a result of partial overlapping of the flowering phase of each flower associated with cool temperatures.

2.2.3 Relative humidity and water vapour pressure deficit

Relative humidity (RH) is the percentage of water vapour in the air at a particular temperature compared to the maximum value of water vapour it can hold at that temperature. RH affects plant growth and development. It affects photosynthesis in two possible ways, namely non-stomatal responses and variations in stomatal conductance (Aliniaeifard and van Meeteren, 2013). Plant responses to water vapour content are best explained in terms of water vapour pressure deficit (VPD). VPD is defined as the difference between the air's saturated water vapour pressure and the actual water vapour pressure. Evapotranspiration (ET) is directly affected by VPD.

Plant growth is affected by high VPD (low RH) coupled with high air temperature. This results in high stomatal conductance and an increase in transpiration rate. Low VPD results in low transpiration rates since guard cells will close the stomata, limiting water loss and therefore reduced nutrient translocation will result. Fruits exposed to higher VPD during growth accumulate more calcium (Montanaro *et al.*, 2006). Low VPD, in turn, leads to low plant transpiration and associated physiological disorders (Aliniaeifard and van Meeteren, 2013). In avocados, calcium-linked disorders are related to internal distribution problems (Cutting and Bower, 1989). Nonetheless, reduction in water loss can lead to maximum use of nutrients. At the same time, low VPD retains cell turgidity and is thereby beneficial in enzyme activity resulting in greater yields (Reddy *et al.*, 1999).

Relative humidity has been shown to have an effect on the flow of water throughout the plant. Higher than average humidity resulted in increased vegetative growth. Mortensen (1986) showed that, in some species, an increase in RH resulted in increasing dry mass, and the number of leaves, flowers and flower buds. During and after fruit set, adequate humidity is of importance since a sharp decrease in humidity immediately after fruit set can lead to fruit drop. In the course of flowering, high humidity conditions increase successful fertilization of self-pollinated stage 2 flowers (Bower and Cutting, 1988). Stage 2 flowers are functionally male.

2.2.4 Wind speed

The reduction in volume of still air around each canopy layer is dependent on wind speed, and as a result there is an increased VPD (Beeson, 2010). Increased VPD results in greater transpiration rates. At low wind speeds, photosynthesis progresses at a normal rate, whilst strong winds result in greater transpiration rates. If transpiration exceeds water absorption, the stomata will partially or completely close, resulting in a decline in the rates of transpiration and photosynthesis.

Wind aids in the process of pollination as well as gas exchange. Adverse effects of wind on avocado production are given by Holmes and Farrell (1993):

a) avocado branches break easily and heavy wind results in mechanical damage;
b) poor fruit set due to flowers that are blown off as well as wind dessicating flowers;
c) poor pollinator activity and pollination;
d) wind-induced stress can hamper fruit growth and development;
e) poor pest/disease control in the orchard;
f) poor external fruit quality due to wind scarring.

2.2.5 Precipitation

In horticulture, water is the main factor limiting production. This directly affects the quality and quantity of yield. Most avocado cultivars are sensitive to water stress. An annual rainfall of more than 1000 mm is required for avocado production (Sheard *et al.,* 2006). Since, most areas receive less than this, irrigation is required (du Plessis, 1991). In South Africa, 60% of the available water is used in agriculture, with 90% being used for fruit production under irrigation (Taylor and Gush, 2009; Le Roux *et al.,* 2015). Reduced yield of avocado trees has been attributed to reduced water availability (Lahav and Whiley, 2002). Water supply to avocado trees is vital during flowering and fruit growth (du Plessis, 1991; Lahav and Whiley, 2002). Excessive rainfall or irrigation is associated with *Phytophthora cinnamomi* root rot and hypoxia/waterlogging (Schaffer, 2006).

2.3 Manipulation of the microclimate by shadenetting

The use of shadenetting has gained widespread use in protecting horticultural crops from excessive solar irradiance (Iglesias and Alegre, 2006). Additionally, shadenets minimise environmental stress like wind and hail as well as biotic stress such as pests (Teitel *et al.,* 2007). Hailstorms, excessive solar radiation and wind speeds can greatly affect yields and fruit quality.

Shadenets are manufactured in different types and colours, and the choice of shadenets depends on the requirements of the farmer in question (Cohen *et al.,* 2011). Factors which determine the choice of shadenet include transmittance, colour and shading percentage. Regardless of the different properties (optical and physical) of various shadenets for a specific use, they all reduce the amount of solar radiation especially through diffusion and scattering. Black shadenets with a shading factor of 40-80 % are normally used for ornamental crops and nurseries (Shahak *et al.,* 2004). Yellow and blue shadenets comprise pigments identified to attract whiteflies and thrips (Shahak *et al.,* 2004). Use of coloured shadenets with different wavelength transmission have been reported to result in different plant and microclimatic responses (Shahak *et al.,* 2004; Rajapakse and Shahak, 2007).

The common shadenets used are photoselective shadenets, which are able to increase the comparative fraction of scattered radiation, whilst absorbing a number of spectral bands (Shahak *et al.,* 2004). Non-photoselective nets do not contain additives. Thus they are not able to alter the spectral quality of radiation. Photoselective nets absorb the different forms of wavelength, UV, green (G), yellow, red (R), far red (FR) and infra-red (IR) differentially. An increase in the proportion of scattered to diffuse radiation influences photomorphogenic or physiological responses of plants. Scattering enhances the infiltration of radiation into the inner canopy (Rajapakse and Shahak, 2007). Under shading, diffuse irradiance increases thus increasing radiation use efficiency. Radiation use efficiency (RUE) is the quantity of accrued biomass in relation to the solar radiation intercepted by a plant or crop (Hossain *et al.,* 2014).

2.3.1 Microclimate

The installation of shadenetting modifies the microclimate of the covered area. The use of shadenets affects air, plant and soil temperature, RH, solar irradiance and wind speed (Stamps, 2009; Bosco *et al.,* 2014). Changes in these microclimatic factors affect plant growth and development. Specific changes on microclimate and their effects on avocado production need to be determined..

2.4 Summary

Microclimate greatly influences crop productivity, and also a number of plant processes. In avocado production, the microclimate can be a limiting factor which can negatively impact avocado fruit production. Increasing interest in the use of shadenetting to manage the microclimate may have a positive impact on avocado fruit production. A reduction in solar radiation can enhance photosynthesis and plant growth thus increasing production efficiency. Most of the research carried out on the use of shadenet is based on greenhouse crops such as tomatoes, flowers and lettuce. Ample research has been done on fruit crops such as apples. However, the influence of shadenetting on and associated responses by avocados is still unclear, and hence they need to be researched.

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CHAPTER 3: MICROCLIMATIC CHANGES ASSOCIATED WITH THE USE OF SHADENETTING IN A SUBTROPICAL CLIMATE

3.1 Abstract

The use of protected cultivation for tree fruit crops is becoming increasingly popular, especially the use of shadenetting. Protected cultivation is associated with many advantages, especially in the face of adverse weather conditions. Possible advantages of protection include a reduction in air temperature, solar irradiance, and wind speed. This study, in a subtropical climate, was undertaken from July 2014 to November 2015 at Everdon Estate, Karkloof, South Africa to investigate the effects of 30% crystal shadenet on the microclimate of 1.6 ha of '3-29-5'(Gem®) avocados. Part of the orchard was covered with shadenet (1.6 ha) whilst the remainder was not. Two automatic weather station (AWS) systems were programmed to simultaneously collect data from both treatments. Results showed that the microclimate was altered under the 30% crystal shadenetting used with the greatest change being in the wind speed and the solar irradiance which was reduced by nearly 19%. Calm conditions prevailed under the shadenetting most of the time compared to windier conditions in the open. Air temperature was between 0.5 ºC and 0.9 ºC higher under the shadenet during the day, whilst canopy temperature was lower than the corresponding measurements in the open orchard. Canopy temperature in the open field was 3 ºC and increased to 13 ºC greater in winter and spring respectively. Relative humidity was slightly reduced under shadenet. Precipitation under shadenet was nearly 40% less than in the open orchard. The shadenetting created a very different microclimate compared to the open environment, which favoured the production of high quality avocado fruit.

Keywords: '3-29-5', canopy temperature, protected cultivation

3.2 Introduction

With the continued cost-price squeeze farmers are facing globally, leading farmers are investigating means to remain profitable. Protected cultivation is an option available to farmers to improve fruit quality and ensure a viable profit margin. Avocado farmers are no exception. In the face of adverse weather conditions, microclimate is the most affected aspect which has a direct effect on the yield and quality of fruits (Fraga *et al.*, 2012). Wind damage, frost damage, hailstorms, effective rainfall and sunburn are among the main microclimatic problems affecting avocado fruit quality, particularly for subtropical climates. The protection of orchards with shadenetting has gained widespread use in protecting horticultural crops especially from excessive solar irradiance (Gindaba and Wand, 2005). Well-documented information is available for apples whereby farmers tried to protect the orchard against hailstorms and sunburn (Middleton and McWaters, 2002; Gindaba and Wand, 2005; Smit, 2007; Bosco *et al.*, 2014).

Microclimatic changes associated with use of shadenetting include: temperature (air, leaf, soil, and canopy), RH, wind speed and solar radiation (Pérez *et al.*, 2006; Stamps, 2009). Precipitation was reduced using exclusion cages (Lawson, 1994). Shadenets were shown to alter air, plant and soil temperatures and RH of the orchard environment (Middleton and McWaters, 1997; Shahak *et al.*, 2004; Solomakhin and Blanke, 2007). Daytime air temperatures under the shadenets have been reported to be greater than in the open orchard. However, night air temperatures were reported to be lower (Stamps, 1994; Pérez *et al.*, 2006). Middleton and McWaters (1997) reported a 1-3 °C difference in daytime air temperatures and an insignificant impact on the night air temperatures. In contrast, Abdrabbo *et al.* (2013) noted that the use of different coloured nets resulted in different air temperature differences. Increased air temperatures were noted in the open orchard, then under white netting and the lowest being under black. The difference in air temperature was explained in terms of solar radiation interception compared to air temperature gain by the different coloured shadenets. Reduction in air temperature and RH have also been attributed to reduced wind speed levels inside shadenets (Stamps, 2009). Elad *et al.* (2007) reported RH to be greater under shadenet than outside. Use of hail netting in apple orchards in Australia resulted in a 10-15% increase in humidity (Middleton and McWaters, 2002).

The main aim of this part of the study was to determine the effect of shadenetting on the microclimate of the '3-29-5' avocado trees for subtropical conditions.

3.3 Materials and methods

3.3.1 Description of the study area and location

The experiment was conducted at Everdon Estate located in Howick, KwaZulu-Natal province, South Africa (29° 26'37''S, 30°16'22''E, 1080 m altitude). The estate is in the bioclimatic region 3 which experiences cool mesic conditions, a characteristic of a mist belt climate. The area receives mostly summer rainfall with an average of 1052 mm per year and experiences an average maximum and minimum air temperature of 26.1 and 15.0 ºC in January and 19.4 and 6.7 °C in July. The orchard is planted in a North-South orientation with a between spacing of

7 m and a within row spacing of 4 m. row-tree. Irrigation was carried out using micro-jet sprinklers and irrigation scheduling was based on matric potential measurements of soil moisture from a pair of tensiometers placed under the shadenet and in the open orchard. The tensiometer were at a depth of 300 mm and 600 mm for both the open orchard and shadenet areas. Measurements were obtained from the farm management for 2014 and 2015 seasons.

Figure 3.1: 30% crystal shadenet covering '3-29-5' avocados at Everdon Estate.

The microclimatic study was conducted in an orchard of '3-29-5' (Gem®) avocado trees. Microclimatic measurements were taken within one commercial block (same planting date, variety, soil, rootstock, and orchard management) where shadenetting was erected over a section of the orchard (1.6 ha) and the remainder remained uncovered (control) (0.2 ha). Trees were planted in 2010and had been grafted on Dusa® rootstock. The crystal shadenet with a 30% shading factor was supplied by PlusNet (Randfontein, South Africa) and was installed in May 2014. Two automatic weather station (AWS) systems were simultaneously used. The sensors used at each weather station included a thermophile solar pyranometer, infrared thermometer (IRT), leaf wetness sensor (LWS), rain gauge, and standalone air temperature and relative humidity (RH) data loggers. Instrumentation details are included in Table 3.1 and Figure 3.2. The AWS systems, equipped with a Campbell 21X data logger, were installed at the centre of each treatment. Sensors were mounted 2 m above the ground and the variables were measured at 30 s intervals, and stored in the 21X data logger at 20 minute intervals over the whole monitoring period (Figure 3.3). The AWS was operational at 14h00 on 4 July 2014 soon after erection of the shadenetting. The LWS at each location was placed 0.5 m above ground at 45° with respect to the horizontal, to represent leaves and so as to allow water drainage (Figure 3.4). The infrared thermometer faced south at an angle of 45° with respect to horizontal ground.

Transmission coefficient

Transmission coefficient of the net was determined throughout the duration of measurement by using the formula:

$$\text{Transmission coefficient (\%)} = \frac{\textbf{Solar irradiance (W m}^{-2}\textbf{) transmitted through the shadenet}}{\textbf{solar irradiance (W m}^{-2}\textbf{) in the open field}} \times 100 \quad (3.1)$$

Thermal time

Thermal time for the duration of the study for both the open and shade environments was calculated using;

$$\tau = \sum_{n=0}^{i} (T_{average} - T_0)\,\Delta t \quad (3.2)$$

where $T_{average}$ is the daily average air temperature (°C) from the Hobo air temperature data;

T_0 is the base temperature for the plant (°C) of 10 °C (Lahav and Trochoulias, 1982);

n and i are the number of days;

and Δt is equal to 1 day.

Days with negative thermal time were ignored.

Table 3.1: Details of the various sensors used in the study

Parameter	Sensor	Model
Canopy temperature	Infrared thermometer	Apogee IRT model IRR-P (half angle of 22^{o}): Apogee Instruments Inc., Logan, UT, USA
Wind speed	Cup anemometer	Model 03001 RM Young Company, Traverse City, MI, USA
Solar irradiance	Thermophile pyranometer	CMP3, Kipp and Zonen B.V., Delft, The Netherlands
Precipitation	Spoon rain gauge	Pronamic RAIN-O-MATIC (0.254 mm resolution), Pronamic ApS, Ringkøbing, Denmark
Leaf wetness	Leaf wetness sensor	LWS Decagon Devices Inc., Pullman, WA, USA
Air temperature and relative humidity (RH)	Stand alone hobos with six plate gill shield	U23-001, Onset Computer Corporation, Massachusetts, USA),

Figure 3.2: AWS set-up in an open orchard. The visible sensors are 1) thermophile solar pyranometer, 2) spoon rain gauge 3) wind speed sensor 4) standalone Hobo® (air temperature and relative humidity) and 5) infrared thermometer

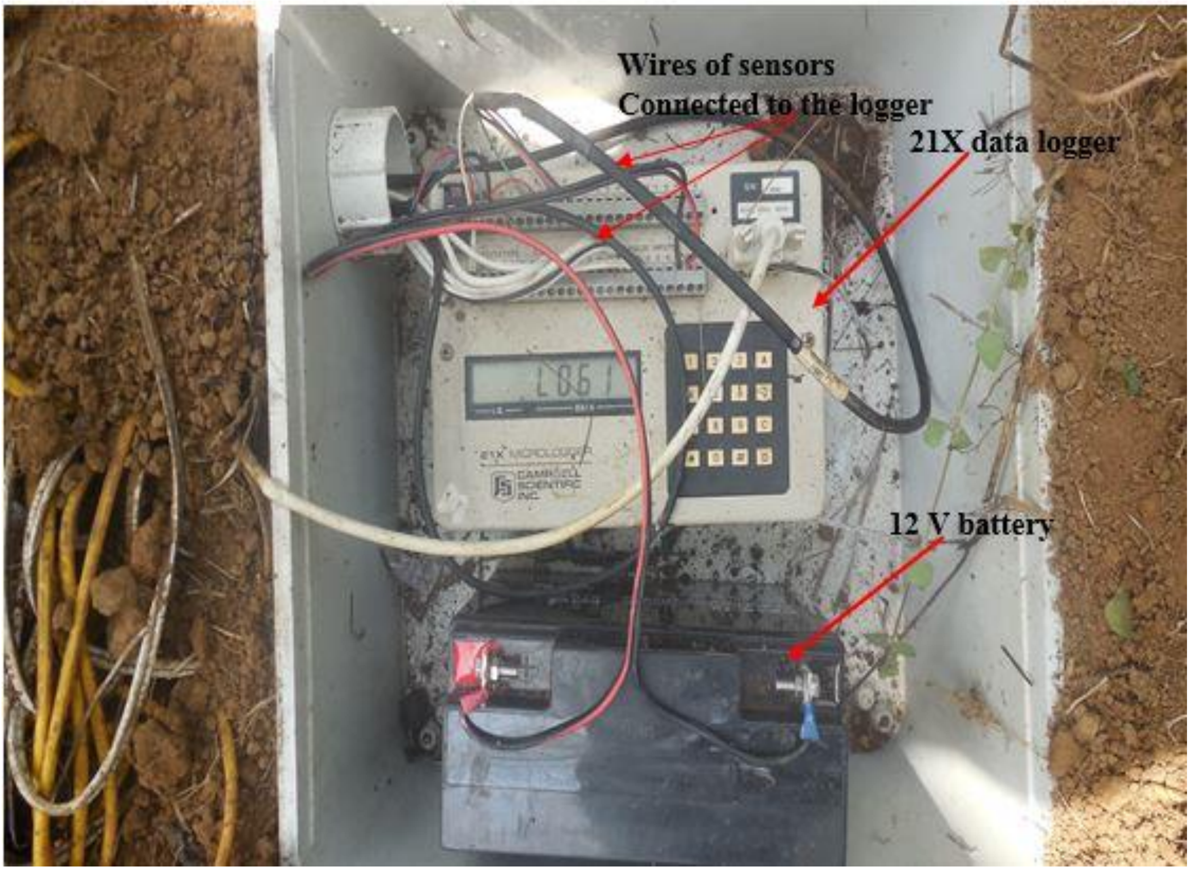

Figure 3.3: campbell 21X data logger (top), powered by a 12V, 18 A h battery (bottom), used at the research site

Figure 3. 4: Leaf wetness sensor in the open orchard

3.3.2 The spatial air temperature and relative humidity variation within the shadenet

The spatial variation of air temperature and relative humidity under shadenet were determined at different locations in the shadenet. The air temperature and RH were measured at 18 points in a 6 × 3 grid within the shadenet (Figure 3.5). Continuous air temperature and RH measurements, at 5 min intervals were obtained using Hobo datalogger (Table 3.1).

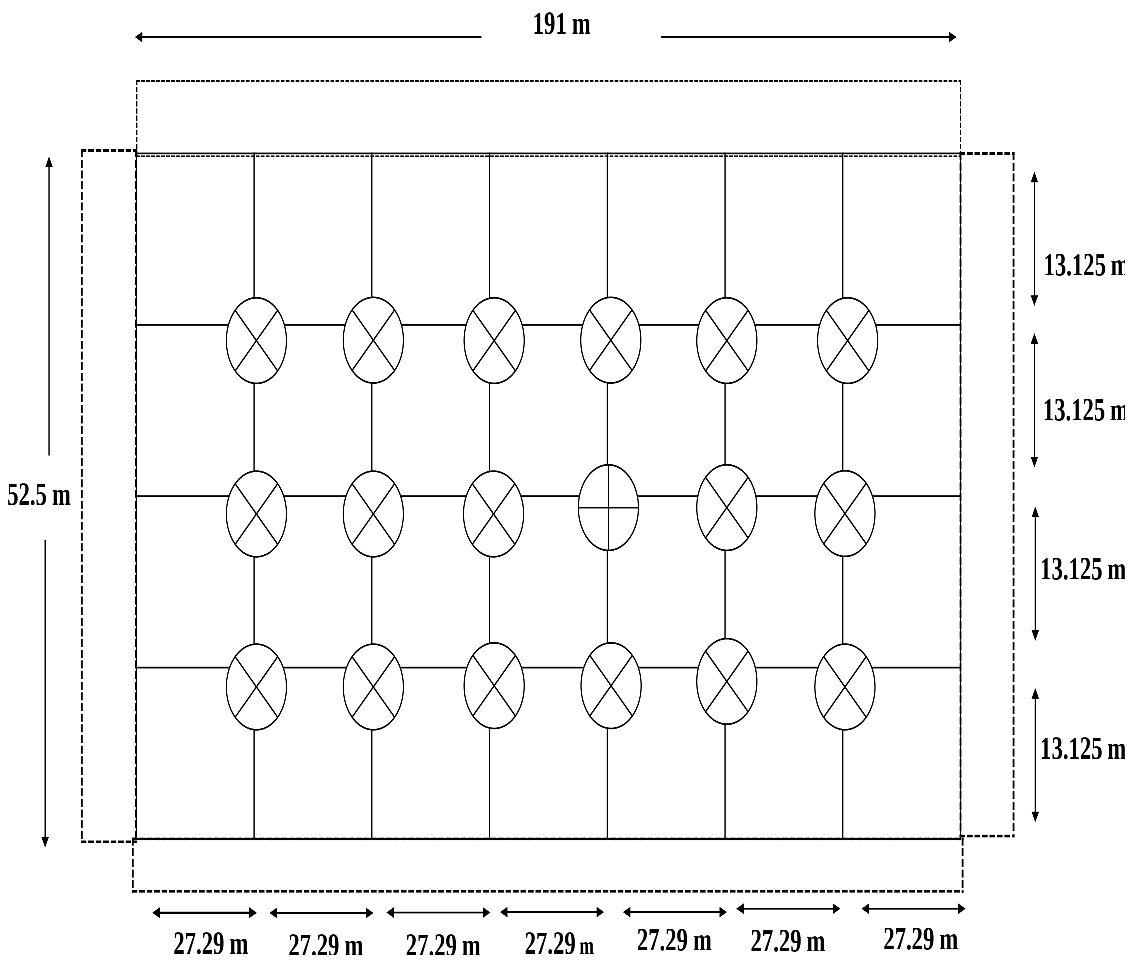

Figure 3.5: Schematic presentation of the HOBO layout under the shadenet

⨂ Air temperature and RH sensor

⨁ Air temp/RH sensor at the AWS

3.4 Results and discussion

3.4.1 Spatial variation of air temperature and RH inside the shadenetting

The spatial differences in air temperature (Figure 3.6) and RH (data not shown) between sensors were negligible. Variation of the microclimate within an orchard can have a great impact on fruit tree performance. Thus, if there is a major variation, growth, development, yield as well as quality can be affected. Since the spatial differences in air temperature and RH were negligible, a single central AWS system under the shadenetting was used to provide weather information during the study. The negligible spatial differences in air temperature can directly influence water vapour pressure. Because of negligible air temperature and RH, water vapour pressure was likely to be uniform throughout the shadenetted area. Hence, the avocado trees at different positions under shadenet are likely to have similar transpirational behaviour**.**

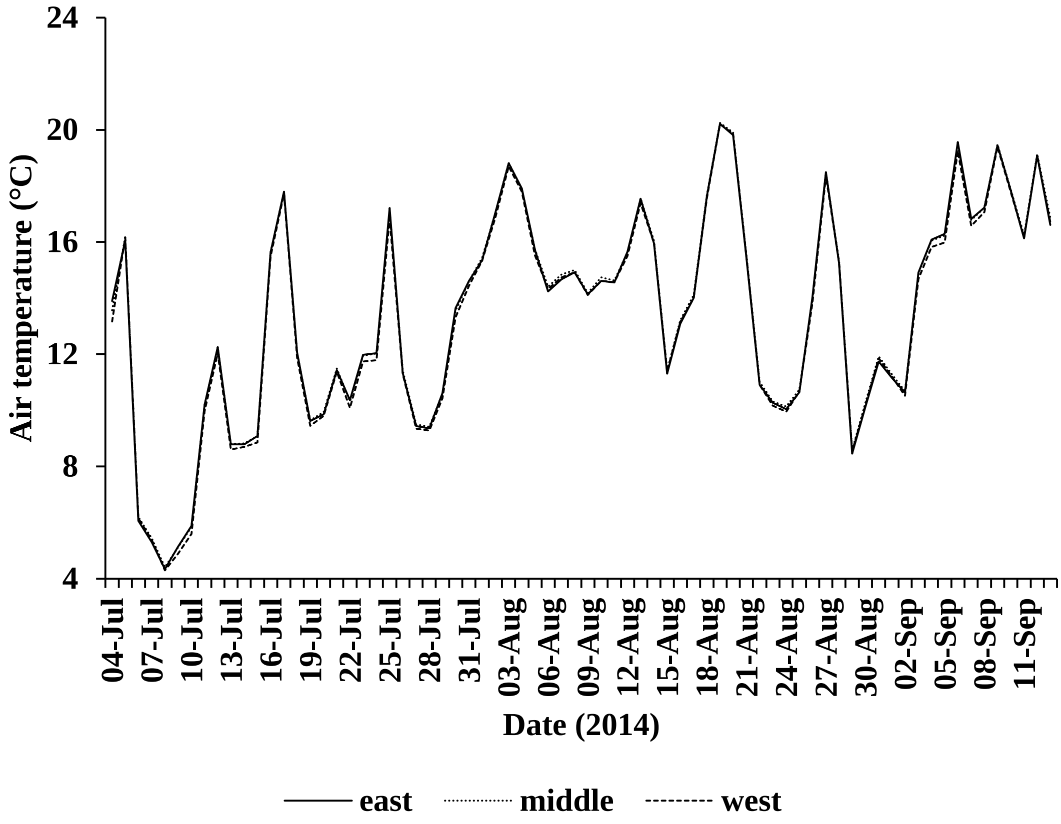

Figure 3.6: Spatial variation of air temperature (°C) across the shadenet

3.4.2 Air temperature and thermal time

Air temperature under the shadenet was between 0.5 and 0.9 ºC higher during the day and lower during the night compared to the open field measurements. This is consistent with what was reported by Stamps (2009), who attributed low air temperatures during winter to possible radiation frost. Radiation frosts are a result of clear sky and dry air as well as absence of wind to mix the air especially at night. Air temperature for all seasons followed the same trend, even though the difference in winter was slightly reduced compared with the other three seasons mainly due to cloud cover (Figure 3.7). The selected days for all seasons clearly outlined the same trend, with the maximum air temperature being recorded around 14h00 for both the shadenet and open orchard. Daily air temperature differences between treatments were within 0.5 °C (Figure 3.8). The shadenetted orchard was cooler in summer and warmer during the other seasons. The positive air temperature differences during summer, spring and autumn can be associated with the fact that the shadenet in use may have reflected less infrared radiation, absorbing more heat. Negligible wind speed under shadenetting could also have played a role in the slightly increased air temperature due to less mixing of air thus reducing heat loss (Tanny *et al.*, 2013). Maximum air temperatures (Table 3.2) under the shadenet were slightly greater than in the open orchard.

In relation to thermal time, measurements were carried out throughout the study period. Under Under shadenet a higher accumulation of degree days of 2777.1 °C than in the open field (2698.6 °C) was found. However, difference in thermal units is likely to be too small (3%) to have significantly altered any physiological events of '3-29-5' avocados. Given the total accumulation of degree days, it is unlikely for there to be a large difference in degree days required for completion of different phenological stages. Cultivar response to air temperature, flowering and ripening are mainly controlled by thermal range during these periods (de Souza *et al.*, 2011). Hence based on thermal time and the weather experienced, air temperature is unlikely to affect the perfomance of the trees under both treatments.

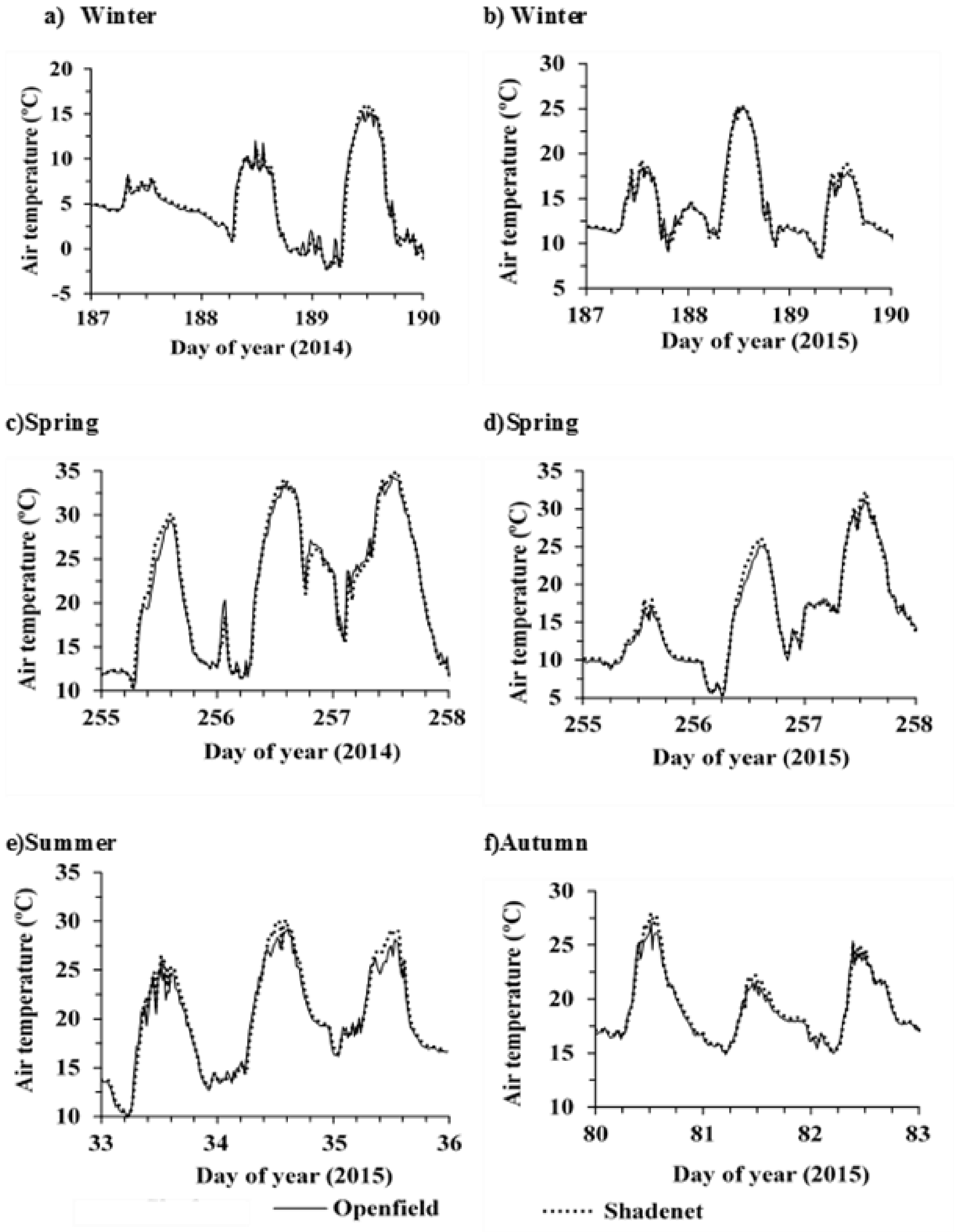

Figure 3.7: Air temperature comparison, for 20-min measurements, between shadenet and open orchard during different seasons a) Winter 2014; b) Winter 2015; c) Spring 2014; d) Spring 2015; e) Summer 2015; f) Autumn 2015

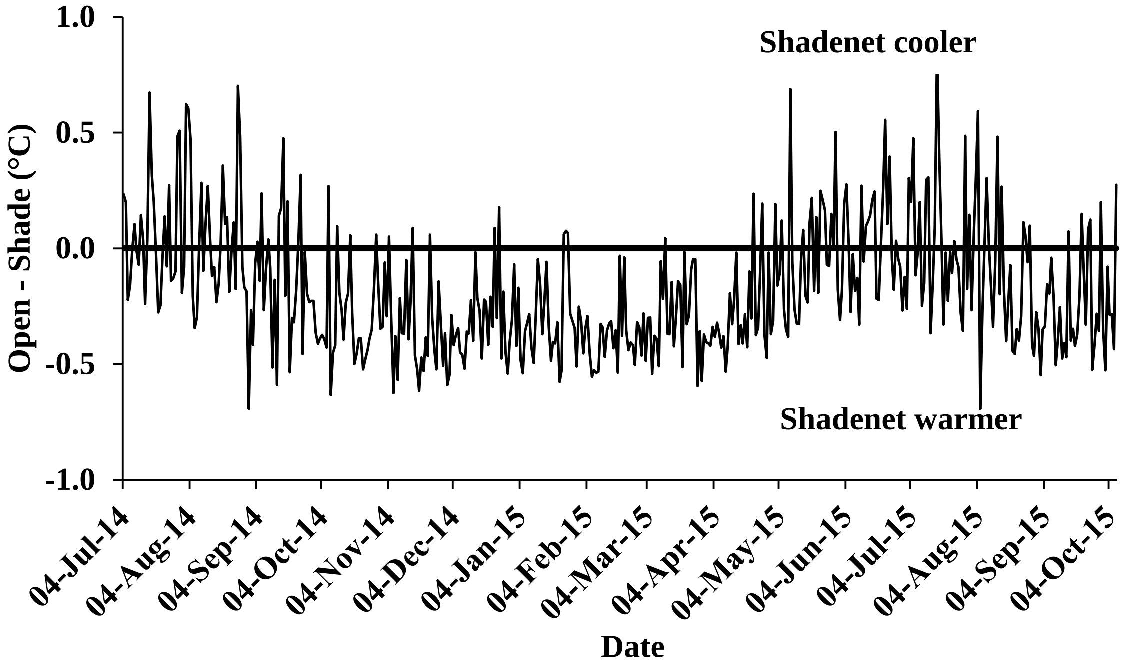

Figure 3.8: Daily average air temperature difference between open orchard and shadenet f from the 4th of July 2014 and to the 5th of October 2015

3.4.3 Relative humidity

The relative humidity pattern differed with season (Figure 3.9), with the difference between the two treatments ranging up to 8%. As depicted in Figure 3.9, for the majority of the time, RH was slightly greater (1-5 %) in the open orchard than inside the shadenet. These results are in contrast with what has been reported by many researchers before (Elad *et al.*, 2007; Stamps, 2009; Meena *et al.*, 2014), who reported greater RH recorded in the shadenet attributing it to reduced wind speed. Meena *et al.* (2014) used green, black, white and red shadenets. In this study, higher RH could be due to the presence of a dam near the open site. Hence, besides transpiring trees, the dam could have had an influencing effect, increasing the RH in the open orchard. Large variations in RH cause discrepancy in plant biological responses for example transpiration, pollination and indirectly photosynthesis (Savage, 2014). Low RH is associated with increased transpiration.

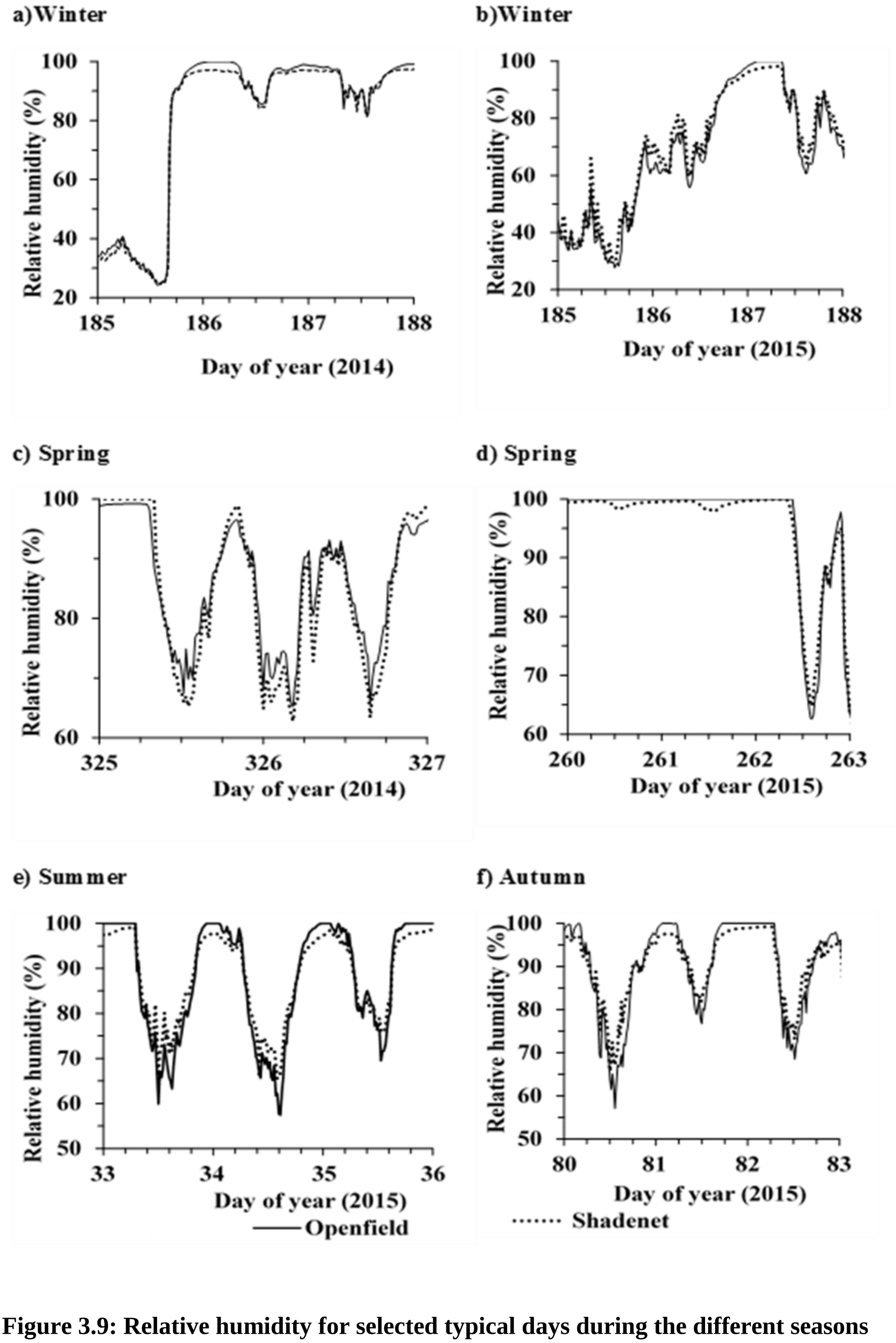

Figure 3.9: Relative humidity for selected typical days during the different seasons

3.4.4 Water vapour pressure deficit (VPD)

Throughout the day, VPD under the shadenetting was lower than the open field (Figure 3.10). Low VPD is associated with high stomatal conductance (Vico *et al.*, 2013). VPD is directly linked to transpiration. However, in this study, there seemed to be a discrepancy in RH and VPD results due to small difference in RH between treatments.

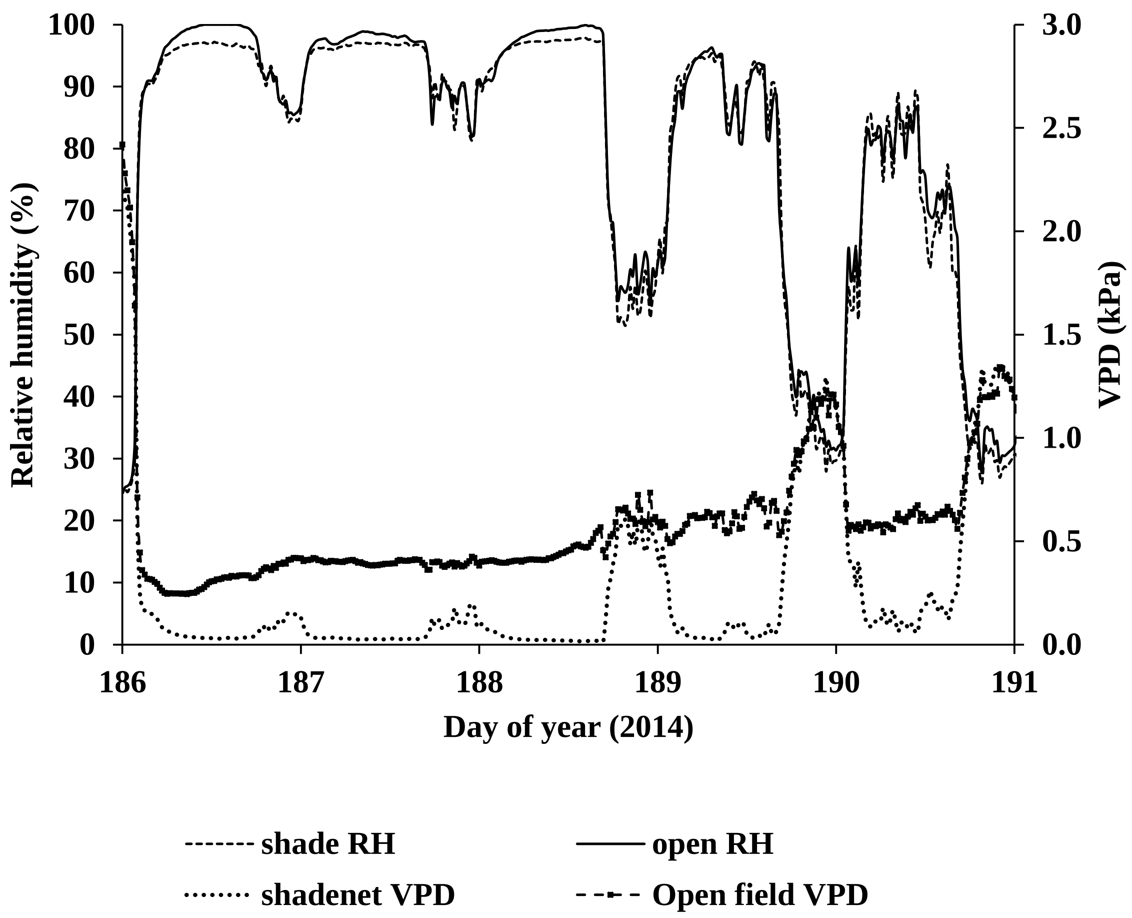

Figure 3.10 : Relationship between relative humidity and VPD from day 186 to day 191, 2014

3.4.5 Solar irradiance

Consistently, there was reduced solar irradiance recorded under the shadenet (Figure 3.11). An average transmission coefficient of around 81% was calculated (Figure 3.12). Over the 12-month period, the transmission coefficient tended to decrease (Figure 3.12) from greater than 85% in the initial months to less than 80 %. This can be attributted to aging or dust accumulation of the shadenet in use. Similar results were reported using different colournets by Middleton and McWaters (2002) and Bastías *et al.* (2012). The maximum solar irradiance received on a sunny day in the open field was 1210 W m^{-2} as compared to 1016 W m^{-2} under the shadenetting. However, the reduced values are not expected to affect productivity in avocado. Since Bower *et al.* (1977) and Bower (1978) reported the PI compensation point to be at 200-250 W m^{-2} for avocado (approximately 20% of incoming solar radiation) with trees receiving more than sufficient solar irradiance for photosynthesis. Rosenberg *et al.* (1983) mentioned that C3 plants can be saturated at irradiance levels as little as a quarter of that for full sunlight. The reduction of solar irradiance by shadenetting can also have an effect on the incidence of sunburn in fruits, but reduction in sunburn was not be evident in this trial because '3-29-5' avocado bears a large proportion of its fruit inside the canopy.

3.4.6 Canopy temperature

Canopy temperature follows the same diurnal course with temperatures being low in the morning and quickly increasing to a maximum around midday, and then decreasing as the day progresses (Figure 3.12). Canopy temperature peaked earlier in the open field due to lower solar irradiance (20%) received by plants under the shadenet. The trees under shadenet (Figure 3.13a) were 3.5 ºC cooler than those in the open orchard. In spring 2015 (Figure 3.13b), the differences in extremes were as high as 13 ºC on day 257. The given differences between shadenet and open orchard may be as a result of energy balance changes associated with a decrease in incoming solar irradiance (Nobel, 1999). The differences in solar irradiance are clearly depicted in Table 3.2 and are likely to result in a greater sensible heat flux for the open orchard compared to the shadenetting treatment. The differences in sensible heat flux between the open and shadenetting orchards implies that there would be differences in the energy balance for the two environments. This however, was not the focus of this study, but would be an interesting avenue of research to follow on from this study.

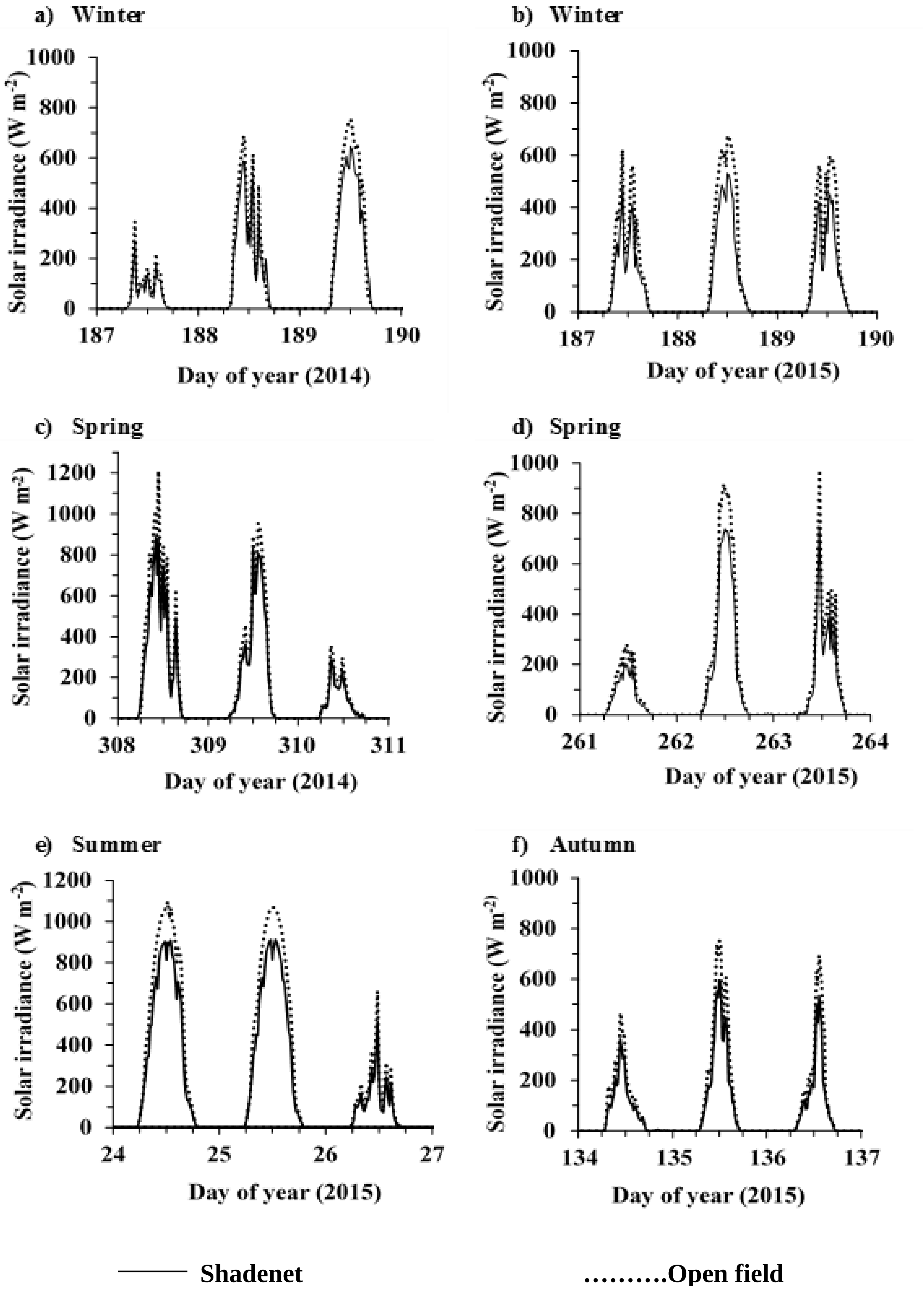

Figure 3.11: Seasonal trends in diurnal solar irradiance for a 3-day period a) winter 2014 (7 - 10 July); b) winter 2015 (7-10 July); c) spring 2014; d) spring 2015; e) summer 2015; f) autumn 2015

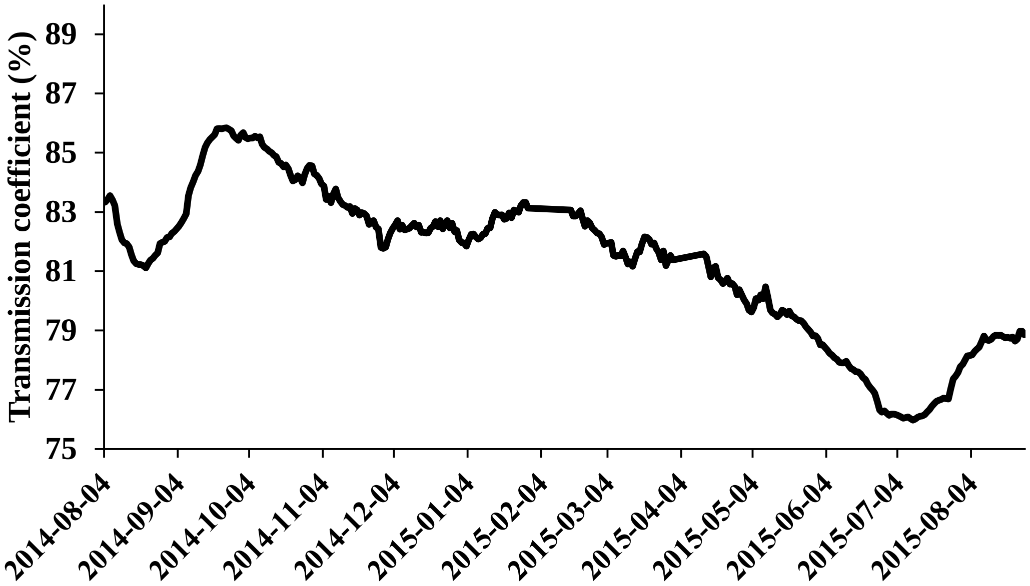

Figure 3.12: Calculated transmission coefficient of the 30% crystal shadenetting from July 2014 to August 2015. The graph shown is for a moving average with a period of 30 days.

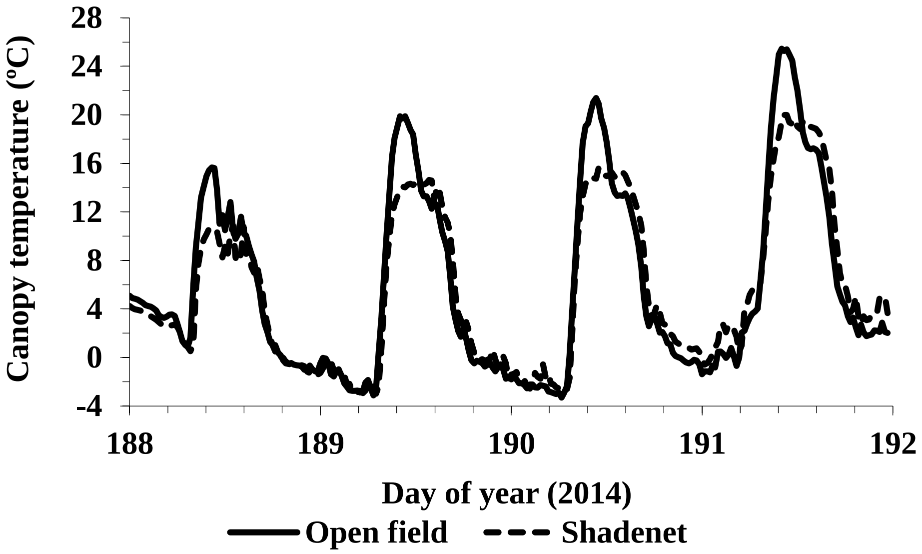

Figure 3.13: Diurnal course of canopy temperature from day 188 (8 July) to day 191 (11 July 2014)

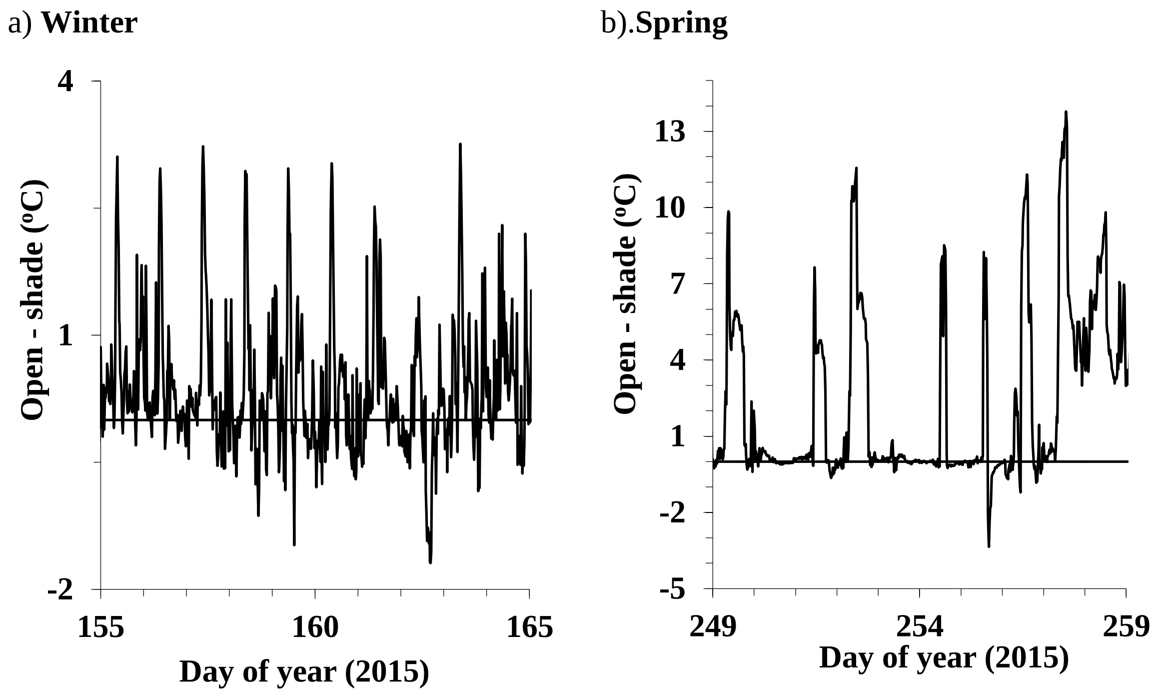

Figure 3.14: Canopy temperature differences of 20 min data between two seasons: a) day 155 (4 June) to day 165 (14 June) and b) day 249 (6 September) to day 259 (16 September).

3.4.7 Relationship between air and canopy temperature

The difference between the canopy and air temperatures are almost negligible when the temperatures are low (Figure 3.15). There were large differences in the canopy temperature, but slight and opposite differences in the air temperature (Figure 3.15). This can be due to the influence of solar irradiance absorbed by the canopy. Differences can arise depending on the water status of a plant hence canopy and air temperature difference is used as an indicator of plant water status (Duffkova, 2006).

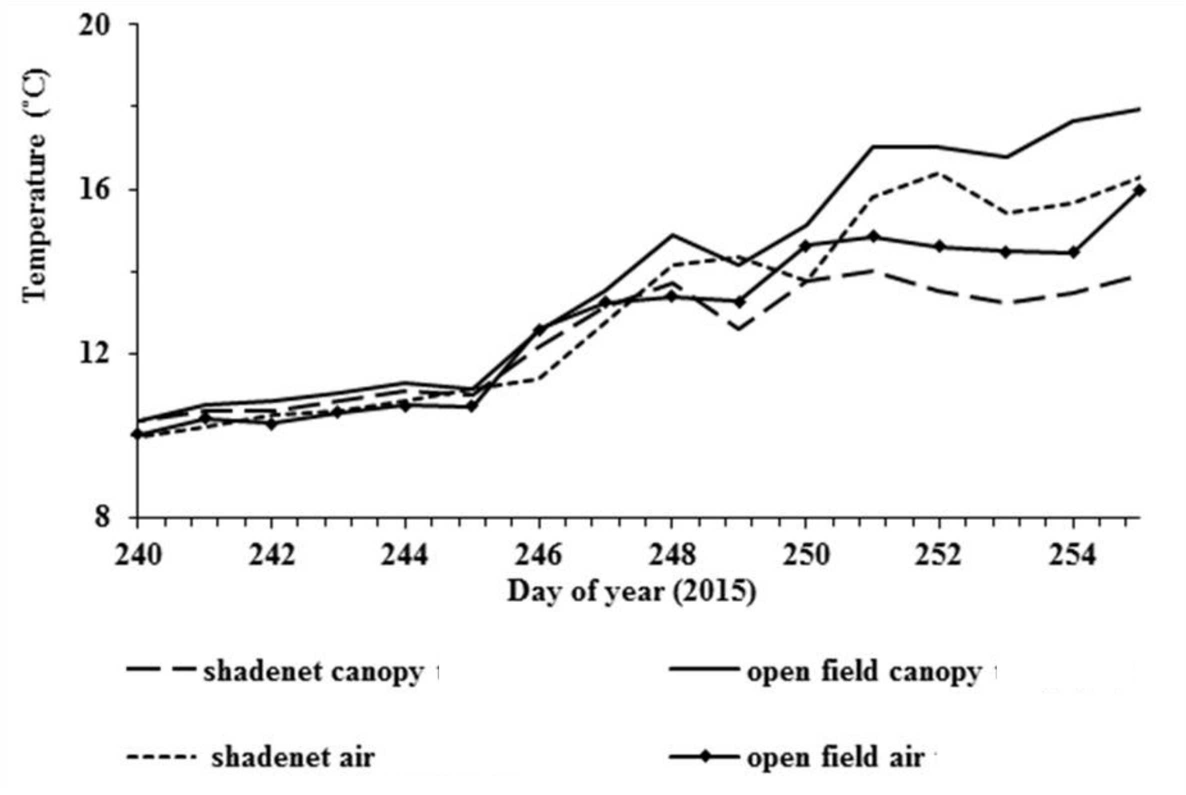

Figure 3.15: Daily average canopy and air temperature for a 15-day period from day 240 to 255

3.4.8 Precipitation

The rainfall distribution from July 2014 to September 2015 shows that overall rain penetration through the shadenet was reduced by 40% (Figure 3.16). This result concurred with the results from a study by Lawson *et al.* (1994) whilst working with insect exclusionary cages. Uncovered plots received more rainfall than covered plots during the two years of their study. The difference in measured rainfall between the two environments may therefore necessitate different irrigation schemes, but that would also be dependent on the transpiration (Chapter 4).

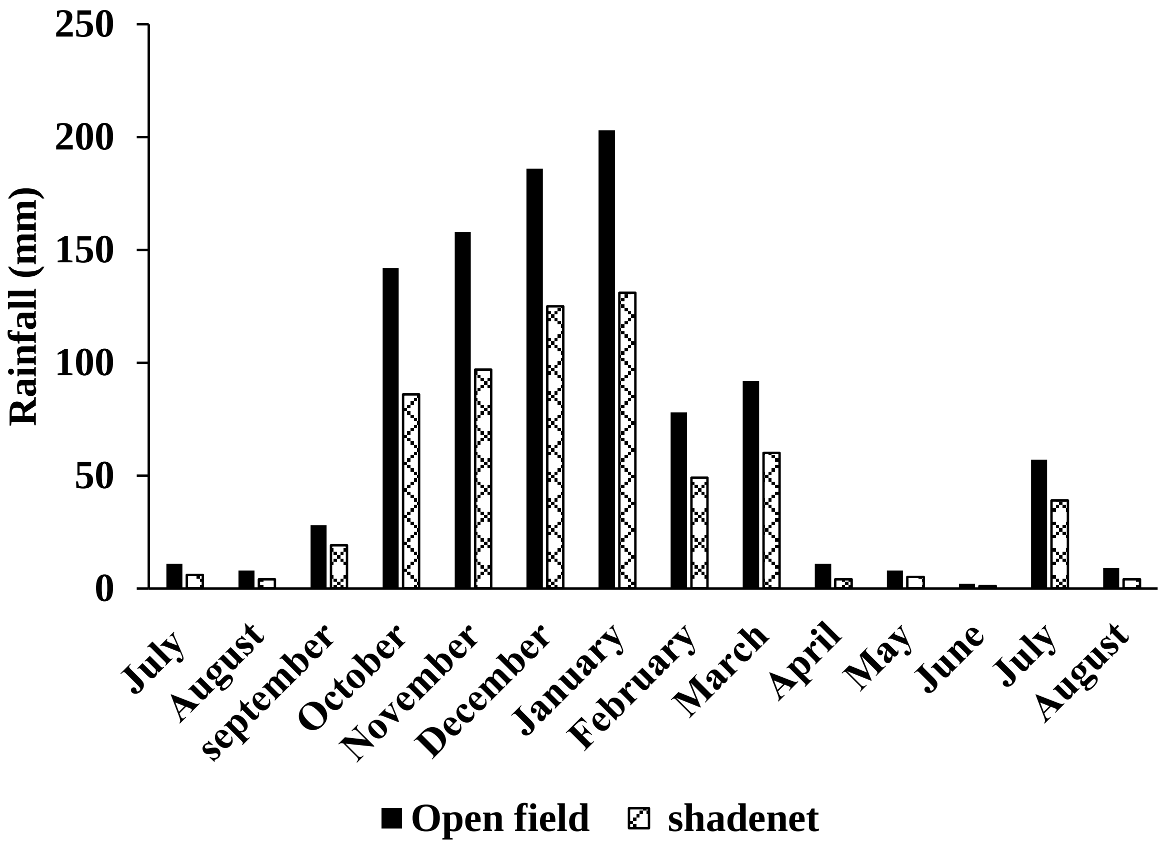

Figure 3.16: Total monthly rainfall received from July 2014 to August 2015

3.4.9 Wind speed

Wind was reduced to below the limit of detection under the shadenet throughout all the seasons (Table 3.2), whilst in the open orchard considerable wind speed was recorded. This agrees with results reported by Tanny and Cohen (2003), Tanny *et al. (*2008) and Stamps, (2009). However, Stamps (2009) attributed the unmeasurable wind speed levels to the percentage of reduction which varies with the shading factor. Reduction of wind to negligible levels resulted in the reduction of wind scarring of fruits under the shadenet as compared to the open orchard.

3.4.10 Leaf wetness

The leaf wetness duration (LWD) was 7% longer in the open (results not shown). The deviation usually occurred between midnight and 08:00. However, there was no sign of disease threat in both treatments. This positive results augers well for the future use of shadenetting.

3.5 Conclusion

The use of shadenet altered all aspects of the microclimate compared to the open environment. Solar irradiance, wind speed canopy temperature and precipitation were altered to a much greater degree than air temperature and RH. However, a change in the microclimate can be a cause for concern since most plant processes depend on air temperature. Higher air, soil and canopy temperatures can result in a negative impact on net photosynthesis, and possible decreased growth rate. The decreased growth rate would be an excellent finding in avocado. However, in this study there was a very small difference and one would not expect any adverse effect on '3-29-5' avocado growth. The effect of the altered microclimate on avocado growth will be covered in Chapter 5. Further research still need to be done to clarify the effects of different coloured nets of different densities on the microclimate within an orchard. The full benefit of shadenetting will be evident during adverse conditions of high winds, hail and intense rainfall.

Table 3.2: **Comparison of monthly values of selected microclimatic variables measured using the AWS systems (inside and outside) in 2014**.

		SHADENET						OPENFIELD					
Microclimatic factors		July	Aug	Sept	Oct	Nov	Dec	July	Aug	Sept	Oct	Nov	Dec
Air temperature (°C)	Max	28.59	28.23	34.90	34.80	31.30	34.49	27.05	28.62	34.36	34.89	30.85	34.60
	Min	-2.41	1.33	1.17	5.49	7.46	10.28	-2.31	1.18	1.07	5.13	7.07	10.20
	Mean	10.86	14.76	17.34	15.2	16.58	18.73	10.91	14.81	17.21	14.9	16.25	18.41
Relative humidity (%)	Max	98.08	99.8	99.08	99.42	99.58	99.80	100	100	100	100	100	100
	Min	17.45	14.89	14.59	18.66	38.11	35.18	16.77	12.31	13.29	16.52	38.04	36.02
Solar radiation	Max ($W\ m^{-2}$)	654.5	789	911	1011	1016	982	783	909	1034	1149	1210	1166
	Total ($MJ\ m^{-2}$)	317.0	387.1	477.8	391.5	461.1	435.9	387.2	487.7	589.6	478.9	370.9	543.2
Wind speed ($m\ s^{-1}$)	Max	0	0	0	0	0	0	2.59	3.26	4.42	3.10	3.54	2.45
	Average	0	0	0	0	0	0	0.28	0.52	0.46	0.42	0.40	0.29
Rainfall (mm)	Total	6	4	19	86	97	125	11	8	28	142	158	186

3.6 References

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CHAPTER 4: WATER USE IN YOUNG '3-29-5' AVOCADO TREES UNDER SHADENETTING

4.1 Abstract

Water quality and availability are major limiting factors in fruit production in many agricultural regions of the world. Efficient water use in the fruit industry is important because of the industry's dependence on irrigation. Hence, the management of available water resources whilst maintaining fruit yield and quality is of utmost importance. In the face of limited water resources in Southern Africa, there is a need to use the available resources optimally. Shadenetting is thought to play a role in improving water use efficiency. However, there is little information on the role of shadenets in reducing water use of avocado trees. The objective of the study was to determine if '3-29-5' avocado trees under shadenet require less water for growth and fruit production compared to trees in the open field using the thermal dissipation probe (TDP) sap flow method. Lower sap flow values were recorded under shadenet compared to open field trees. Water use was derived from summation of sap flow values. Hence, trees under shadenet used less water compared to trees in the open field. Solar radiation and water vapour pressure deficit (VPD) directly affected the pattern of sap flow in both treatments.

Keywords: sap flow, thermal dissipation probe, vapour pressure deficit (VPD)

4.2 Introduction

In horticulture, water quality and availability are the main limiting factors in agricultural production that directly affect fruit quality and yield. In South Africa, 60% of the available water is used in agriculture, with 90% being used for fruit production under irrigation (Taylor and Gush, 2009; Strydom, 2010; le Roux *et al.,* 2015*)* However, due to population increase and urbanisation, water use in South Africa has been shown to be on the increase (Blignaut *et al.,* 2009). South Africa has been identified as a water scarce country (Department of Water Affairs and Forestry (DWAF), 2004; Hedden and Cilliers, 2014) and it has been projected that by 2020, South Africa is likely to run out of surplus surface water. In situations where water supplies are limited, there is a need to use the available water resources sparingly. The growing water shortages worldwide coupled with increased irrigation costs have led to the development of methods that minimize water use and improve water use efficiency (Jones, 2004). In agriculture, water use inefficiency is the most common term used to describe the water problem

(Tejero *et al.,* 2011). Efficient water use in the fruit industry is important since it depends on irrigation, and hence the management of available water resources, whilst maintaining fruit yield and quality is imperative.

Avocado (*Persea americana* Mill) is a subtropical fruit tree, sensitive to flooding as well as water stress. Hence, it should be supplied with enough water for growth without flooding the rootzone (Bower and Cutting, 1988). Most avocado orchards in South Africa are irrigated, and previous research has associated under-irrigation with reduced growth, smaller leaves, poor yields and postharvest ripening as well as inferior storage quality of fruit (Chartzoulakis *et al.,* 2002; Kruger and Magwaza, 2012). On the other hand, over-irrigation together with prolonged wet conditions promotes *Phytophthora cinnamomi* root rot. Generally, the optimal application of irrigation water is possible when the water requirements of given trees is known. At present, in South Africa, recommendations for irrigation in the avocado industry are based on soil properties as well as monitoring soil water (Roets *et al.,* 2014). Lahav and Whiley (2002) mentioned that irrigation scheduling should be regulated through the use of several variables including daily changes in fruit and tree diameter, leaf thickness, leaf water potential and sap flow velocity. tensiometers have been used for a long time by farmers to monitor soil water due to their ease of use. In the case of use of crop coefficients, irrigation decisions are based on coefficients that were established in other countries with different climatic conditions.

In spite of avocados being grown in high rainfall areas of South Africa, dry spells and periods of inadequate rainfall do occur (Roets *et al.*, 2013*)*. The appropriate management of irrigation has to be effected in the face of the limited water resources. Common methods for determining water requirements of avocados trees is by using crop factors, even though it does not provide accurate results. Transpiration (sap flow) accounts for the largest amount of water used by plants (Fernandez *et al.,* 2008). Sap flow studies have been used and carried out on a number of fruit trees and orchard crops (Ortuno *et al.,* 2006; Fernandez *et al.,* 2008; Steepe *et al.,* 2008) as well as greenhouse crops so as to determine water use but there is limited information on avocados. Irrigation scheduling can be improved by measuring crops' physiological variables *in vivo* (Jones, 2004).

The use of shadenetting in fruit farming has been gaining popularity, for improved fruit quality but also for improving water use efficiency and decreasing plant water stress (Prinz and Malik, 2004; Aboutallah *et al.*, 2012; Holcman and Sentelhas, 2012). Water uptake by plants is influenced by physiological and environmental factors, mainly solar radiation and water vapour pressure deficit (Jones, 1992). Hence, any reduction in net radiation can directly reduce the transpiration rate of trees under shadenet. However, there is no information on the role played by shadenets in reducing water use of avocado trees.

The objective of this part of the study was to determine if '3-29-5' avocado trees under shadenet require less water for growth compared to trees in the open field using the thermal dissipation probe (TDP) method. This provided insight in the response of avocado trees' sap flow response to the microclimate as well as the phenological stage.

4.2.1 Determining water use of fruit trees

Irrigation requirements of plants are calculated by determining water use of the whole plant. However, it is challenging to measure whole tree water use compared to field crops because of their large size. To ensure the adequate supply of irrigation water, irrigation scheduling is used to make a decision whether to irrigate and also how much water to apply. There are three main types of irrigation scheduling methods based on soil, plant and weather.

4.2.1.1 Soil-based irrigation scheduling

Soil-based irrigation scheduling is determined by soil water content or soil water potential (or soil matric potential) measurement with a variety of devices, among them tensiometers and neutron and capacitance probes. In avocado production, tensiometers (Figure 4.1) are commonly used (Du Plessis, 1991; Guvorich *et al.*, 2006), even though they are now being replaced by a more automated means like capacitance probes. Tensiometers are regularly operated in pairs, one in the root zone (300 mm) whilst the other is below root zone (600 mm). Desired water application is enabled by allowing a certain level of soil water depletion in the root zone. Du Plessis (1991) reported the recommended soil matric potential as -30 kPa for light (sandy) soils and -50 kPa for heavy (clayey) soils before irrigation can be applied. In South Africa, 50 to 60% reduction of easily plant available water in the root zone is usually recommended.

Figure 4.1: A picture of pair tensiometers (300mm in background, 600mm in foreground) in the trial orchard at Everdon Estate

4.2.1.2 Weather-based scheduling

Weather-based irrigation scheduling involves the measurement of numerous meteorological data, which include air temperature, RH, wind speed and solar radiation. The microclimatic data is used alongside an evaporation pan with specific crop factors. However, crop factors do not show the water status of either the plant or soil (Du Plessis, 1991). In South Africa, crop factors derived in other countries with similar climatic conditions are usually used. The major drawback of using crop factors, is the risk of under-irrigation if the crop factor is too low or over-irrigation when the factor is too high.

4.2.1.3 Plant-based irrigation scheduling

Plant-based irrigation scheduling is based on visible symptoms, plant water status, fruit trunk and diameter changes and sap flow measurement (White and Raine, 2008). Visible symptoms refer to signs of stress that one can see on a tree such as curling of leaves or leaf drop. This is an old fashioned way which has been deemed inefficient in determining the water needs of a tree and likely to cause reduction in yield. Even though plant water status, especially leaf water potential, has been used, it cannot be trusted due to its dependence on variable weather conditions which control stomatal opening and closing. Xylem water potential or stem water potential have been determined as more stable means of determining plant water status (Jones, 2004). Predawn leaf water potential is sometimes used, but was found to be unaffected by disparities in soil water. Diurnal variation of fruit and stem diameters are related to variations in soil water content. For fruit trees, the diurnal changes have been used to develop irrigation needs (Fernández and Cuevass, 2010).

4.2.2 Sap flow measurement

Sap flow measurements are extensively in use for real time measurements of plant water use. These measurements involve quantifying whole tree transpiration by evaluating the proportion of sap rising up the stem and are based on conduction and convection of heat in xylem tissue (Smith and Allen, 1996). The use of thermo-electrical means for sap flow measurement have given physiologists a means of precisely studying whole tree water use and water relations. It must be noted that, horticultural practises such as grafting, training and pruning make it difficult to carry out routine measurements. Sap flow measurements have been used to assess transpiration rates and show water relations in plants (Ortuno *et al.,* 2004; Alarcón *et al.*, 2005). Advantages of sap flow measurements are that they are easily programmed, and can be readily operated under field conditions (Swanson, 1994). Sap flow enables the measurement of transpiration as a single entity separate from evapotranspiration (ET). A number of sap flow measurement methods have been developed (Smith and Allen, 1996). Three general methods used for sap flow determination are heat balance, heat dissipation and heat pulse methods. In irrigation scheduling, sap flow was noted to be a good indicator of plant water status. However, several flaws associated with sap flow measurements have been reported (Uddin, 2014). Intrusive sap flow measurement is associated with wounding of the stem. Furthermore, sap flow measurement methods tend to underestimate transpiration rate (Steepe *et al.*, 2010).

4.2.3 Shadenetting and water use

Shadenets have been used for some time, especially in greenhouses (Stamps, 2009). They decrease the evaporative demand, and hence decrease transpiration. Alarcón *et al.* (2006) assessed sap flow as a marker for transpiration and tree water status in pot-grown apricot trees. Savage *et al*. (2000) reported an instantaneous reduction in sap flow rate when a portion of the

E. grandis tree was shaded from direct solar radiation. However, on removing the shade sap flow rate increased instantly.

Reduction in water use has been linked to low water vapour pressure deficit under the shadenets, even though it may not be the case for all crops. Sap flow has been indicated to be an inaccurate estimate of transpiration in case of rapid rehydration and dehydration. Under water stress, sap flow underestimated actual transpiration whilst when over-irrigated, it overestimated actual transpiration (Alarcón *et al.,* 2000). The objective is to determine the water use of the avocado trees under the shadenet and open field.

4.3 Materials and methods

The study was conducted on '3-29-5' trees planted in 2010 at Everdon Estate, Howick in KwaZulu-Natal, South Africa (29° 26′37″S, 30°16′22″E, 1080 m altitude). The estate is in bioclimatic region 3 which experiences cool mesic conditions, a characteristic of a mist belt climate. The area receives an average rainfall of 1052 mm per year. It experiences mean maximum and minimum temperature of 26.1 and 15.0 °C respectively in January and 19.4 and 6.7 °C respectively in July (Moore-Gordon and Wolstenholme, 1996). The orchard had a north-south orientation and rows of 7 m × 4 m spacing. Irrigation scheduling was based on tensiometers. Irrigation was supplied by micro-sprinklers with a discharge rate of 5 mm per hour. FAO Penman Monteith equation was used to calculate reference evapotranspiration (ET_o) using AWS data.

4.3.1 Theory of thermal dissipation probe (TDP) method of sap flow measurement

The thermal dissipation method was originally proposed by Granier (Granier, 1987). It is also known as the Granier method. The TDP method was established to suit tree crops of varied morphologies and xylem structures which include mango, mangosteen and banana (Paudel *et al.,* 2013). Spatial variability of sap flow can be a problem during measurement, and this led to an improved Granier method which proved to be effective (Lu, 2004). TDP measurements have related well with water use approximations from other sap flow, meteorological and gravimetric methods (Clearwater, 1999; Paudel *et al.,* 2013). Continuous power supply is applied using needle probes and the temperature difference between the two probes is dependant on the sap flow measured.

According to the Dynamax TDP manual (2010), the Granier method was constructed based on the liquid velocity heat dissipation theory. Sapwood dimensions enables the upscaling of velocity to sap flow rate.

$$K = \frac{dTm - dT}{dT} \tag{4.1}$$

where K is unitless, it is a constant for computing sap flow, dT is the measured temperature difference (°C) between the heated needle, referenced to the lower non-heated needle at a fixed distance from the heated one, and dTm is the value of maximum dT in °C when there is no sap flow. dTm is determined by finding the maximum dT value for the given day and tree. According to (Granier, 1987), average sap flow velocity V (cm s^{-1}) could be related to K by an exponential expression;

$$V = 0.0119 \times K^{1.231} \tag{4.2}$$

where V is the sap flow velocity in cm s^{-1} and is converted to sap flow rate as shown:

$$Fs = As \times V \times 3600 \left(\frac{s}{h}\right) \tag{4.3}$$

Where Fs ($cm^3\ h^{-1}$) is sap flow, and As is the cross sectional area of sap conducting wood (cm^2).

The above calculation were imbedded in Microsoft excel. According to Smith and Allen (1996) and Lu *et al.* (2004), the main advantages of using TDP method is ease of setting up, simple sap flow calculations and lower costs.

4.3.2 Sap flow measurements

Sap flow was measured in '3-29-5' avocado trees planted in 2010 grown under shadenet and the open field using the Dynamax Flow system based on thermal dissipation (TDP) method (Dynamax Inc., Houston, TX, USA). Three trees were used in each treatment with a single probe inserted in each tree. Tree diameter surveys were done on trees near the AWS system due to limited wire length. Two days before placing the gauges on the plants, stems were prepared by removing some foliage on the lower stem to provide a bare stem area for the gauges. Immediately prior to gauge installation, stem diameters were measured over the entire heat source placement area and a small amount of electrical insulating compound applied.

For a single probe, consisting of two needles two holes were drilled in the trunk with a vertical spacing of 40 mm. The holes were made to a depth of 30 mm since TDP30 probes were used. This ensured that the sensor was positioned within the active sapwood area (Figure 4.2). After probe insertion, the exposed parts of the hole were covered with Prestik (Blue tack) to preclude water from reaching the needle shaft. Thermal insulation around the TDP probe needles was provided by foam quarter eggs on both sides of the needles. Direct solar radiation on the tree was prevented by tightly wrapping the trunk area with a reflective bubble and securing the top of the bubble wrap with cable ties (Figure 4.3).

The probes were connected to a data logger (CR10X, Campbell Scientific, Logan, UT, USA) with voltages recorded after every 20 minutes at a scanning interval of 30 seconds. The heated probe was supplied with a constant electric voltage from a 70 A h car battery and it was regulated using a voltage regulator (UKZN electronics department). It was therefore possible to maintain constant power of 3 W with the temperature difference between the probes monitored. Sap flow was measured from March to November 2015. Automatic weather systems were set up in both treatments to measure meteorological variables (rainfall, wind speed and solar radiation). Readings were taken every 30 s, and the data averaged and stored every 20 minutes by the Campbell 21X data logger (Campbell Scientific Inc.,). RH and air temperature were monitored every 5 minutes using U23-002 Hobo data loggers (Onset Computer Corporation, Pocasset, MA, USA), and VPD, in kPa) calculated using:

$$VPD = e_s - e_a \quad (4.4)$$

$$e_s = 0.6108 \times e\left(\frac{17.27 \times T}{T + 273.3}\right) \quad (4.5)$$

and

$$e_a = e_s \times \frac{RH}{100} \quad (4.6)$$

where e_s is the saturation vapour pressure (kPa), e_a is vapour pressure of the air (kPa), T is air temperature in ˚C and RH is relative humidity (%).

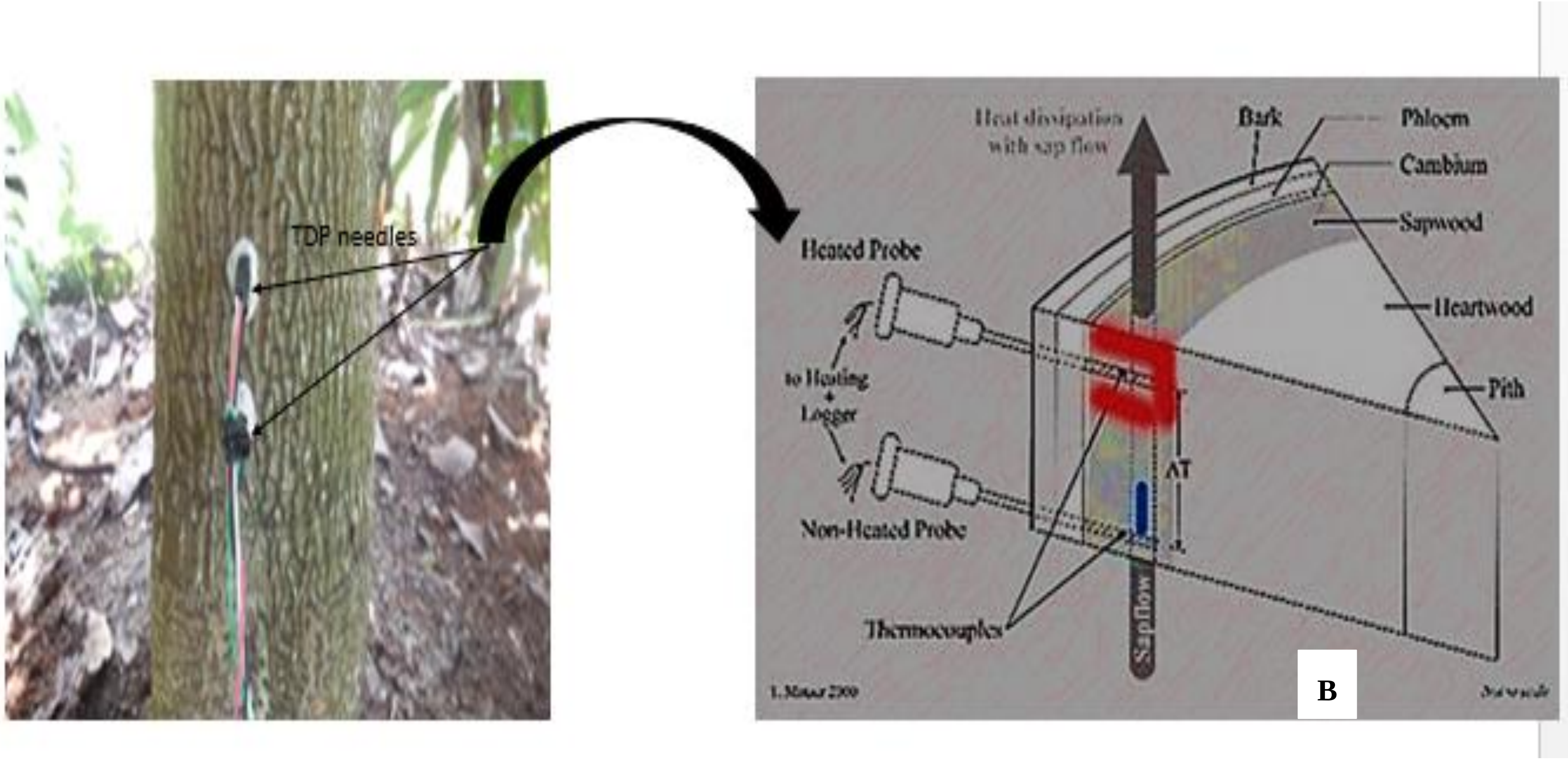

Figure 4.2: TDP needles inserted in the avocado tree trunk at Everdon Estate. (B) Working principle of the thermal dissipation probe method (taken from www.itc.nl)

Figure 4.3: An avocado tree with TDP probes for sap flow measurements (a) foam quarter eggs or foam quarter-spheres on both sides of the TDP needles to protect the sensor wiring, (b) Reflective bubble wrap to prevent the sun from shining on or beneath the area under measurement which may lead to large thermal gradient on the site

4.3.3 Leaf area index and other measurements

Leaf area index (LAI) measurements were recorded with a Li-COR LAI2200 Plant canopy Analyser (Li-COR, Lincoln, NE, USA) for the duration of sap flow measurements at regular intervals. LAI readings were taken from measurements above and below the canopy of the sample trees. Above-canopy readings were recorded in open areas near the sample trees, whereas canopy readings beneath the trees were taken at four different spots around the base of each trees. The lens of the LAI2200 was covered by a cap with a 90˚ opening, reducing the interference from nearby areas and the operator. Below-canopy measurements were recorded at a standard height of 0.5 m from the ground. Most LAI measurements were taken under diffuse light i.e. early morning, late afternoon or during overcast days. The final LAI estimates were calculated by the software of the instrument.

Stem diameters of the sample trees were measured every two weeks. The diameter was used to calculate the sapwood area (*A*) from the stem circumference (*C*) where

$$A = \pi r^2 \tag{4.7}$$

and

$$r = \frac{C}{2\pi} \tag{4.8}$$

The actual calculation of sapwood area was not taken into consideration since this is a comparative study. Tensiometer readings were taken every Monday, Wednesday and Friday.

4.3.4 Upscaling of sap flow

In this study, sap flow (g/20 min) was scaled up by multiplying sap flux density by the cross sectional area which was determined by measuring stem circumference every month. Daily water use (kg day^{-1}) was calculated by summing the 20-min sap flow measurements. The daily water use was converted to transpiration by dividing by crown area.

4.4 Results and discussion

4.4.1 Effect of microclimate on sap flow

Microclimatic parameters in this study were measured from the two automatic weather station (AWS) systems (Chapter 3). A study on stem sap flow by Wang *et al.* (2008) showed that the main driving forces of transpiration (sap flow) were photosynthetically active radiation (PAR) and VPD in the absence of water stress. Using Granier's thermal dissipation probe method, sap flux density was more dependent on PPFD than on VPD (Wang *et al.,* 2008). In this study, there was a curve linear relationship between VPD and sap flow ($r^2 = 0.709$) and solar radiation and sap flow ($r^2 = 0.7536$) under shadenet compared to open field (Figure 4.4). The determination coefficient of sap flow, VPD and solar radiation in the open field was low ($r^2 = 0.5887$ and $r^2 = 0.7098$). This difference in relationship between the parameters under measurement can be attributed to a more uniform protected environment under shadenet which is not easily susceptible to fluctuations compared to the open field fluctuation due to effect of wind or instant cloud cover. The other reason may be because sap flow is not only determined by VPD and solar radiation, but also by wind speed, air temperature and plant available water. The wind speed under the shadenet was reduced to negligible values while it was consistent outside (Chapter 3). However, sap flow was also directly proportional to the air temperature, canopy temperature and inversely proportional to RH (data not shown).

The effect of solar irradiance and VPD on sap flow is shown in Figure 4.5. Sap flow rates gradually increased in the morning until they reached the peak in the afternoon, and decreased until sunset. On any given day sap flow increased with increase in VPD and decreased as VPD declined. On day 130 and 131, the fluctuation in solar irradiance also resulted in sap flow fluctuation (Figure 4.5). Daily patterns in Figure 4.5 were in line with what was reported by Wullschleger *et al.* (2001) when analysing sap flow of nine chestnut oak trees. He reported that daily radiation determined seasonal sap flow and daily amount compared to water vapour pressure deficit.

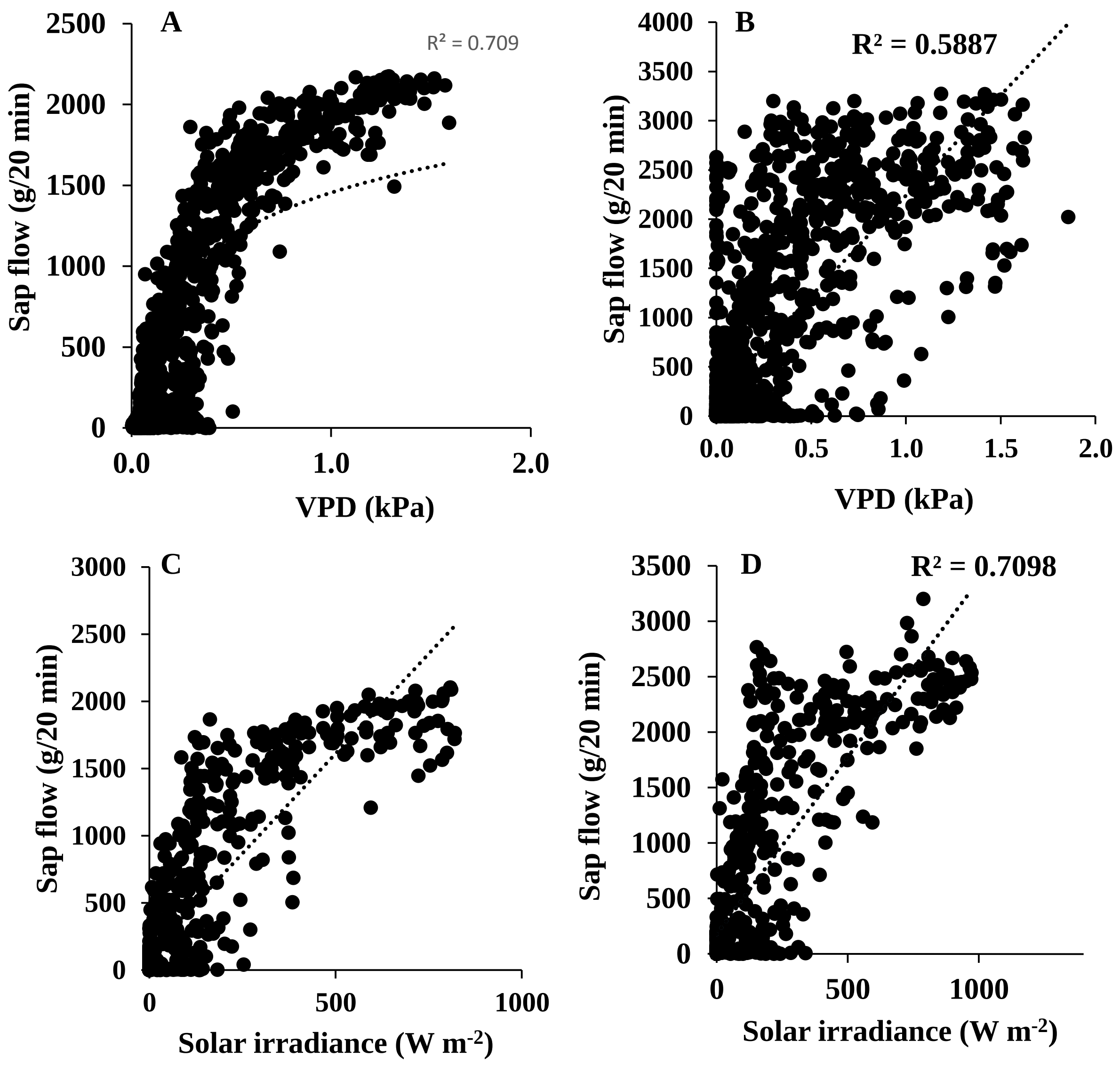

Figure 4.4: Relationship between 20 min sap flow data, water vapour pressure deficit (VPD) and solar irradiance under shadenet (A and C) and open field (B and D). The data used is from day 80 to day 130.

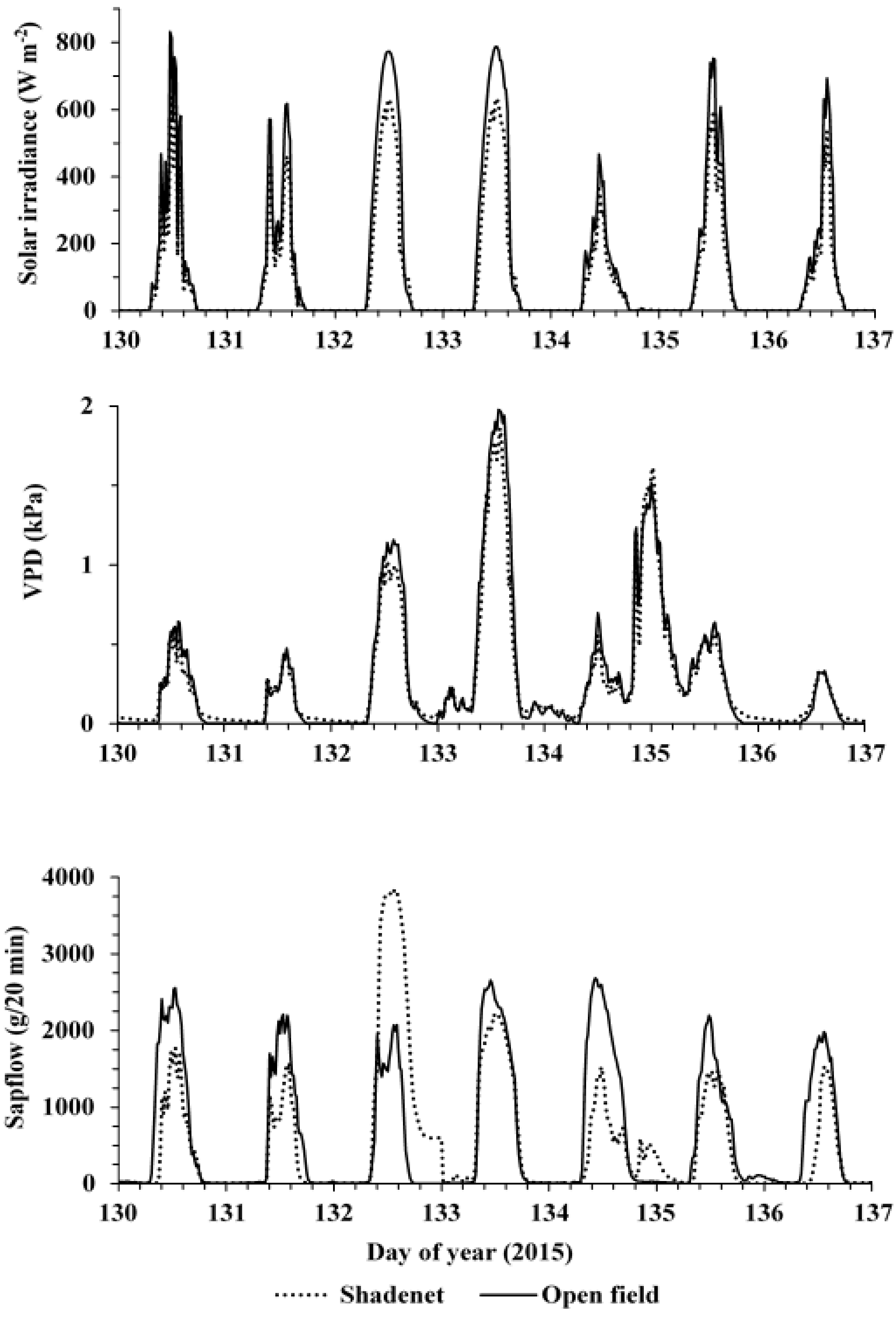

Figure 4.5: Daily patterns of average sap flow of 3 avocado trees in g/20min. The first two graphs represent the main microclimate in form of solar irradiance and vapour pressure deficit (VPD) from day 130 to 137.

4.4.2 Reference evaporation (ET_o)

The daily reference evaporation (ET_o) was calculated from July 2014 to October 2015 (Figure 4.6). The weather information used was obtained from AWS systems under shadenet and in the open field. The crop coefficient used was 0.6 based on what was reported by Carr (2013). Carr (2013) reported the crop coefficient to be within the range of 0.4 and 0.6, so for this study the upper limit was used. The calculated daily ET_o values were less than 3.5 mm in winter (2014 and 2015) and between 4 and 6 mm in summer for both treatments. The high summer values are as a result of high evaporative demand. ET_o values were lower under the shadenet compared to open field. The total ET_o for the study period was 592.3 and 714.2 mm for the shadenet and open field respectively in 2014, whilst in 2015 it was 669.4 and 855.5 mm respectively. This is attributed to the combined effect of the microclimatic parameters under the shadenet namely negligible wind speed and reduced solar irradiance. During the whole study period, the average ET_0 under the shadenet was 21% less than the open field. The results were in line with those found by Tanny *et al.* (2014) using banana plantations under screenhouses and Refaie *et al.* (2012), working on Grand Nain banana under red and black shadenets.

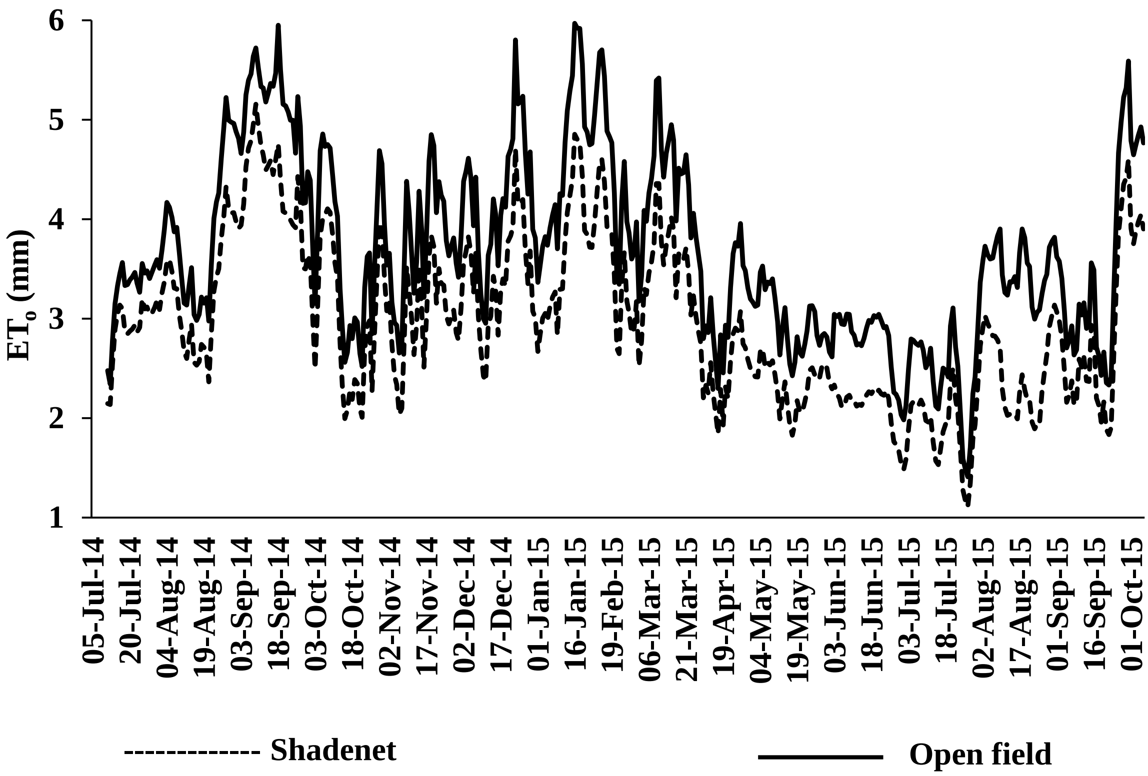

Figure 4.6: Weekly moving averages of order of reference evapotranspiration (ET_0) in mm day^{-1} using ET_o from the 5th of July 2014 to October 2015

4.4.3 Sap flow

Daily sap flow (Figure 4.7) for both treatments ranged from 15 to 85 kg day^{-1} between day 126 and 246 (2015). However, from day 246 onwards, sap flow rates were almost the same. This can be attributed to the low VPD for that period. The calculated transpiration (Figure 4.8) followed the same trend as that of the sap flow. A possible reduction of transpiration can be as a result of stomatal activity. Reduction of wind speed as well as the general modification of all microclimatic parameters can affect transpiration and other related processes which may indicate water use in plants. Sap flow rates are indicative of water use by the '3-29-5' avocados. From the results, trees under shadenetting tended to use less water compared to the open field even though less rainfall was received under shadenet (Chapter 3)

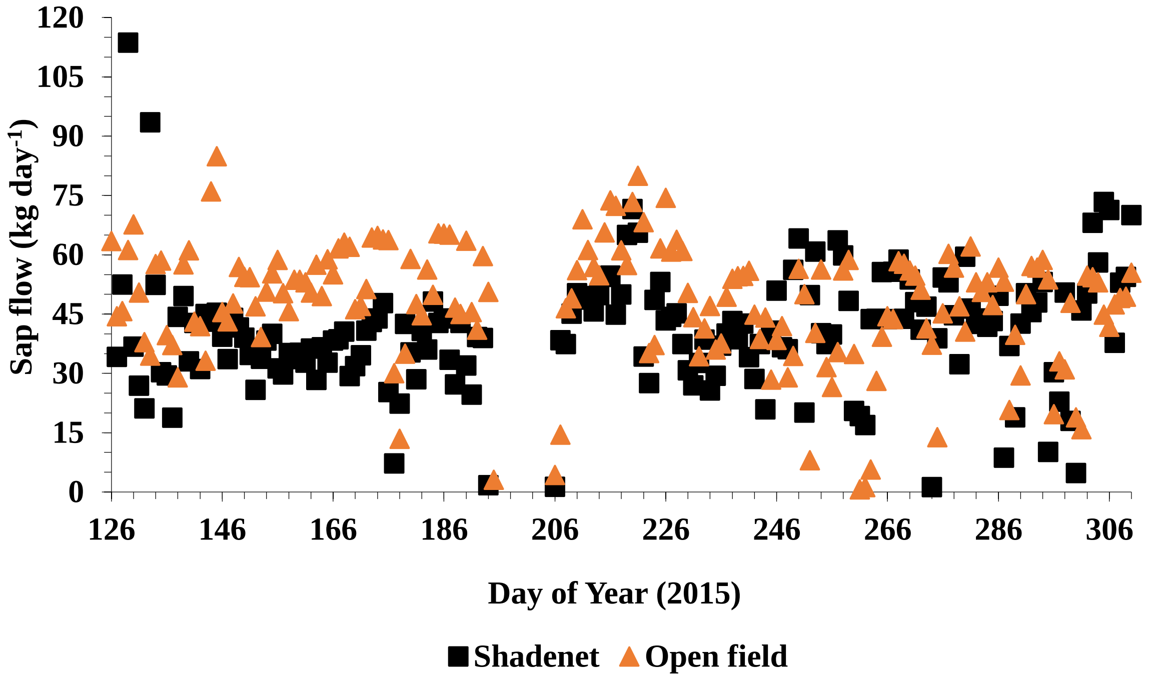

Figure 4.7: Daily sap flow (kg day^{-1}) from day 126 to day 310. Missing data between day 194 and 204 was due to power problems

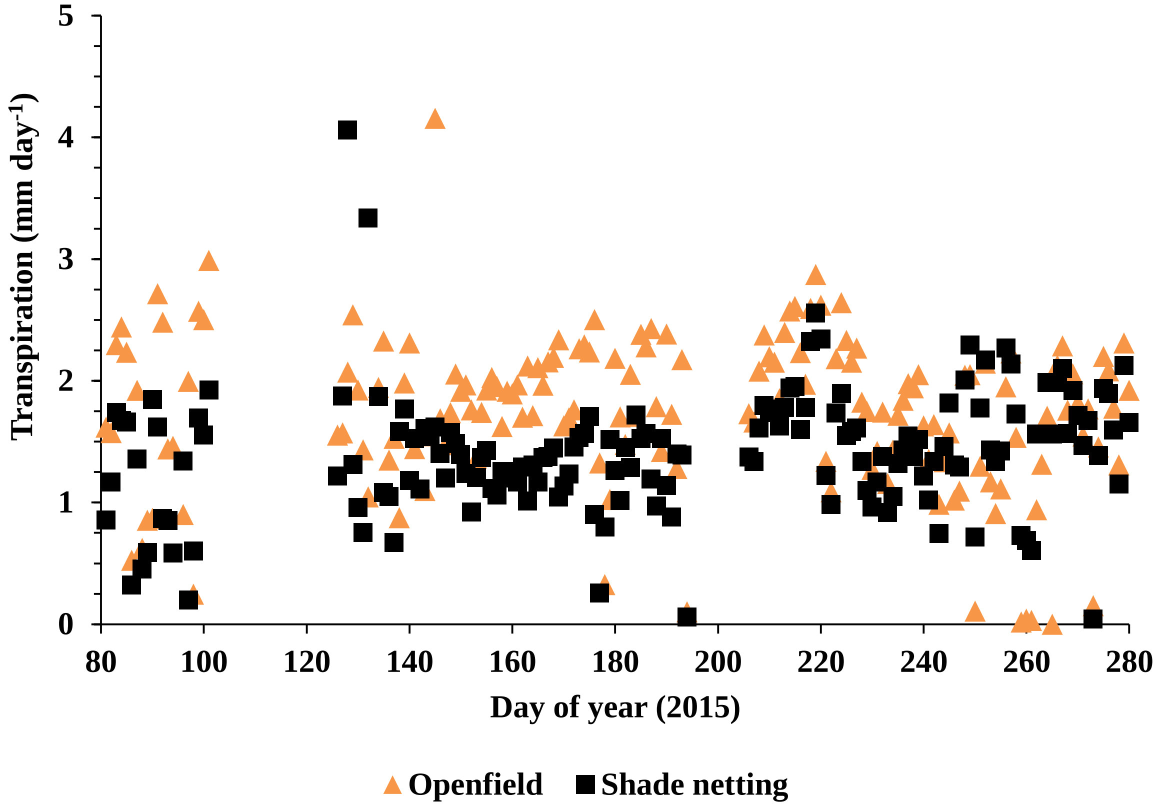

Figure 4.8: Transpiration as calculated from TDP sap flow measurements between day 80 and 310. The gaps in the data are as a result of voltage regulator maintenance and power supply problem

4.4.4 Leaf area index (LAI)

The LAI of the sample trees ranged from 2.79 m^2 m^{-2} at the beginning of sap flow measurements in March 2015 to 4.56 m^2 m^{-2} in November 2015 under the shadenet. Whilst in the open field LAI values were greater than under shadenet ranging from 2.92 m^2 m^{-2} to 4.65 m^2 m^{-2} at the end of the project. The gradual increase in LAI contributes to leaf area hence a possible increase in total evaporation.

Table 4.1: Leaf area index values ($m^2\ m^{-2}$) from March to November 2015. Each value is a mean of three values from the trees used for sap flow measurement

	Shadenet	Open field
March	2.79	2.92
April	2.94	3.00
May	3.13	3.00
June	3.38	3.35
July	3.92	3.98
August	4.16	4.42
September	4.27	4.66
October	4.38	4.61
November	4.56	4.65

4.5 Conclusions

The study was able to show the comparative water use between shadenet and open field using the thermal heat dissipation (TDP) method. High sap flow rates in the open field were an indication of greater water use in the open field. The results of the study are promising. Hence there is a need to do further research to determine water use in avocados using different validated sap flow methods. These can provide a platform for irrigation scheduling using sap flow. The use of shadenetting can potentially provide a means of coping with the ever decreasing water supplies in South Africa especially in areas that experience high solar irradiance.

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CHAPTER 5: VEGETATIVE AND REPRODUCTIVE GROWTH RESPONSES OF ‘3-29-5’ AVOCADO GROWN UNDER SHADENET IN A SUBTROPICAL CLIMATE

5.1 Abstract

Fruit tree production under shadenetting has increased in recent years and is nascent in avocado cultivation. There is little knowledge on the effect of shadenetting (i.e. reduction of solar irradiance) on avocado fruit and shoot growth as well as growth responses to changes in the photosynthetically active radiation (PAR). The aim of the present study was to determine the effect of use of 30% crystal shadenetting on avocado growth and flowering. Four-year old ‘3-29-5’ avocado trees were covered with 30% crystal shadenetting with the remainder of the orchard left uncovered (open field). The crystal shadenetting reduced the solar irradiance under shadenet by 19% compared to the control. The fruit growth rate was greater under the shadenet whilst the shoot growth was greater in the open field. Bee activity improved under shadenet with the addition of extra beehives. Flowering stages and flowering intensity followed the same trend for both treatments.

Keywords: ‘3-29-5’ avocado, bee activity, flowering, fruit growth

5.2 Introduction

The key objective in any orchard is profit and sustainability, and profitability relies on the production of high quality fruit. Productivity is influenced by solar energy (Jones, 2013). Jones (1998) concurred that orchard productivity depends on the interactions between microclimatic factors and the resultant influence on plant processes such as photosynthesis, respiration, transpiration and translocation. Moreover, tree productivity relies on the interaction and balance between root and shoot growth, flowering and fruiting. Above all, the photosynthetic capacity of the tree controls production (Kirschbaum, 2011). Wolstenholme (1995) discussed factors affecting productivity in avocado production as “evolutionary adaptive strategies”, “tree architecture and branching pattern”, environmental limitations, as well as diseases and extreme weather events such as hail, wind and drought.

There is growing popularity of using shadenet to ensure sustainable fruit production and quality by controlling adverse weather effects on tree growth and productivity. In general, the need for improved fruit quality and increased risk of damage to crops are the drivers for the use of shadenet. Covering fruit trees with shadenet protects fruit from sunburn in areas with excessive solar irradiance and trees from wind and hail damage, in areas with high frequency of hailstorms and strong winds. The use of shadenet is associated with many vegetative and reproductive plant responses: flowering, change in tree vigour, and external as well as internal fruit quality (Stamps, 2009). These changes or responses are associated with modifications in the microclimatic conditions such as air temperature and RH, solar irradiance and PAR. PAR plays a role in photomorphogenesis and thus has an imperative part in growth responses including photosynthesis, fruit colour development, flower initiation, carbohydrate allocation in addition to variations in growth pattern of leaves, shoots and fruits (Correlli-Grappadelli *et al.,* 1994).

In avocado production, low harvests are frequently linked to vigorous vegetative growth and are also limited by insufficient vegetative growth (Köhne, 1988). Hence, production can be improved by management practices that lessen vigorous growth. Nonetheless, in order to maximize yields, better rootstocks have been developed, as well as proper fertilisation, irrigation, physical and chemical tree growth management (Köhne, 1988). Despite productivity being affected by several factors, the most critical step is pollination which leads to fruit set (Dixon and Sher, 2002). Avocados have a synchronous dichogamy which limits closed pollination. Nevertheless, the effect of shadenet on morphophysiological responses has not been determined under field conditions.

Growing plants under shadenet results in different responses since plants respond differently to PAR, quality and amount. The interaction between species, cultivar and environment, management practices and shadenet is complex. Iglesias and Alegre (2006), working on 'Mondial Gala' apples, determined that the increase in tree vigour under black and crystal shadenet was due to a reduction in radiation levels and heat stress. These reductions would decrease plant water stress, improve the rate of photosynthesis and accessibility of carbohydrates, and consequently increase tree vigour. Retamales *et al.* (2008) worked on high bush blueberry cultivar Berkely in Chile using four types of coloured nets black, red (50%), gray (35%) and white (50%). Increased internode, leaf and shoot lengths as well as leaf width were observed under black shadenetting which reduced PAR the most, whilst no change was observed under red, gray and white. In kiwifruit, the number of flowers and inflorescences per shoot were reduced under shadenet (blue, gray, red and white) ranging from 20 to 27% compared to the no net treatment (Basile *et al.,* 2008).

In relation to fruit size, Gindaba and Wand (2005) reported a decrease in fruit growth of 'Cripps Pink' and 'Royal Gala' apples under shadenet, while Smit (2007) working on 'Royal Gala', 'Cripps Pink', 'Fuji' and 'Braeburn' under 20% black shadenet found an increase in fruit growth under shadenetting. Iglesias and Alegre (2006) noticed no change in apple fruit growth and concluded that shadenetting did not have an effect on fruit size. The diameter of 'Topred Red Delicious' (TRD) apple was not influenced by shadenet (Shahak *et al.*, 2008). However, Lakso and Correlli-Grapadelli (2012) noted an instantaneous decrease in fruit growth when covered by 30% netting. All these fruit growth responses under shadenetting have been linked to a reduction in radiation availability (Gindaba and Wand, 2005).

The aim of the study was to evaluate the effect of shadenet on: 1) tree growth, 2) bee activity, 3) flowering intensity, and 4) flower opening and closing. The hypothesis was that there would be an increase in fruit and shoot growth under shadenet and possible negative effects on bee activity.

5.3 Materials and methods

The experiment was conducted in the subtropics in a commercial orchard located on Everdon Estate outside Howick, KwaZulu-Natal province, South Africa (29° 26′37″S, 30°16′22″E, 1080 m altitude) in the 2014 and 2015 seasons. This portion of the experiment was done on the same part of the orchard as in Chapter 3.

5.3.1 Fruit growth

In February 2015, '3-29-5' avocado trees were tagged with coloured tags for growth studies. Fruit were randomly chosen on the sides of the tree and were only tagged after the November fruit drop. Two fruits per tree (20 trees per treatment) of dove-egg size were selected. The tagged fruit were marked at the equatorial position or at the place of greatest diameter (Figure 5.1). Fruit growth (length and diameter in mm) was measured with a digital calliper at the marked position. All measurements were done between 10h00 and 12h00 (Lee and Young, 1983) fortnightly. Fruit growth rate (mm day^{-1}) was calculated by dividing the difference in measurement between two measurement dates by the number of days in the interval. At harvest, mean fruit mass and total yield per tree were also recorded.

Figure 5.1: A tagged fruit marked at the point of greatest diameter being measured for growth

5.3.2 Shoot growth

On the same trees used for fruit growth, a shoot at each cardinal point was randomly selected. Shoot growth (mm) was recorded at the same time and date as fruit growth using a measuring tape which was calibrated using a digital calliper. Measurements were done from a marked reference node to the base of the terminal bud. Measurements were from the start of the terminal bud to the end point.

5.3.3 Flower and shoot rating

The same 20 trees were monitored for flowering intensity as well as flower and shoot rating. Flower and shoot rating were monitored visually on a scale of 1-6 in table 5.1 (Alcaraz *et al.*, 2013; Salazar-Garcia *et al.*, 2013).

Table 5.1: Scale for shoot and flower rating

Stage	Description
1	Implied floral bud initiation
2	Inflorescence
3	Flower development (anthers and gyna formation)
4	Flower development and ovule development
5	Anthesis
6	Fruit set

On each of the trees, four inflorescences located in the four quadrants were randomly selected for the study. Flowering and shoot intensity were monitored according to Table 5.2. This study took place during '3-29-5' flowering season from early August to early October 2015. Identification of the different stages was guided by Figure 5.2.

Stage 1

Stage 2

Stage 3

Stage 4

Stage 5

Stage 6

Figure 5.2: Different floral development stages (Anonymous, Westfalia)

Table 5.2: Flowering intensity rating scale (adapted from Cutting (2003))

Score	**Description**
1	Normal indeterminate flowering with vigorous growth (>30 flowers)
2	Light flowering with vigorous growth (20-30 flowers)
3	Very light flowering with vigorous growth (10-20 flowers)
4	Very light flowering with vigorous growth (<10 flowers)
5	Vegetative growth without flowers
6	Light determinate flowering with moderate vegetative growth
7	Heavy determinate flowering with moderate vegetative growth
8	Very heavy determinate flowering with weak vegetative growth
9	Very heavy determinate flowering without vegetative growth
10	Very heavy determinate flowering associated with leaf drop

5.3.4 Flower opening and closing and bee activity

Flower opening was measured using a scale by Ish-Am (2008). '3-29-5' is an A-type cultivar which opens in the female stage in the morning and closes in the afternoon to re-open the following afternoon in the male stage. Flower opening and closing and possible overlap were monitored when the inflorescence was at stage 4 (Figure 5.2). Flowering stages were measured using the terminology of Ish-Am (2008) (Table 5.3). Five trees from the 20 trees used for growth measurements were used for this part of the study. On each of the trees, four inflorescences were labelled and flower opening and closing was monitored in 2-h intervals from 08h00 to 16h00. Bee activity was measured on half of the tree (northern and eastern sides) and later equated to bee count per tree assuming an almost equal number of bees is active on the other half of the tree. The number of bees per tree was counted using a handheld tally counter. Bee activity was rated according to Table 5.4. Since bee activity and flower opening are related to weather conditions, air temperature and RH during this period were recorded (Chapter 3). However, in 2014 a different scale and treatments were used for bee activity. In 2014, bee count was done three times at 0900, 12h00 and 15h00 under the shadenet and in three control sites.

Table 5.3: Flower opening and closing stage ratings (Ish-Am, 2008)

Flowering stage	Description
C1	Closed flower
F1	Female flower opening
F2	Fully opened female flower
F3	Female flower closing
C2	Closed flower in an interim overnight pause.
M1	Opening of the male flower
M2	Male flower releases pollen
M3	Closing of the male flower
C3	Pollinated flower

Table 5.4: Bee activity scale (Ish-Am, 2005)

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

5.4 Results and discussion

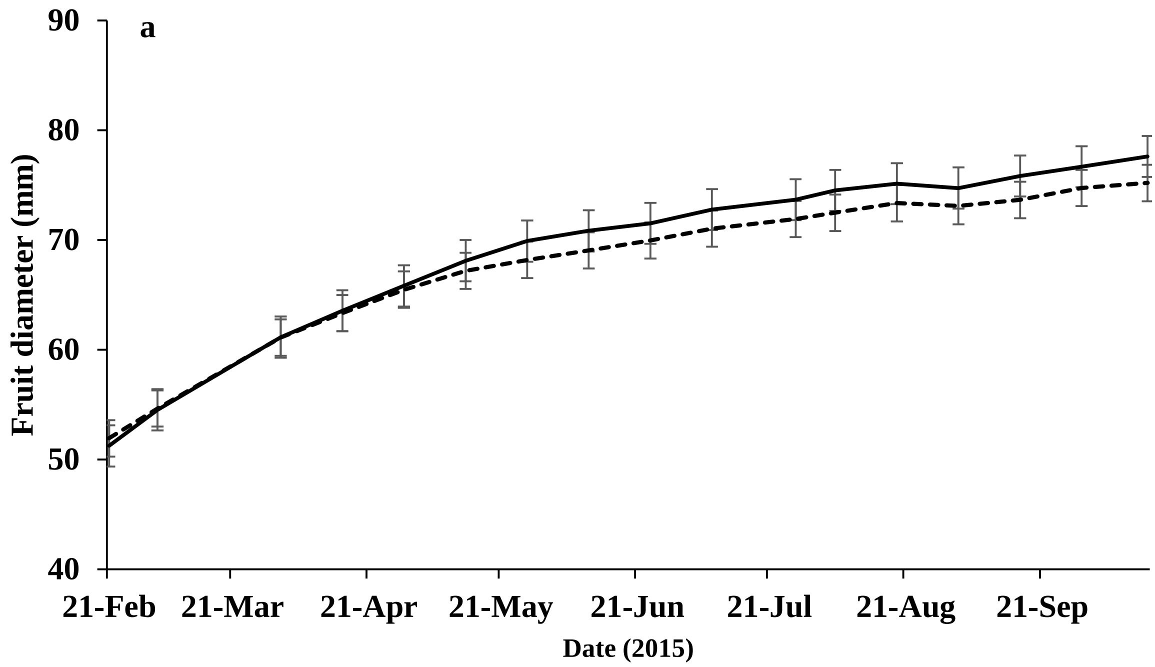
5.4.1 Fruit length and diameter

For the entire season fruit growth under shadenet was greater than in the open field in terms of diameter and length (Figures 5.3a and 5.4a). At the commencement of the measurements, fruit size was the same for both treatments, but the difference increased as the season progressed. Changes in fruit length were consistent with fruit diameter with fruit under shadenet larger. Relative growth rates were greater under shadenet.

The higher fruit growth rate under shadenet was consistent with results of apple fruit growth (Smit, 2007; Shahak *et al.*, 2008; Solomankin and Blanke, 2008), peach (Shahak *et al.*, 2008) and kiwi fruit (Basile *et al.*, 2008). The increased growth rate of '3-29-5' fruit under shadenetting may be attributed to sufficient accessibility of water and nutrients, and variations in supply and amount of photo-assimilates and changes in hormone balance (Craita and Gerats, 2013). Increased growth rate can also be a result of reduced photo-inhibition and heat and PAR stress from the scattered and reflected radiation under the shadenet. Since tensiometers were used to schedule irrigation, water is an unlikely cause of differences between shadenet and open field. However, reduced evapotranspiration under the shadenet may result in water being more accessible causing increases in carbohydrate production and availability in leaves which will in turn be utilised for fruit growth (Raveh *et al.*, 2003).

Changes in the microclimatic conditions under shadenet are likely to have had an effect on fruit size. In an environment with high air temperature and low RH, fruit expansion can be reduced as a result of high VPD (Bastías *et al.*, 2012, 2014). However, the role of VPD was not clearly shown in this study, since diurnal fluctuations in fruit size were not determined. Hence, in future research there is a need to measure diurnal fluctuations which may help give a clearer indication of the role of VPD and transpiration among other factors.

Wunche and Lakso (2000) argued that the larger fruit size attained under shadenet was likely due to the efficiency of the tree to convert energy into fruit. If the plant is using less energy to maintain itself (from reduced stress), then it can expend more energy on growth. The 30% crystal shadenetting used in this study reduced the incoming solar irradiance by 19% (as shown in Chapter 2). Reduced PPFD, as a result of the netting, resulted in less demanding microclimatic conditions which may have led to an increased net CO_2 assimilatio. The resulting additional photosynthates are then available for increased fruit growth. A decrease in the available PPFD affects carbohydrate distribution between fruit and shoots (Corelli-Grappadelli *et al.*, 1994). Hence, in this study, fruit growth under shadenet may have increased at the expense of shoot growth.



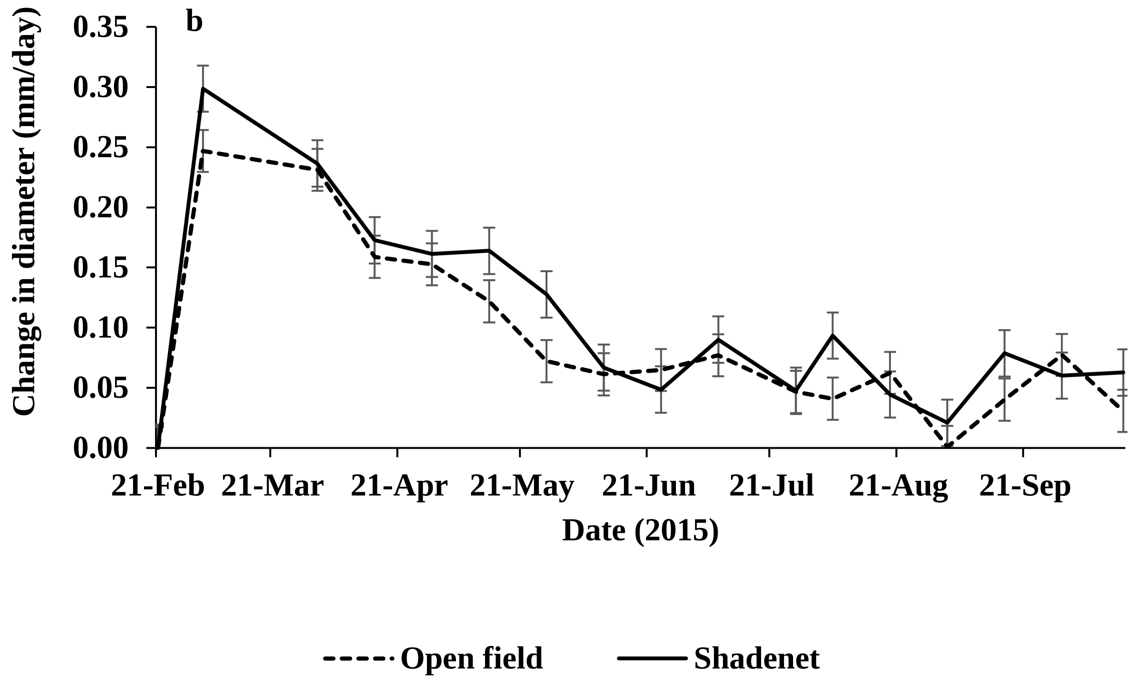
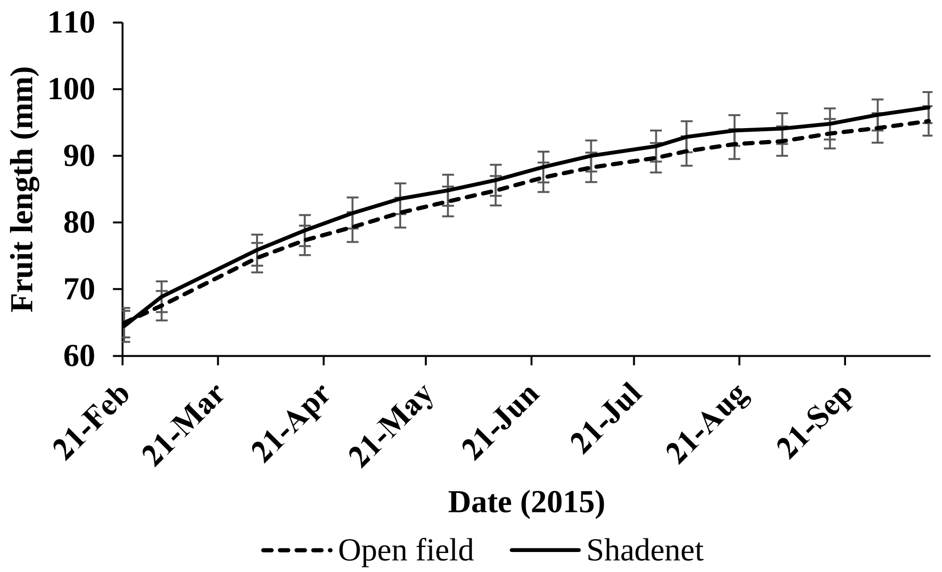


Figure 5.3: a) Average change in fruit diameter (mm) from February 2015 until harvest and b) rate of change in fruit diameter in mm per day. The data are the mean of 40 fruits per treatment. Vertical bars on points are SE of the mean

a)



b)

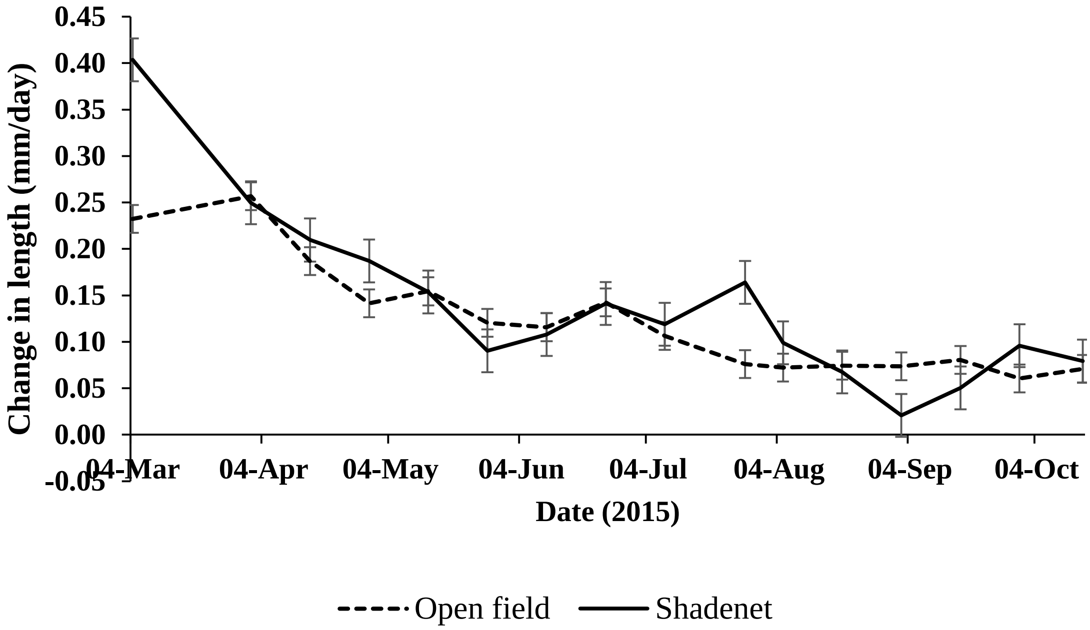


Figure 5.4: a) Average increase in fruit length increase for both treatments and b) average rate of change in fruit length. Each data point on the graph represents an average of 40 fruits per treatment. Vertical bars on points are SE of the mean

5.4.2 Shoot growth

The average shoot length of trees under shadenet was reduced compared to the open field. Under shadenet, shoot growth was greatest on the north facing shoots, followed by south-, west- and east- facing shoots (Figure 5.6a). In the open field, the greatest increase was on the north facing, south-, east- and west facing shoots (Figure 5.6b). The rate of shoot growth on the '3-29-5' avocado trees used in the study was between 0.025 and 0.3 mm day^{-1}. In this study, the cumulative shoot length had, possibly, a tendency towards a sigmoidal pattern (Figure 5.5) for both treatments which is distinctive of shoot growth pattern of many plants (Schroeder, 1953). The results of shoot growth were not consistent with results from other studies (Retamales *et al.*, 2008; Bastías and Correlli-Grapadelli, 2012) that reported a greater shoot length under photoselective netting in comparison to apple trees grown in the open field.

In this study, shoot growth at different aspects varied. However, in the open field they tend to be greatest on the side with most solar irradiance, which is the north side. However, differences between the overall shoot growth of the different sides of the tree were insignificant (Table 5.5). Thus the possibility of shadenetting or open field experiencing competition for photoassimilates from the different parts was highly unlikely. Nonetheless, the slight differences can be as a result of shoot position on the tree. In the study, there was no apparent link between microclimatic factors such as air temperature, rainfall and soil water, on shoot growth. This can be attributed to increased radiation scattering under the net resulting in greater "whole tree" photosynthesis under the net.

From the results obtained in the study, the start and end of shoot growth was not affected by shadenetting. The difference in shoot length can also be attributed to physical features of shoots for instance shoot length at the beginning of the study (Dixon, 2007). Dixon (2007) further reported that shoot length and thickness has an impact on the extent, rate and period of shoot growth. Better radiation levels on the north quadrant may have had an influence on greater shoot length associated with that side. However, shoot growth does not take place independently of other phenological events, hence shoots can compete for nutrients. Indeterminate shoots compete with developing shoots for photoassimilates. Shoot growth measurement were carried out over only one season. If the trend continued, there may be significant differences in the medium term. This may affect the pruning strategy of the orchard.

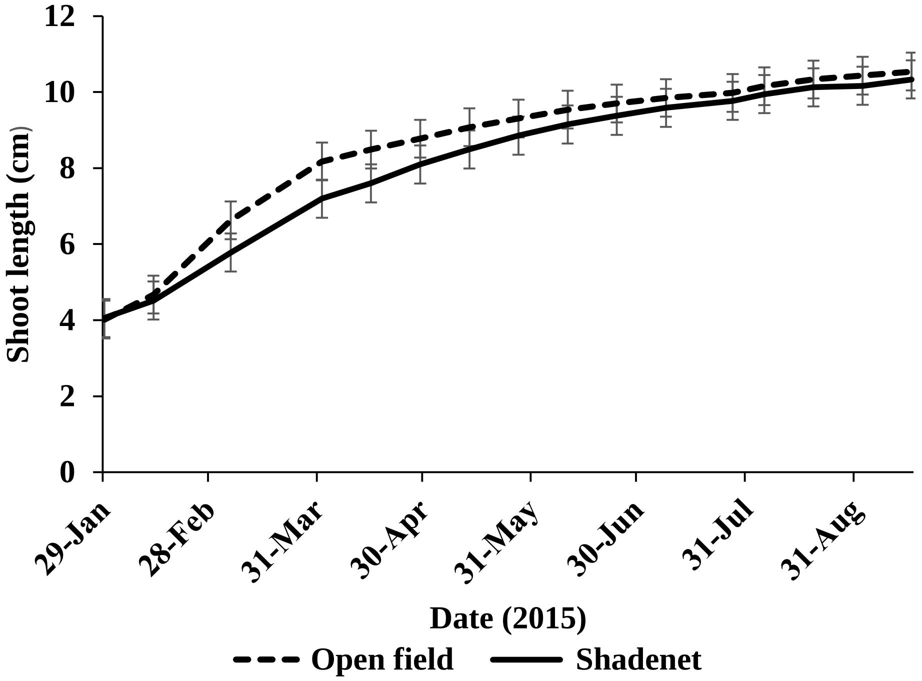
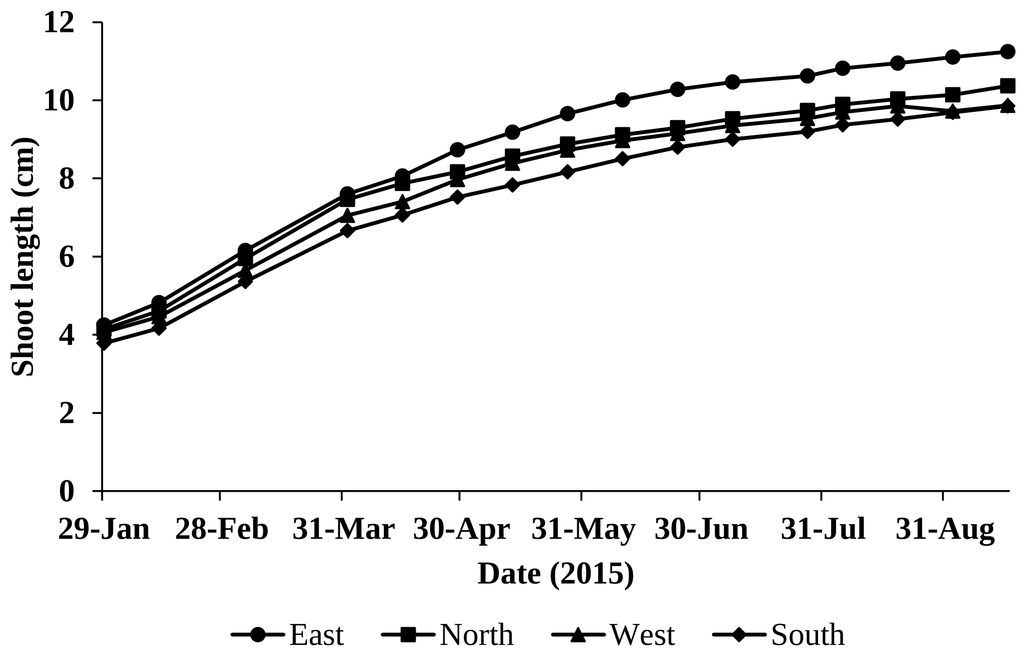


Figure 5.5: Cumulative shoot length of both treatments from January to September 2015. Each point on the graph represents an average of 80 shoots. Vertical bars on points are SE of the mean

a)



b)

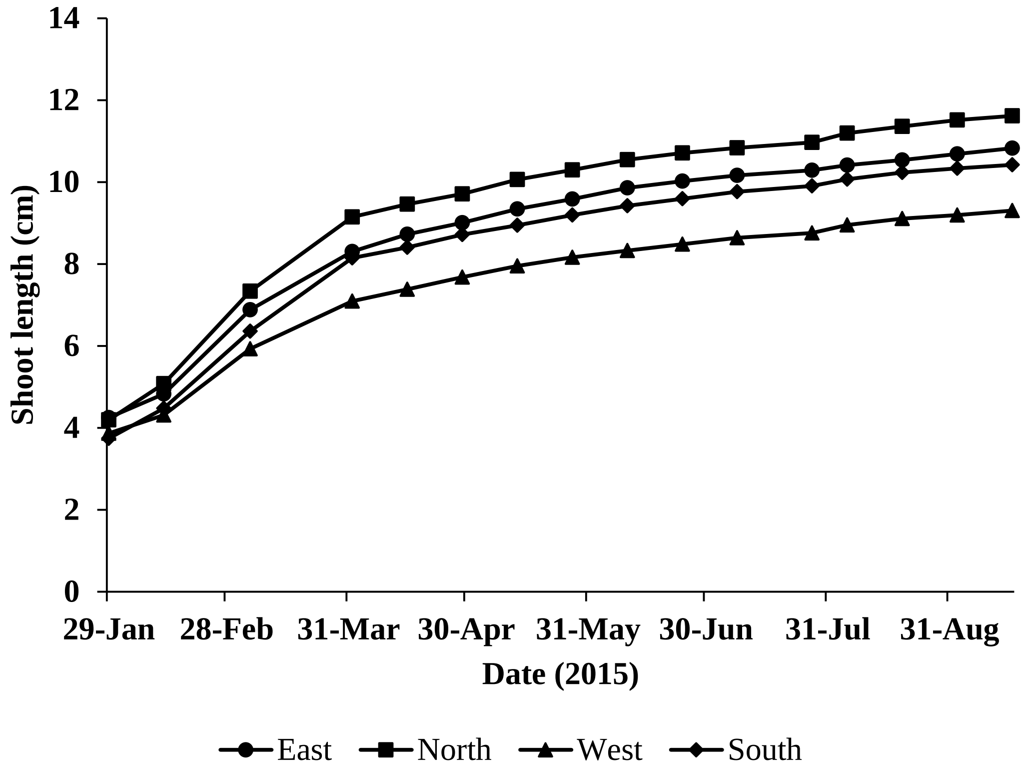


Figure 5.6: Average increase in shoot length on each shoot measured at a two-week interval on each cardinal face of '3-29-5' avocado tree under a) shadenet b) open field. Each point at a given date is an average of 20 trees. Vertical bars on points are SE of the mean

Table 5.5: Results from the analysis of average total shoot growth (mm) and growth rate (mm/day) of '3-29-5' avocado trees.

Characteristic	Aspect	Shadenet	Open field	P-value
Shoot length (mm)	East	90.00	89.80	0.984
	North	83.60	96.30	0.097
	West	81.20	77.00	0.513
	South	77.80	86.10	0.248
Shoot growth (mm/day)	East	0.3	0.2	0.674
	North	0.2	0.3	0.684
	West	0.2	0.2	0.752
	South	0.2	0.2	0.931

*Significant at $p<0.05$

5.4.3 Bee activity

Bee activity during the 2014/15 season was moderate with an average of six bees per tree (Figure 5.7) which was below the recommended 20-40 bees per tree under Israeli conditions (Dixon and Sher, 2002). However, the reduction seemed to be independent of treatments since both treatments had limited bee activity. During the 2014/2015 season there were five hives under the shadenet. The introduction of more beehives under shadenet during 2015/2016 season increased bee activity under net when compared to 2014/2015 season. Despite the recommended three hives per hectare (van den Berg, 2001), 20 hives were placed under the shadenet which was within the Ish-Am (2008) recommendation. In 2014, bee activity was rated three times a day and the results given as an average number of bees per tree at a given time of day (Figure 5.7). The greatest number of bees was observed around midday with a decline in bee activity as the day progressed. This is thought to be as a result of high air temperature usually recorded around midday and the dependence of bee activity on air temperature.

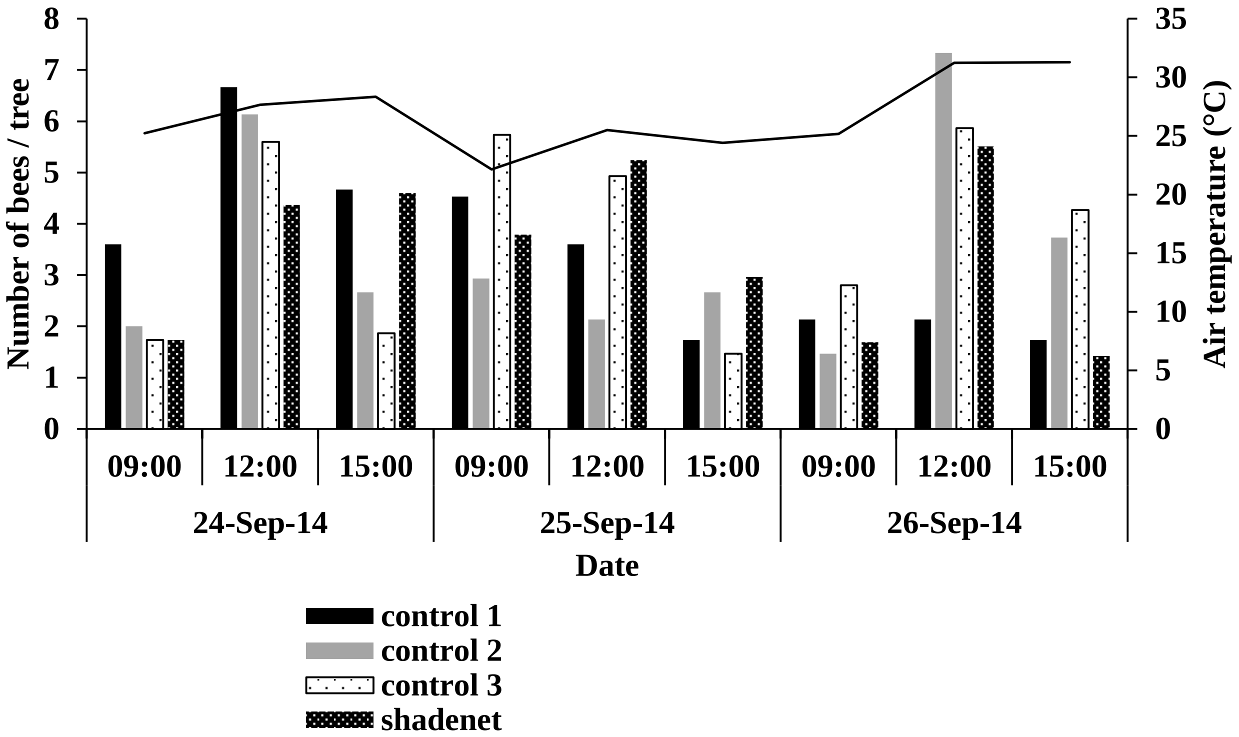


Figure 5.7: Bee activity in the 2014/2015 season. Control 1, 2 and 3 are control blocks with 10 trees from each block used. However, the time taken to go around the blocks did not allow for bee counting within the same period of time. The black line is showing maximum temperature at each given time measured by Hobo air/rh temperature sensors.

During the 2015/16 season, bee activity increased regardless of treatment compared to the previous season. Microclimate seemed to play a role in bee activity with higher activity being noted on the 15th September when air temperature was greater than 30 °C (Figure 5.8). The average number of bees per tree was 33 in the open field as compared to 24 under shadenet. Bee activity reached a peak at noon and declined in the afternoon for both treatments. On the 14th of September the number of bees under shadenet was 50% higher, and this can be attributed to the windy condition in the open field which affected bee foraging activity. Weather conditions played an important role for both treatments since no bee activity was seen on the 17th and 18th of September when the average air temperature was less than 13ºC and it was raining during both days. This is consistent with normal behaviour of bees (Dixon, 2006). Bee activity was affected by air temperature, humidity, wind speed and rainfall regardless of the treatment. However, more bees are probably required for avocados especially under the shadenet. The upper limit of the standard recommendation (i.e. 10 hives/ha) appears to be sufficient though.

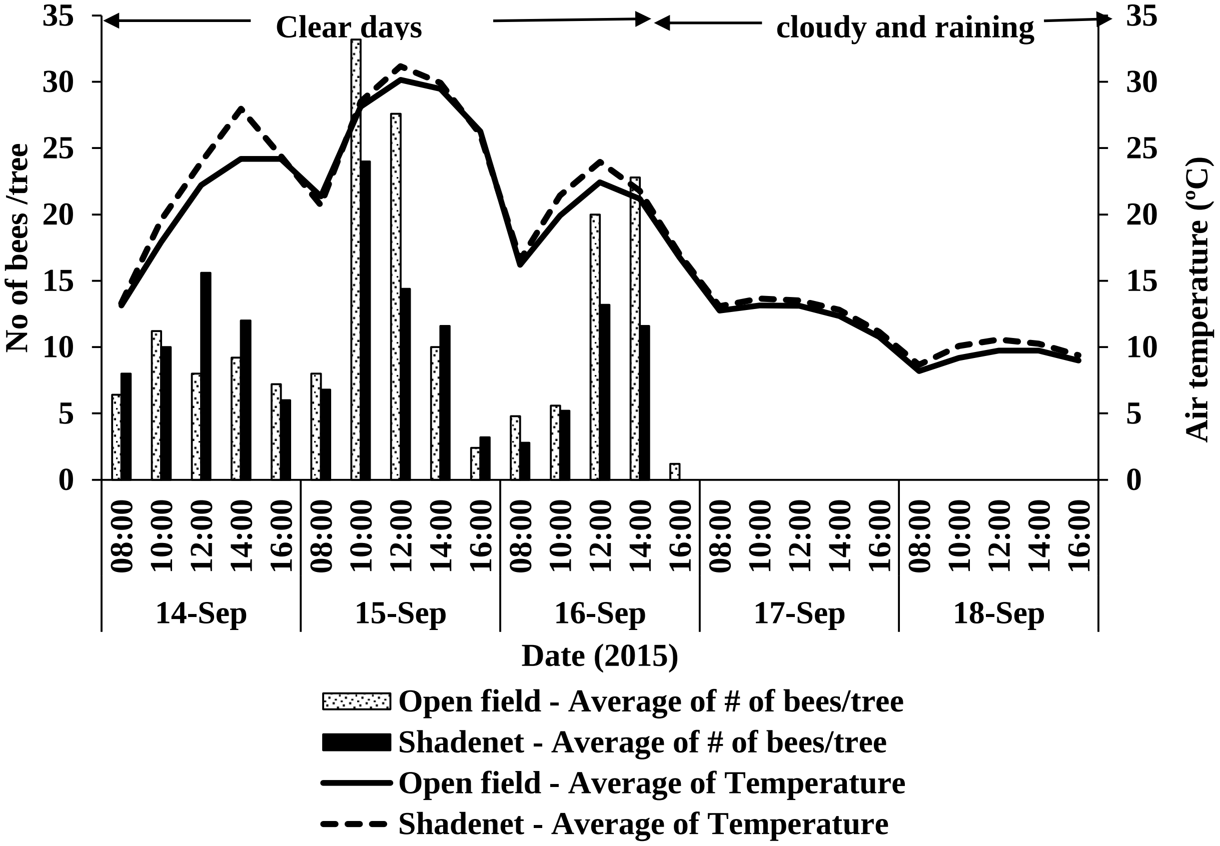


Figure 5. 8: Bee activity and corresponding temperatures at a given time from 14 to 18th September 2015 under shadenet and open field

5.4.4 Flowering intensity

The flowering intensity was high for fruit trees under shadenetting (Table 5.6). Shahak *et al.* (2008) linked high flowering intensity under photoselective nets to the microclimate. Flowering intensity is greatly influenced by the radiation quantity and quality. Since Avocado is a day neutral plant, flowering intensity is more dependent on temperature than quantity and quality of radiation.

Table 5.6: Final flowering intensity determined for twenty trees with four shoots per tree for spring flush units.

Treatment	Score	% of trees
Shadenet	1	10
	2	10
	3	10
	7	30
	8	40
Open field	1	20
	2	5
	3	30
	4	15
	6	10
	7	20

5.4.5 Flower opening and closing

'3-29-5' is an A flowering type cultivar. The opening and closing of '3-29-5' flowers seemed not to be affected by shadenetting (results not shown). Flowering opening and closing was independent of the treatments, following the same trend for both shadenet and open field. Hence, differences in pollination must be affected by factors other than flowering dichogamy. However, another microclimatic condition that can affect pollination is RH since it dries out pollen and stigmas (Waser *et al.*, 2001). Humid conditions maintains receptivity of stigma to pollen even though pollen may fail to fertilise the flower (Davenport, 1986). Flower closing was delayed from the 16th to the 17th September 2015 due to cold weather and rain. Flowering is affected by low temperature whilst cool nights, cloudy mornings or windy days can delay opening and closing of morning flowers (Dixon, 2006).

5.5 Conclusions

The 30% crystal shadenetting resulted in increased fruit growth of '3-29-5' avocados and reduced shoot growth. Although bee activity was reduced under shadenetting, there was adequate bee activity to set an adequate crop according to guidelines. However, this needs to be determined at harvest in 2016. Shadenetting did not affect the daily course of flowering. Flower opening and closing was influenced by the environmental factors, and not affected by shadenet. However, flowering intensity was greater under shadenet.

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6 THE EFFECT OF SHADENET ON ‘3-29-5’ AVOCADO FRUIT QUALITY AND YIELD UNDER COOL SUBTROPICAL CONDITIONS IN SOUTH AFRICA

6.1 Abstract

The objective of this study was to evaluate the effect of 30% crystal shadenetting on avocado fruit quality and yield of ‘3-29-5’ avocado. The study was carried out during the 2014 and 2015 seasons. Evaluation of the fruit quality was based on the incidence and severity of wind scarring, lenticel damage, sunburn and physiological disorders after two weeks in storage. Wind damage was significantly reduced by up to 50% under shadenet in both seasons. Open field fruit had minimal sunburn so the difference was negligible. This was because ‘3-29-5’ bears a large proportion of fruit inside the canopy, away from direct sunlight. Physiological disorders were absent in both treatments, despite the late harvest in late November. The average yields for shadenet was 16.50 and 14.73 t ha^{-1} in 2014 and 2015 respectively, while for open field it was 14.73 and 9.18 t ha^{-1}.

Keywords: fruit quality, post-harvest, sunburn, wind damage, yield

6.2 Introduction

The avocado industry in South Africa is export-oriented. Hence, there is a need to produce export quality fruit. Despite South Africa being one of the leading exporters to Europe, it is still having problems with fruit quality. Nelson (2010) reported the 2009 avocado export season to Europe had been marred by fruit of poor external quality. Good fruit quality is as a result of the interaction between pre- and post-harvest treatments, and hence the necessity to enhance fruit quality after harvest. In the face of competition from other avocado producing countries such as Peru, pre-harvest protocols to increase the proportion of export grade fruit, by improving external fruit quality, are needed. Use of shadenetting is one method that has been gaining popularity as a means to improve fruit quality in vegetable and fruit crops.

Avocado (*Persea americana* Mill) is a climacteric fruit with regular ethylene production after harvest (Kader, 1997). It only ripens after being detached from the tree. Changes in taste and texture characterise fruit ripening, making it a fruit acceptable for consumption. Improved avocado quality is based on correct cultivar choice as well as growing practice (Ferguson *et al.*, 1999). The black-skin cultivar '3-29-5' was determined to be suitable as a late season crop (Blakey and Wolstenholme, 2014). Smith *et al.* (1997) identified size, shape, flavour, firmness, storage life, scarring, internal disorders, diseases and insect damage (White *et al.*, 2009) as the main avocado fruit quality constraints.

Definition of fruit quality depends on the whole value chain with each link having its own opinion of fruit quality. In general, fresh fruit quality has been regarded as a lack of defects or degree of excellence (Shewfelt, 1999). It has also been defined as a number of features that make fruits or vegetables acceptable to customers and consumers. However, eating quality is of importance and is determined by fruit maturity based on maturity indices (Kader, 1992). Avocado fruit ripening and post-harvest quality has been found to be affected by chilling injury, temperature, growing conditions, and maturity at harvest (Arpaia *et al.*, 2004). Colour plays a key role in the appearance of fruit and vegetables and can therefore influence the customer's perception of the product quality. The distributors in the avocado industry do not like receiving hard but coloured avocados, due the presumption that the fruit has begun to ripen prematurely, but late season black-skin cultivars are often coloured at harvest. However, the avocado industry involves a number of key players with different quality interests. The important quality characteristics in avocado are outlined in Table 6.1.

Table 6.1: Quality parameters valued by different members in the avocado supply food chain (Schaffer *et al.*, 2013)

Grower	Packer	Agent	Retailer	Consumer
Size	Size	Size	Size	Size
Shape	Gradable defects (% pack out)	Consistent/ predictable level of defects	Shape	Shape
Skin defects	Freedom from pests	Same fruit size for the whole pallet	Skin colour	Skin markings
Maturity	Maturity	Predicting ripening	Absence of skin defects	Ripeness stage
		Maturity	Absence of diseases	Flesh defects
		Absence of disease	Ripeness stage	Flavour
		Freedom from pests	Maturity	Texture

6.2.1 Quality characteristics of avocado

Quality attributes of horticultural produce include sensory, nutritive, physical and chemical attributes (Abbott, 1999; Forero, 2007; Kassim *et al.*, 2013). Eating quality is also of importance to the consumer and this includes colour, texture, flavour and aroma (Lee *et al.*, 1983). Quality characteristics are grouped into physical, sensory and chemical properties. Food safety is also important when exporting avocado fruit.

6.2.1.1 Physical attributes

Skin colour, texture, firmness and physiological disorders make up the physical quality parameters. The parameters entail outward appearance of a fruit that have a great impact on consumers.

Skin colour

Colour change in fruit and vegetables illustrates a physiological stage, and hence a pointer to quality in post-harvest. The colours that are observed in fruit and vegetables are as a result of pigments within the product. Plant pigments are grouped into four classes, namely chlorophylls, carotenoids, flavonoids and betalaine (Kays, 1999). Skin colour can provide a sign of fruit ripening (Cox *et al.*, 2004), although it varies among different avocado cultivars. ‘Hass’ and other “black-skin” cultivars undergo colour change from green to purple or even purple-black. Cox *et al.* (2004) reported the colour change in Hass to be due to decrease in chlorophyll, L, hue and C and increase in cyanadin-3- glucoside. Skin colour is usually measured by a chromameter or colorimeter or by eye colour rating using a panel of experienced panellists (Kassim *et al.*, 2013). Colour parameters include lightness (or brightness) (L), redness or greenness (a) and yellowness or blueness (b) (Maftoonazad and Ramaswamy, 2008, Kassim *et al.*, 2013).

Chroma and hue angle can be calculated as given by Maftoonazad and Ramaswamy, (2008):

$$C = \sqrt{(a^2 + b^2)} \quad (6.1)$$

$$Hue\ angle = \tan^{-1}\left(\frac{a}{b}\right) \quad (6.2)$$

Texture and firmness

Texture is a noteworthy pointer of avocado quality. In food products, texture is known as the total feeling that is provided with food in the mouth (Sams, 1999). Oil content is the main component of avocado (Chen *et al.*, 2009) and has been said to contribute to smoothness (Hofman *et al.*, 2002; Magwaza and Tesfay, 2015). However, Chen *et al.* (2009) demonstrated that texture was independent of an increase in oil content over harvest period. Texture is directly affected by genetics, soil moisture and temperature which ultimately affects cellular structure, and other components such as RH, and nutrient availability (Sams, 1999). Temperature stimulates metabolism, and hence ultimately has an effect on cellular structure and other components that regulate the texture (Sams, 1999). Fruit strength and the ability to resist damage when in transit is due to the relationship between texture and firmness. Texture and firmness decline as fruit ripen.

Fruit firmness in avocados is important in evaluating the degree of ripeness (Mizrach and Flitsanov, 1999; Flitsanov *et al.*, 2000; Arzate-Vázquez *et al.*, 2011). Landahl *et al.* (2009) described firmness as the force required to reach an earlier defined deformation during textural evaluation. Fruit firmness, maturity stage and storage time were shown to be strongly correlated (Mizrach *et al.*, 2000). Firmness of an unripe fruit is affected by storage temperature, and in particular low temperatures. Firmness of avocado fruit can be satisfactorily described by the fruit resistance to penetration (Kassim, 2013).

Physiological disorders

Physiological disorders result from non-living components of the environment. The most common cause are nutritional deficiencies, especially calcium. Calcium is an essential nutrient that has a critical role in fruit quality mainly due to its role as a cell wall component and in cellular signaling. Generally, sufficient Ca enables the fruit to withstand internal breakdown. Fruit are more prone to physiological disorders when they are ripe although fruit are predisposed to disorder development due to pre-harvest factors (Ferguson *et al.,* 1999). The increase of post-harvest disorders is more likely to increase with increased storage time as a result of several factors ranging from low temperature to low oxygen and carbon dioxide concentration (Morretti *et al*., 2010). Grey pulp increases later in the season, and is high in fruit that are hung late (Blakey and Wolstenholme, 2014).

6.2.2 Sensory properties

Flavour is the key sensory property which entails aroma and taste (Abbott, 1999). Total soluble solids (TSS) and titratable acidity are essential for general sensory quality (Mattheis and Fellman, 1999). Meilgaard *et al.* (1991) as cited by Mattheis and Fellman (1999), defined 'flavour' as a mixture of simple perceptions ranging from sweetness to bitterness. Volatiles in the oil are the main component of flavour (Chen *et al.*, 2009); however, avocado flavour depends on cultivar and maturity.

6.2.3 Chemical properties

Chemical attributes entail total soluble solids (TSS), total titratable acid (TTA), moisture content, dry matter and oil content.

6.2.3.1 Total soluble solids

The amount of TSS in a fruit is complementary of the carbohydrate pool which is mainly sugars (Kader, 1992). During ripening, sugar content declines (Liu *et al.,* 1999). Therefore, sugar determination provides information on fruit ripening. Carbohydrates are important in the growth and development of avocado fruit (Tesfay *et al.*, 2012). In avocados, five key soluble sugars are found and these include a less common seven carbon (C7) reducing sugar D-mannoheptulose, its reduced polyol form, perseitol, sucrose, fructose and glucose (Liu *et al.*, 1999) making 98% of the TSS. During ripening, there is a rapid decline in TSS which is associated with an increase in oil content (Liu *et al.*, 2002).

6.2.3.2 Dry matter, moisture and oil content

In South Africa, moisture content is the commercial maturity indicator ranging between 69 and 75%, depending on the cultivar in question (Kruger *et al.*, 1995, Mans *et al.*, 1995). However, the minimum moisture content for '3-29-5' is 77%. Another indicator of fruit maturity is oil content (Özdemir and Topuz, 2004; Özdemir *et al.*, 2009; Gamble *et al.*, 2010, Blakey, 2011). However, the world maturity indicator for avocado is dry matter and oil content of the mesocarp. Carlifornia and New Zealand are among the avocado industry using dry matter as a maturity index (Arpaia *et al.,* 2001; Woolf *et al.,* 2003). As the fruit matures dry matter and oil content increase (Lee *et al.*, 1983). Özdemir and Topuz (2004) reported an 8% oil content as the standard for marketing avocados. Oil content increases as fruit matures whilst concurrently there is a reduction in water content, thus is commonly expressed as percentage dry matter. Thus supports what had been set in 1925 by the California Avocado Standardization Bill which stated that oil content should be at least 10-11% of the fruit mass (Blakey and Wolstenholme, 2014).

6.2.4 Shadenetting and fruit quality

In previous studies, it has been shown that colour as well as density of the shadenet has an influence on fruit quality and tree growth. In South Africa, Smit (2007), working on four different apple cultivars, using 20% black shadenetting noted a decrease in sunburn and TSS in all cultivars. The lower TSS values were attributed to changes in CO_2 assimilation as well as water availability. Earlier, Gindaba and Wand (2005) working with kaolin particle film, evaporative cooling and 20% shadenet also noted a decrease in sunburn. The 20% shadenet also exhibited greatest colour reduction in 'Cripps Pink' and 'Royal Gala' apples. However, TSS and starch conversion were not affected by any of the treatments. Fruit firmness was more so reduced by shadenet than by the other treatments. In grapes, coloured shadenetting influenced rate of development (Shahak *et al.,* 2008). Shahak *et al.* (2008) and Gindaba and Wand (2005) reported reduced fruit russetting in pears as affected by pearl and red netting. In peaches, shadenet resulted in larger fruits with low TSS values and firmness (Shahak *et al.,* 2004).

In a study conducted in Chile on highbush blueberries grown under different coloured shadenets of different shading percentage, all shadenet treatments had no effect on the fruit soluble solids and fruit mass (Retamales *et al.,* 2006). Sun-exposed avocado fruit were more firm than shaded fruit (Woolf and Ferguson, 2000). Although there are positive effects, excessive sun exposure can damage the photosynthetic process and cause sunburn or injure fruit tissues (Woolf and Ferguson, 2000). Even though using nets mainly for prevention against hail damage, Iglesias and Alegre, (2006) reported no significant differences in fruit size distribution, firmness or fruit mass.

6.3 Materials and methods

The study was carried out during the 2014 and 2015 seasons in a commercial orchard at Everdon Estate (29° 26'37''S, 30°16'22''E) situated outside Howick, South Africa. All fruit under shadenet and in the open field were harvested on 11th of November 2014 and 24th of November 2015. Yield per tree was measured for tagged trees as well as total fruit yield for both treatments. Fruit size distribution and packout percentage was determined at the commercial packhouse. In 2014, fifty fruits per treatment were taken for quality assessments. In 2015, 100 fruits were used for quality assessments. Export grade '3-29-5' fruit (300-371 g) were delivered to the laboratory on the day of harvest. Fruit were stored for two weeks in a cold room with an initial temperature of 5 °C which was reduced to 3 °C after two days and fruit were thereafter ripened at room temperature (21 ± 2) °C, after which their external and internal fruit quality was evaluated according to the International Avocado Quality Manual (White *et al.,* 2009).

6.3.1 Skin colour

'3-29-5' is a black-skinned cultivar. Fruit colour was visually determined for fifty (2014) and 100 (2015) fruit using a scale provided by the International Avocado Quality Manual (White *et al.*, 2009): 1, emerald green; 2, forest green; 3, approximately 25% coloured; 4, approximately 75% coloured; 5, purple; and 6, black. Skin colour was evaluated at intake, out of storage and again at ripeness.

6.3.2 Fruit firmness

Fruit firmness was measured before storage, out of storage and at ripeness on each fruit. It was measured according to Köhne *et al.* (1998) by means of a handheld densimeter (5-mm tip) (Bareiss, Oberdischingen, Germany). For each fruit measurements were taken on two opposite sides located in the equatorial zone. '3-29-5' avocado fruit were considered ripe when the average firmness reading was 65 units. Fruit were gently hand-squeezed to assess firmness according to a scale provided by White *et al.*, (2009) to prevent bruising of the fruit from multiple densimeter readings.

6.3.3 External fruit quality, physiological disorders and diseases

Black cold (discrete patches), brown cold and lenticel damage (skin spotting) were also evaluated upon removal from cold storage. Fruits were cut longitudinally and rated for severity of body rots (anthracnose), stem end rots and also the severity of internal disorders like grey pulp (diffuse flesh discolouration) and vascular browning.

6.3.4 Moisture content

A sample of 10 fruits per treatment was used to determine the moisture content. The fruit sample was collected every two weeks from week 36 until harvest at week 46. In the 2015 season, moisture measurements began from week 33 until harvest in week 48. A sample from the equatorial region of the fruit was cut. Approximately 10 g of the sample was oven dried for 48 h at 65 °C and then re-weighed. Moisture content was determined as;

$$Moisture\ content\ (\%) = \frac{mass\ of\ fresh\ sample\ (g) - mass\ of\ dry\ sample\ (g)}{mass\ of\ fresh\ sample\ (g)} \times 100$$

6.4 Results and Discussion

6.4.1 Moisture content

In this case study, the orchard was covered to protect the fruit against adverse weather so that the fruit can safely be hung into summer. Therefore, minimum maturity for '3-29-5' avocados was not of importance in this study. The moisture content at harvest in 2014 was 63% (37% dry matter) under the shadenetting and 62% (38% dry matter) in the open (Fig 6.1). In 2015 fruit were harvested 2 weeks later during week 48. The moisture content at harvest was 60.8% for both open field and shadenet.

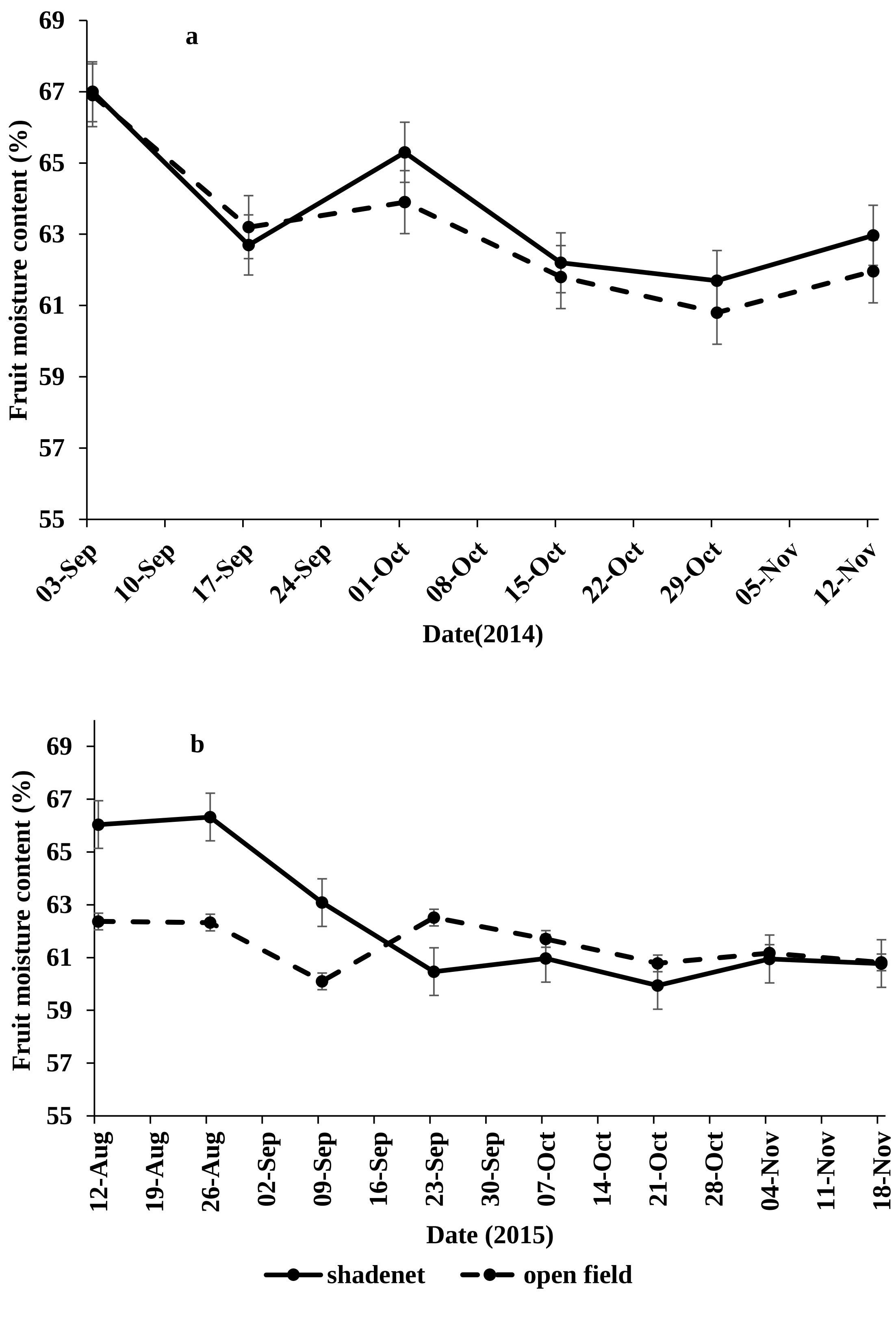

Figure 6.1: Fruit mesocarp moisture content of '3-29-5' avocado fruits for (a) 2014 and (b) 2015.

6.4.2 Yield, packout and fruit size distribution (FSD*)*

Mean yield per tree (kg tree^{-1}) decreased for both treatments year on year (Figure 6.2). However there was a 29% reduction in the open field compared to 10% under shadenet. Since yield reduction was experienced in both treatments relative to the previous year, there is no clear relationship between treatment and yield. This is likely because of alternate bearing because the 2014 season had a remarkably good yield and the fruit were hung late which induces some alternate bearing. However, yield is dependent on tree vigour and pollination (Middleton and McWaters, 2002). Other factors affecting yield include air temperature and RH due to their role during flowering and fruit set. Stored reserves in the tree avocado trees also affect yield. They are depleted after an 'on year' and thus there is insuffiient reserves to support a big crop the following season. Even though bee activity was reduced under shadenetting compared to the open (Chapter 5), in this study the focus was not on the effect of shadenet on pollination.

The yield results were in contrast to those reported by Retamales *et al.* (2008). They reported a 31% yield increase of high bush blue berry in the first year, followed by a 26% to 45% increase in the second year. The yield varied with the colour and density of the shadenet. The yield increase was attributed to better fruit set than fruit size. In table grapes, 30% yellow nets increased yields whilst 30% gray reduced yields in comparison to no net control (Shahak *et al.*, 2008). In kiwi fruit, blue, gray, red and white shadenets reduced yield, even though the reduction was minimised due to greater fruit size under shadenet (Basile *et al.,* 2008).

From these previous results of other fruit trees, the reduction in yield with respect to the avocado orchard under study, may also have been influenced by the colour of the shadenet in use. On the other hand, shadenet does not guarantee an increase in yield. The shadenet needs to address the most limiting steps in production to have an effect on such issues as severe water shortage, overgrown orchard, and insufficient bees that will limit fruit set. The FSD from 2015 (Figure 6.3) showed that there was an increased proportion of large fruit compared to FSD for 2014. However, medium-size fruits are favoured commercially.

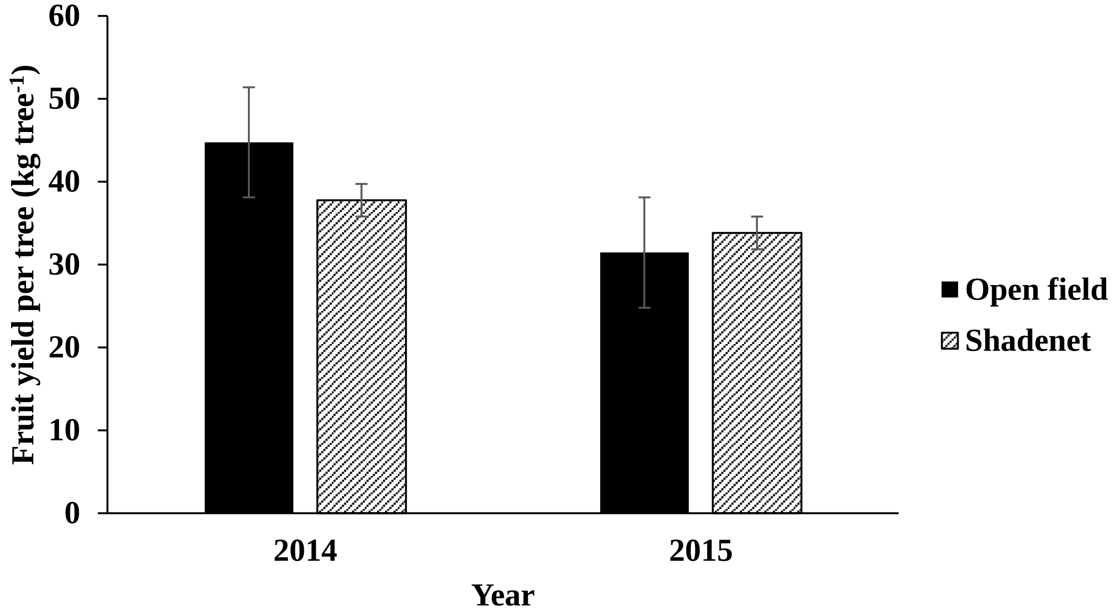

Figure 6.2: Mean yield (per tree) of '3-29-5' avocado trees. Each point represents a mean of 20 trees.

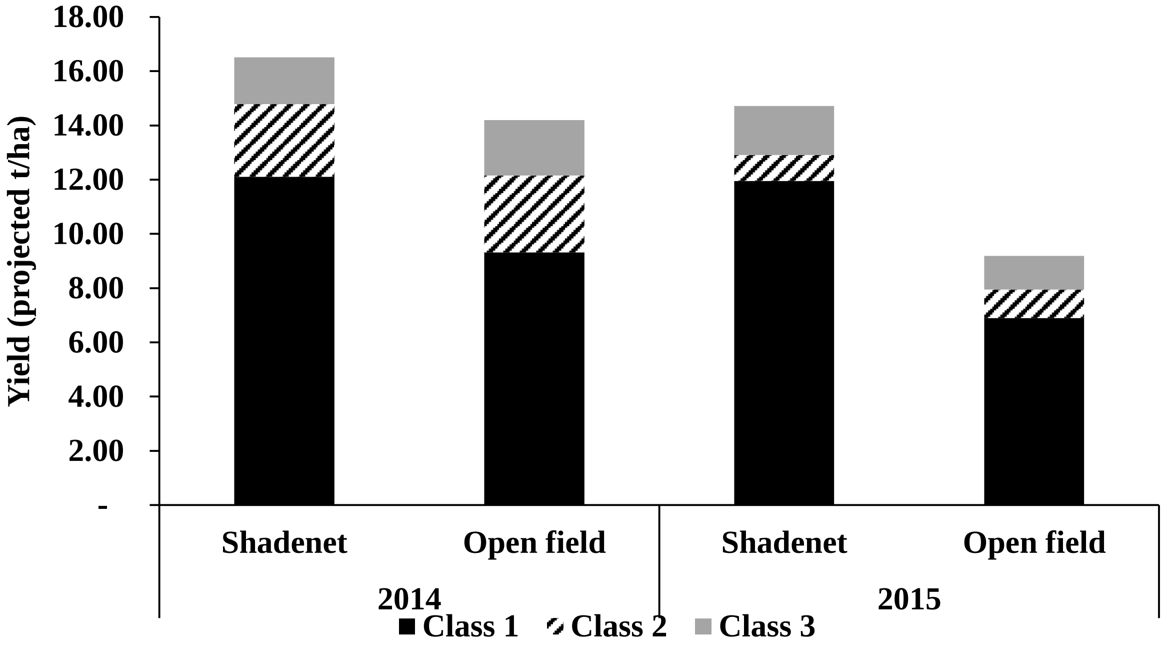

Figure 6.3: Projected yield and pack out for 2014 and 2015 under shadenet and open field: class 1 is export grade, class 2 is local market grade and class 3 is factory grade

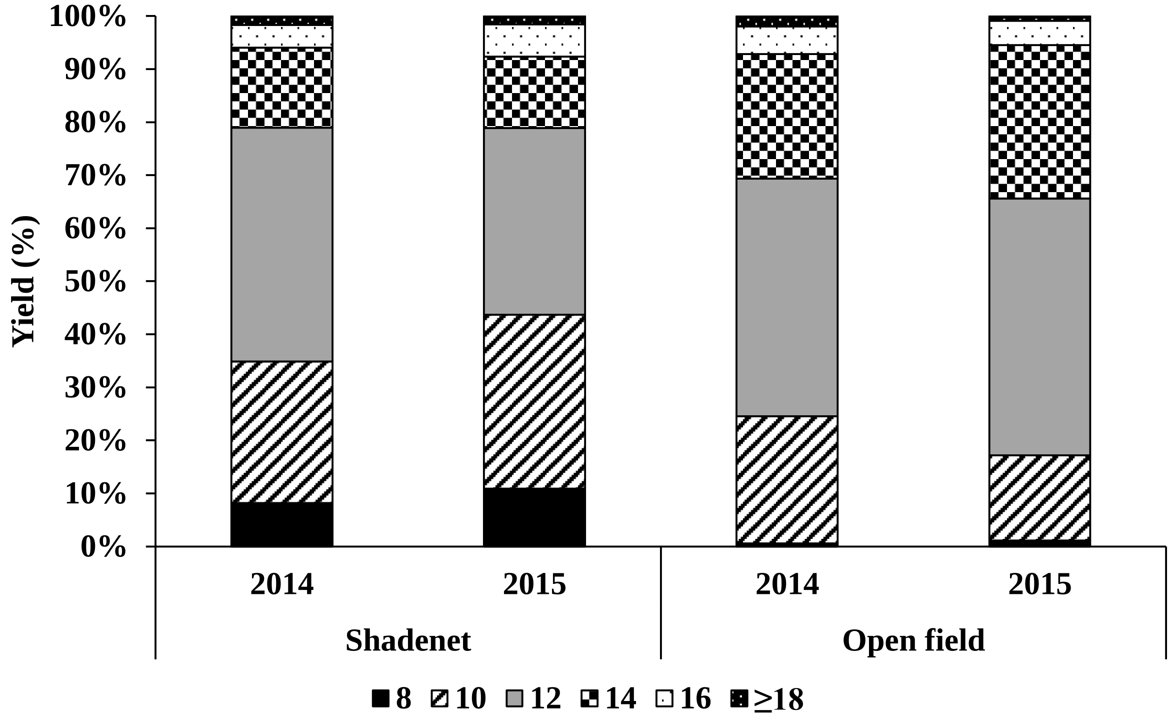

Figure 6.4: Fruit size distribution (FSD) for '3-29-5' avocado in 2014 and 2015 under shadenet and open field. The numbers 8 to 18 represents the number of fruits in a 4kg carton. Count 8 are larger fruit whilst count 18 are very small fruits.

6.4.3 Sunburn

In 2014, more than 90% of fruits in the open orchard were free from sunburn compared to 87 % under the shadenetting (Figure 6.5). Even though the difference may be small, this may have been because the shadenet was erected sometime after fruit set and the fruit had already been exposed to excess temperatures. The percentage of fruit free from sunburn is still excellent and it is unlikely that further inputs will be needed to reduce sunburn. In 2015, the percentage of clean fruits increased for both treatments with 97 and 98% for shadenet and open field respectively. The rating of 1 represents marketable in a ripening programme and ratings 2 and 3 are not. So in 2015 shadenet is almost 100% suitable for a ripening programme, this will in turn have a significant financial benefit. The reduction in sunburn could be because trees are larger and more leaves will shade more fruit. In South Africa, shadenetting reduced sunburn in apples (Gindaba and Wand, 2005, 2006; Smit, 2007). Sunburn in fruit is as a result of high air temperatures and exposure of fruits to excessive radiation (Sams, 1999; Woolf and Ferguson, 2000). However, the low incidence of sunburn in this study may be due to the fact that '3- 29- 5' bears fruits inside the canopy. Even though the shadenetting reduced the air temperature and canopy temperature slightly, there are no clear differences in sunburn incidence in both treatments.

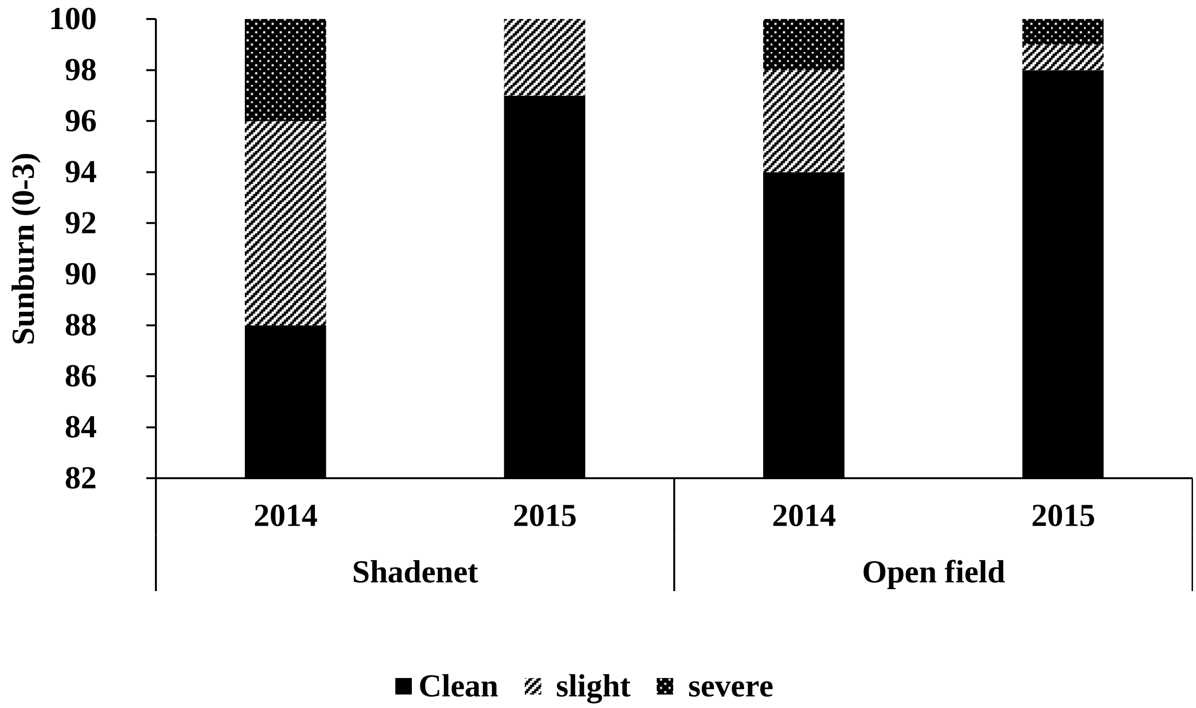

Figure 6.5: Incidence of sunburn (expressed as a percentage) in fruits harvested in 2014 and 2015: 0 is clean fruit, 1 is slightly affected, 2 is moderately affected and 3 is severely affected fruit

6.4.4 Wind damage

The use of shadenet reduced wind speed to negligible levels. As a result, wind damage on fruits under shadenet was greatly reduced (Figure 6.6). Trees in the open field had the highest percentage of wind damaged fruits with 50% of the fruits being clean in 2014 and 2015.This can be attributed to the persistent wind recorded outside even though it was termed as a light breeze on the Beaufort Scale.

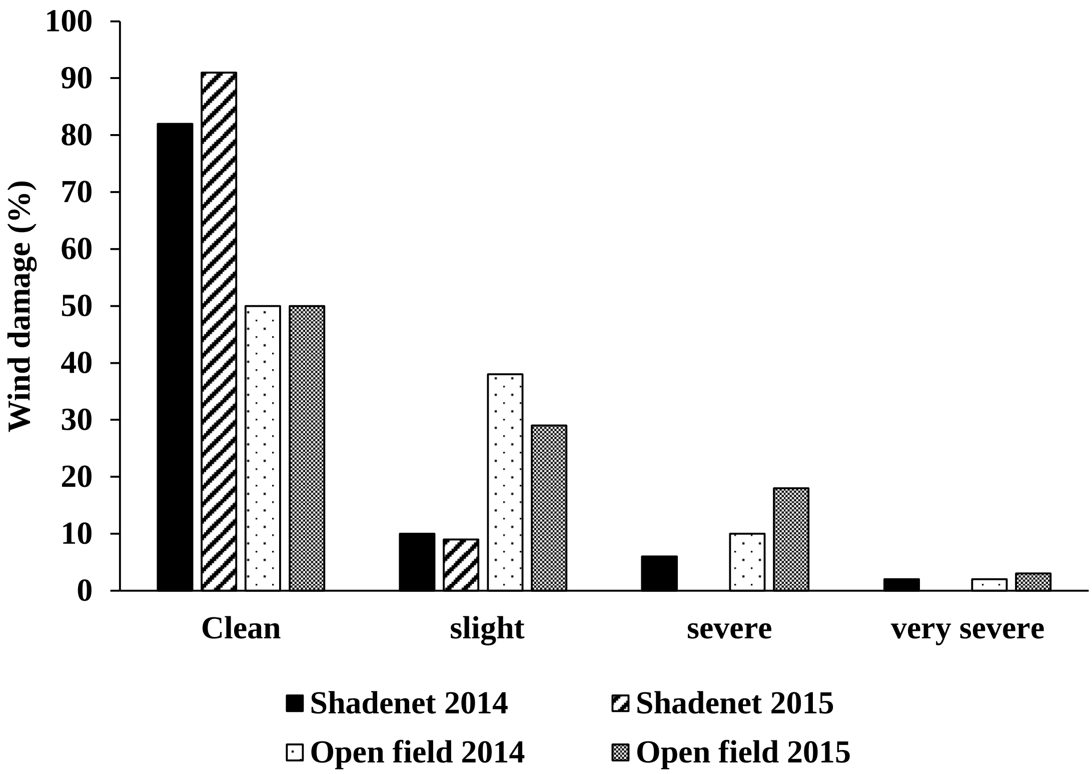

Figure 6.6: Incidence of wind damage as influenced by shadenet and open field in 2014 and 2015. Clean shows no sign of wind damage, whilst very severe and severe are not marketable.

6.4.5 Physiological disorders

In this study, there were no disorders associated with the use of shadenet except for a few incidences of grey pulp which is possible due to hanging fruit late on the tree. Grey pulp was negligible and the fruit may be able to be hung later. Hence shadenet can be used for other parameters except protection against physiological disorders.

6.5 Conclusion

Shadenet over ‘3-29-5’ avocado has been shown to protect the fruit from wind damage and sunburn. However, the use of shadenetting did not seem to have an influence on the yield and occurrence of physiological disorders during the period under investigation. With appropriate orchard management shadenet does not seem to limit yield but does increase fruit quality (Figures 6.5 and 6.6). With better orchard management, and perhaps just time, yield may increase but this will need to be confirmed with more data. The efficiency of shadenetting against hailstorm was not put to the test since the study area did not experience any hailstorm throughout the duration of the study. The potential of shadenet in reducing wind damage and sunburn should be fully exploited since this resulted in increased pack out percentage. However, this is preliminary data and more research is required to understand the effect of shadenet on other avocado quality parameters such as insect and fungal diseases. Fruit quality and yield in the open field was still very good. There seems to be a small marginal difference between shadenet and open increase in yield and quality. Hence, it needs to be considered if the expense of the shadenet warrants these small increases.

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Conclusions

The continuous production of high quality fruit that can meet international standards has always been a challenge. In avocado production, adverse weather events such as heavy or low rainfall, frost, Berg winds, wind speed, hail and higher than normal temperatures can result in yield and quality losses. Shadenetting can potentially provide a solution for many fruit production problems such as damage from sunburn, high wind speed, hail storms, intense rain and other problems encountered during the pre-harvest period. The focus of this study was to investigate the microclimatic changes associated with the use of shadenetting and how these affect tree growth, flowering, bee activity, yield, water use of '3-29-5' (marketed as Gem®) avocado compared to open-field production. Solar irradiance, wind speed, air temperature, relative humidity (RH), canopy temperature, rainfall and leaf wetness were the microclimatic variables under study. The use of shadenet altered many aspects of the microclimate compared to the open environment, in terms of solar irradiance, wind speed and canopy temperature but not as much for air temperature and RH. An intense measurement study showed that under shadenetting, there was almost no spatial variability in air temperature and RH. This result allowed the use of a single AWS system within the shadenetting to be used to represent the shadenet microclimate.

The study investigated the comparative water use between shadenet and open field using the thermal heat dissipation (TDP) method. The relationship between TDP and some microclimatic variables was outlined. The results presented were promising with trees in the open field utilising more water compared to shadenetted trees. Hence in future, shadenet can be extended to areas with limited irrigation water. Even though water use was reduced, increased fruit growth of '3-29-5' avocados was evident under shadenet. There was no clear evidence that yield was affected by the altered microclimate since hanging fruit late can promote alternate bearing. Bee activity was reduced under shadenetting regardless of the recommended bee hives being used. However, in this study it was not clear if bee activity had an effect on the reduced yield.

Generally, with appropriate orchard management, shadenet does seem to limit yield but increases fruit quality. With better orchard management, and perhaps more time, yield may increase but this will need to be confirmed with more seasons' data. The efficiency of shadenetting against hailstorm was not put to test since the study area did not experience any hailstorms throughout the duration of the study. The potential of shadenet in reducing wind damage and sunburn should be fully exploited since this resulted in increased pack out percentage. Increased pack out means more fruit is available for export.

7.2 Recommendations

South Africa is a water scarce country currently experiencing water restrictions. The restrictions are affecting agricultural farmers the most with a restriction of 50%. Therefore, research in areas that help the agriculture industry to mitigate against water shortages without affecting quality and yield are of importance. The research undertaken is one of many types of research being done to cope with adverse weather. The results can be of great importance in the future so as to deal with ever increasing water shortages in South Africa as demand increases. More field experiments still need to be done to evaluate the full potential of using different coloured shadenets as well as different densities before a final recommendation can be made.

The water use results presented in the study (Chapter 4) are based on sap flow measurements. In this study they were enough for the comparative measurement of water use between shadenet and open field. However, in future studies there is a need to validate various sap flow determination methods. This will provide correct water use values for the given orchard. In relation to water use, the use of shadenets can be introduced in many areas in which irrigation water is scarce and solar radiation is high. The results from this study were promising, demonstrating shadenet will be useful in saving water in times of high evaporative demand thus reducing irrigation costs.

The growth, yield and fruit quality results for two years are not enough to give a recommendation due to the alternate bearing nature of avocado trees. As mentioned previously, there is a need for further field studies to determine if yield, growth and fruit quality will remain consistent with the results of the first two years of the study.